Mechanical Engineering Series

Lorenzo Morello
Lorenzo Rosti Rossini
Giuseppe Pia
Andrea Tonoli

The Automotive Body

Volume I: Components Design

Springer

The Automotive Body

Mechanical Engineering Series

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The Automotive Body

Volume I: Components Design

Springer

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About the Authors

Lorenzo Morello

Lorenzo Morello received his degree in Mechanical Automotive Engineering in 1968 at the Politecnico of Turin.

He immediately began his career at the Politecnico as Assistant of Machine Design and Technologies.

Leaving the Politecnico in 1971, went to work at a branch of Fiat dedicated to vehicle studies, one that has been joined to the new Research Center in 1976. He participates in the development of cars and experimental prototypes for the ESV US Program. He has also developed mathematical models for vehicle suspensions and road holding simulations.

Since 1973 he has been involved in a major project for the development of mathematical models of the vehicle, to address the product policies of the company in facing the first energy crisis; as part of this activity he began the development of a new automatic transmission for reduced fuel consumption and a small direct injection diesel engine to be used on automobiles.

Dr. Morello was appointed manager of the chassis department of the Vehicle Research Unit and has coordinated the development of many research prototypes, such as electric cars, of-road vehicle, trucks and buses.

He was appointed manager of the same Research Unit in 1977 and has been leading a group of about 100 design engineers, dedicated to the development of prototypes. A new urban bus with unitized thin steel sheet body, with spot welded joints, a commercial vehicle that will start production later, a small lightweight urban car, under contract from the US Department of Energy, were developed in this period of time.

He took responsibility of the Engine Research Unit in 1980; this group, of about 200 people, was primarily dedicated to the development of new car engines. He has managed the development of many petrol engines according to the principles of high turbulence fast combustion, a direct injection diesel engine for cars, many turbocharged pre-chamber diesel engines, a modular two cylinder car engine and many other modified prototypes.

He was appointed Director of Product Research in 1983; this position included all applied research activities on Vehicle Products of Fiat Group. The Division, with about 400 people, was addressed to power train, chassis and body studies as well as prototype construction.

Dr. Morello joined Fiat Auto in 1983, to take responsibility for the development of new automotive petrol engines and the direct injection diesel (the first in the world for automobile applications). He was appointed Director for Powertrain Engineering in 1987; the objective of this group was to develop all engines produced by Fiat Auto brands. The most important activity in this period was the development of the new engine family to be produced in Pratola Serra, which included more than 20 different engines.

At the end of his career, he returned to vehicle development in 1994, as Director for Vehicle Engineering; this group was addressed to designing and testing bodies, chassis components, electric and electronic systems and to apply wind tunnels, safety center and other facilities.

Dr. Morello retired in 1999 and started a new activity as consultant to the strategic planning of Elasis, a new company in the Fiat Group, entirely dedicated to vehicle applied research.

Along with Fiat Research Center he participated in the planning of courses for the new Faculty of Automotive Engineering of the Politecnico of Turin, and prepared related lecture notes.

He was contract professor of Vehicle System Design and has been contract professor of Automotive Transmission design at the Politecnico of Turin and the University of Naples since 2003; he has also published a text book on this subject, on automotive chassis design, together with Giancarlo Genta, and many articles about the evolution of car technology.

Giuseppe Pia

Giuseppe Pia received his degree in Chemical Engineering in 1970 at the Politecnico of Turin.

After a military service of 15 months in the Italian alpine troops (six of them as official instructor as the Military Alpine School), he joins Stars in 1972, a Company of the Fiat Group, specializing in automotive plastic components and participates into innovation activities, particularly of engine compartment components.

He is appointed as manager in charge of product design and prototypes fabrication with particular reference to stamped dashboards and bumpers in thermoplastic materials. He starts afterwards an in field test program of computer aided design systems and performs the personnel training to the new technique that is gradually substituting the drafting board.

He takes the responsibility for Product engineering at Comind, a Company in the new Fiat Components Group, whose Plastic Division merges Stars. This new assignment includes also the research laboratories and the entire development process, from style and feasibility studies till production.

Since 1980 he is involved in the development of all car body plastic components including fuel tanks. In consideration of the high quality standards requested from car interior components, a new laboratory is developed, under his responsibility to objectively define the most important quality parameters for interior trimming, such as color, gloss and embossment.

After the merge of Comind Plastic Division with Fiat Auto in 1988, he is appointed of the responsibility of Fiat Auto Innovation Department, managing new products development, such as parking sensors, four wheel steering prototypes, automotive radars. He takes the responsibility of car interiors design for the three automobile brands of the Fiat Group.

After six years in this position, he returns to components development at Gilardini, a company of the Fiat Group and he is appointed Director of new automotive products development, such as on-board navigation systems, active noise reduction, magnesium applications for weight reduction on seat structures.

He joins Lear Corporation in 1995, a global American Company for producing interior components, particularly seats; his new assignment is Europe Engineering Vice president and from this position he takes care of Fiat Group seat supplies.

After two years he joins Ergom, a major supplier for automotive plastic components; his responsibility is the development of new car plastic components as fuel systems, fenders, dash boards, interior trimming and pedals.

He retires in 2001, but continues do perform consultancy activities for Ergom till 2002.

Many different consultancy activities both for Fiat and Ergom about body components development and engineers training are performed till 2007.

He has been contract professor of Car Interiors Design at the Politecnico of Turin since 2003.

Lorenzo Rosti Rossini

Lorenzo Rosti Rossini has been graduated in Mechanical Engineering in 1966 at the Politecnico of Milano, with a study on a tubular space frame for a 3 door coupe.

Immediately after he joined the Automotive engineering Section of the Politecnico, with the task to develop new measurement tools, such as a fixture to measure torsional stiffness of vehicles driving on the road.

In 1967 he joined Alfa Romeo and worked for the R.&D. Department till 1973, being involved in special projects, mathematical modeling and virtual analysis of different vehicle subsystems.

In this period, he developed a 16 degrees of freedom multibody vehicle model with random road excitation, to predict the vibrational loss of contact of tyres and the vibrational comfort of vehicle and seats. Moreover, he developed some mathematical models suitable to optimize suspension geometry and components design, models for engine vibration damping devices and unconventional design of hydraulic tappets for overhead camshaft engines.

In the same period, he was appointed as leader for the structure and safety Team, supporting the virtual analysis of structures in car accidents and taking part to the implementation of frame design based upon finite elements analysis.

From 1972, still with Alfa Romeo, he was involved with studies and testing in the international ESV (Experimental Safety Vehicle) Program, contributing to some invention and original patent on occupant protection systems.

In 1974 he moved to Body Design Department of Alfa Romeo, with the task to develop occupant safety subsystems and devices for body vibration reduction; afterwards, he was appointed to lead the Advanced Body Engineering Team. The first body developed by his team has been the Alfa Romeo 33.

From 1980 to 1985, he leaded as Body Chief Engineer the design and testing of new projects, among them the model 164, entirely designed with C.A.D. and mainly analyzed with finite elements method; this process resulted in one of the lightest and stiffest body, as compared with competitors of similar size.

In 1985, he left Alfa Romeo to join Candy S.p.A., a major italian domestic appliances manufacturers, where he remains for two years as Engineering Director, contributing to innovation in design and testing process.

After Alfa Romeo merge by Fiat Group, in 1987 he was invited to join the new company again as Body Design Manager, with a team of about 150 engineers.

In 1991, he was appointed Engineering Director of car body design and testing for the entire Fiat Group, including as divisions Fiat, Lancia and Alfa Romeo; this department staff included about 500 engineers.

Between 1991 and 2001 many patented safety and body components devices have been invented, more than 30 different car and commercial vehicle bodies have been designed. During this period of time, co-design with suppliers has been introduced, as well as simultaneous engineering. He is particularly proud for having promoted the implementation of parametric associative CAD 3D development systems for Body, fitted to archetypes and process flow, taking profit of original parametric associative features developed with the support of IBM and Parametric Technology Inc.

From 1998, his charge integrates also the Safety Centre, a large facility to perform full scale crashes and safety components testing and the Wind Tunnels, that have been widely modified with the purpose to measure cars aerodynamic noise.

He retired in 2001 and established R.DES., a consultancy company to serve car manufacturers and components suppliers in new developments.

He cooperates part time with the Politecnico of Milano to train new graduated engineers and is member of the technical Commission of the Automobile Club of Milano for traffic safety.

Andrea Tonoli

Andrea Tonoli received his degree in Aeronautical Engineering in 1988 at the Politecnico of Turin.

From left: Lorenzo Rosti Rossini, Lorenzo Morello, Andrea Tonoli, Giuseppe Pia

He joined Fiat Aviation Division immediately after and remained in this company till 1991 designing transmission gearboxes.

He developed research activities at the Mechanical Engineering Department of the Politecnico of Turin that allowed him to obtain in 1994 a research doctorate on Machine design and construction, under the guidance of Professor Giancarlo Genta.

Together with other researchers he established in 1993 the Mechatronics laboratory, a research structure within the Politecnico of Turin devoted to study electronic control system applications to mechanical systems.

He joins the Politecnico as Researcher in 1994. In this position he performs many research activities on vehicle systems and related topics, for the Mechanical Engineering department and for the Energetics Department.

The main subjects of research are the following.

Mechatronic system design for automotive applications.

Vibration control with electromechanical active and passive systems.

Parasitic current dampers.

Magnetic suspensions.

Piezoelectric actuators.

Belt transmission mechanical behavior.

Tilting body vehicle dynamics.

Light and hybrid vehicles.

He was appointed associate professor at the mechanical Engineering Department of the Politecnico of Turin in 2005.

He teaches Vehicle body system design, Ground vehicles design and Mechatronic systems modeling.

He has been appointed academic referent to supervise the activity of many Formula SAE/ATA competition teams (see web address: http://squadracorse-polito.com).

He is Director of the Mechatronics laboratory of the Politecnico of Turin (see web address: http://www.cspp.polito.it).

Foreword

These two books about the vehicle body may be added to those about the chassis [1]and are part of a series sponsored by ATA (the Italian automotive engineers association) on the subject of automotive engineering; they follow the first book, published in 2005 in Italian only, about automotive transmission.

They cover automotive engineering from every side and are the result of a significant effort lasting more than five years and now accomplished, addressed to support the academic activities af the Politecnico of Turin and the University of Naples on automotive engineering.

The Fiat Group is, in fact, well aware of the importance of specialized knowledge on the development and management of a highly competitive product and has turned to the Politecnico of Turin for the opportunity of setting up a course on automotive engineering, addressed to first and second level degree achievement, for specialists who will be dedicated to the development, production and continuous improvement of automotive products.

This course was aimed not only to provide new resources for the company, but also to sustain the company itself in the globalization process, only possible with a cultural homogeneity between parts or services suppliers and people in charge of delocated processes.

This course, operative in Turin since the academic year 1999/2000 and in Naples since the academic year 2004/2005, has been planned and begun as a result of a project that involved Professors of the Politecnico, addressed to the automotive disciplines and experts of many companies of the Fiat Group; the participation of these experts was not limited to the planning of specialist courses, but was also extended to the preparation of lecture notes and, quite often, to actual teaching activity.

Fiat assigned this task to the Fiat Research Center, for many reasons.

Fiat Research Center (CRF) has the responsibility not only for designing innovative products, but also for developing new processes for product development and production. In addition, CRF must diffuse and make available to the company's operating sectors the knowledge that derives from new product

[1] Giancarlo Genta, Lorenzo Morello, *The Automotive Chassis,* Springer, 2009.

development, to assure a quick introduction of competitive products to the market.

Finally, CRF is dedicated not only to automobiles, but also to other automotive products and components and to production systems; for this reason it has been possible to include industrial vehicles and component suppliers, taking for granted a greater emphasis on automobiles.

This task was particularly difficult and involved the participation of many specialists of the Research Center and a number of experts from the operating field; the result of this effort consists not only in an integrated studies plan, but also complete lecture notes and audiovisual aids to support lessons and the activities of students.

The quantity of this material has encouraged us to go further, with the intention of transforming this material into reference books in Italian and, possibly, in the English language.

As for "The Automotive Chassis" this book is made by two Volumes.

The first produces the needful cultural background on the body; it describes the body and its components in use on most kinds of cars and industrial vehicles: the quantity of drawings that are presented allows the reader to familiarize with the design features and to understand functions, design motivations and fabrication feasibility, in view of the existing production processes.

The second Volume is addressed to the body system engineer and has the objective to lead him to the specification definition used to finalize detail design and production by the car manufacturer or the supply chain. The processing of these specifications, made by mathematical models of different complexity, starts always from the presentations of the needs of the customer using the vehicle and from the large number of rules imposed by laws and customs.

ATA, our Italian associations of automotive engineers, has overseen publication of the Italian edition; this task fits well with the institutional objectives of the association, to diffuse and foster automotive culture among young people.

Nevio Di Giusto
CRF and Elasis Chief Executive Officer

Preface

In the collective imagination the car body represents the result of an exclusive combination of art and handicraft, namely a product that is put on paper by the hand of a designer and then translated into a physical object by skilled craftsmen, the coachbuilders.

Today the body is an industrial product of a process that is initiated by the designer's creativity, before being developed by a complex interfunctional engineering work and then produced by specially dedicated machinery and highly skilled workers.

The object of this book is to address the engineering design process or 'project' which starts from a model created from a design concept, which is transformed into a virtual prototype with drawings and mathematical models, then into physical prototypes and finally into the finished article through the production cycles.

Therefore the project includes the detailed definition of the final product (product design) and of the operations that must be executed to obtain the working car (process design). A project starts from the technical specifications, a list of the objectives the final product must meet, transforming them into virtual models that are validated by calculations and simulations and finally into the final product.

The scope of this book is not to define how to design commercially successful vehicles but rather to explain how bodies may be developed in order to perform their mission correctly.

The principal objective is to provide the reader and the students of Automotive Engineering with the following specific information:

- The nomenclature and the configurations of the body components and architecture.
- The main functions the body performs in relation to the components incorporated.
- The most suitable materials and technologies applied.
- The criteria applied in order to select the most productive design options and design and testing criteria.
- The regulations and standards to be observed and respected.

Tables, pictures, sketches and drawings are accompanied by theoretical interpretations and practical suggestions resulting from many years of experience.

For this reason the authors regard this book to be not only a training tool for neophytes, but also as a means for stimulating and corroborating the fundamental competences of car manufacturers and part suppliers engineers. Furthermore marketing experts, who have to specify new cars in relation to customers demands and expectations, should benefit from reading this book.

One of the most important points of personnel training by car manufacturers, as for any complex product, is the time necessary to acquire a sound knowledge on the entire body: daily activities are necessarily specific and enable competences to be developed that may be deep but relatively limited to few components and related issues.

The authors consider that these two Volumes could prove very useful to illustrate, even if not in considerable detail, all aspects and issues of all components and sub-systems of the automotive body; contamination is a fundamental engine for cultural growth.

The book starts from the historical evolution of the body architecture in connection with the evolution of design methods, technologies, materials and scientific disciplines. Then the state of the art is presented and the most frequently asked questions are addressed concerning successful and unsuccessful features, different design philosophies and the importance of certain technical and non technical aspects in order to be able to select between the alternative options available.

The chapter sections are organized starting from the general issues before proceeding to the details, the same criterion being applied to introduce the different components.

Practical comprehension should be enhanced with the numerous pictures included; graphs and tables are always presented when is possible to provide practical examples and, in this way, Volume I can be used also as a handbook.

In this book, attempts have been made to integrate and make available every result of the authors' experience gathered in a wide range of professional areas, including practical engineering, applied and academic research.

The subject is particularly complex because the vehicle body must perform many different functions including:

- Space utilization and packaging of car parts, passengers and useful load.
- Ergonomic condition of the operations that the driver and passengers have to perform while using the vehicle, such as access to the interior, operation of controls, seating comfort, internal and external visibility.
- Climatic comfort of the passenger compartment, either for heat generation or subtraction or for heat conduction through the compartment boundaries.
- Acoustic and vibration comfort, including body structures and seats.

- Passive safety, obtained through the structural behavior of the body while collapsing after a crash and by the many devices applied to avoid or reduce passenger injury.
- Structural integrity and aging resistance.

It is extremely important to remember also the aesthetic function that impacts the architecture and details of every visible element of the vehicle and particularly of the body.

In addition, the car body is the part of the vehicle that is more often reviewed or completely redesigned to better match the product to customer's taste and needs; it is important to reflect upon, not only the changes in body appearance, but also to the many new body styles introduced in the last period of time. As a result, the development of a new car body is the task that automotive engineers are more likely to meet during their professional career.

With the experience in the organization and supply of courses at the Automotive Engineering Faculty, a deliberate choice was made to include in the automotive body also those vehicle parts which are not usually covered in similar books on this topic.

Specifically, when considering the body shell, usually made of steel sheet, which performs the most important structural jobs, it has been decided to include other components that can be opened or removed, glasses, headlights, wipers and other details which may rely on completely different technologies but must be conceived together with the body shell.

In the same way, when describing car interiors, the explanation could not be limited to their shape and function but rather extended to also include parts of their fabrication process in order to better understand how they influence customer perceptions.

This book offers two different views of the body: The first is the design of their parts and the related design criteria, as consequence of the fabrication technology; the second is the system engineering that derives technical specifications from customer needs and system operation.

Since many car body functions are correlated with human operation and interaction, the chapters dedicated to Ergonomics, Acoustic, Vibration and Climatic Comfort and Passive Safety are supplemented by outlines on the relevant Physiology, considered necessary to better understand the subject and aim for the following results:

- Thoroughness of the perimeter of this book.
- Possibility of consultation from different points of view: nomenclature, functions performed, design criteria, calculation methods, detail design.
- Multidisciplinary approach; functions and characteristics explained by considering technical, technological, marketing, economic motives that influence them.
- Integration of theory and praxis, conceptual analyses being enriched by details, remarks and hints derived from the direct professional experience of the authors.

Acknowledgments

The authors wish to thank Fiat Research Center for having made the preparation of this book possible, not only by supporting the cost of this work, but also by supplying a great deal of technical material, essential to produce an updated and application-oriented text.

The authors particularly appreciated the suggestions and information they received from Paolo Mario Coeli, Massimo Caudano, Efthimio Duni, Kamel Bel Knani, Stefano Mola, Silvia Quattrocolo, Roberto Puppini, Fabrizio Urbinati, Davide Vigè.

A relevant contribution came also from managers and specialists of FIAT Automobiles and IVECO; we remember particularly Giancarlo Bertoldi, Lino Bondesani, Giuseppe Fasolio, Giulio Manstretta, Federico Pasetti e Dario Rosti from the first Company and Angioletta Boero e Giuliano Coscia from the second.

The authors' gratitude must also be shown to the part Suppliers that have provided a major part of the illustrations of the first Volume, and particularly Denso Thermal Systems S.p.A. for HVAC Systems, Ergom Automotive S.p.A. for dashboards, Fibro S.p.A. for parcel shelfs, Johnson Controls Automotive S.r.l. for door panels, Lear Corporation S.r.l. for seats, Rieter Automotive Fimit S.p.A. for roof lining and TRW Automotive Group Occupant Safety Systems Division for safety belts air-bags. Without their contribution this book would be neither complete nor topical.

This book has, in addition, benefited from the lecture notes prepared by Fiat Research Center to sustain the teaching activity of the courses of Automotive Body Design, Car Interior Design and Automotive Body System Design, within the course of Automotive Engineering of the Politecnico of Turin and of the Master in Automotive Engineering of the Federico II University of Naples.

The authors wish to remember the late Dr. Pierluigi Ardoino who supplied the lecture notes of his seminars at different Universities; they were used to write the first part of the chapter on passive safety, addressing Biomechanics.

Particular thanks are conveyed to Donatella Biffignandi of the Automobile Museum of Turin for the help and material supplied for the preparation of the historical section.

The authors are also indebted with their editors: David Storer, car body senior research engineer at FIAT Research Center, deeply revised the English text; Natalie Jacobs, publishing editor at Springer, put the finishing touches on the book.

1

Introduction to Volume I

Volume I is entirely dedicated to the primary parts of the car body with some mention about commercial and industrial vehicle[1]. Body shell, body components and body interiors components are considered in respective chapters.

A decision was taken to dedicate the first chapter to the history of the car body, with particular reference to the body work and its parts, enabling current car architectures to be explained in an appropriate context, presenting them within process of evolution.

Some types of body separated from the chassis frame are introduced; initially such bodies were made of wood, then of composite structures, including wooden skeletons covered by steel panels, before arriving at more recent solutions made entirely of steel.

The consequences for the car architecture, and the industry in general, of non unitized body and unitized body are introduced.

The second chapter is introductory in nature and focuses on the graphical representation of the body parts which exhibit certain specific features due to the fact that they are made of thin panels, sometimes without a stable shape. Computer Aided Drafting (CAD) systems, specifically developed for this purpose, are introduced together with some examples regarding steel sheet components.

Some mention is made also of the development process for aesthetic shapes, despite not being addressed directly within this book; nevertheless this process

[1] We define as commercial vehicles, vehicles for transportation of goods or minibuses derived from or produced with car technologies; industrial vehicles are also vehicles for transportation of goods or busses, but they are produced with specific technologies. GVW of these vehicles is usually over 3.5 t.

L. Morello et al.: The Automotive Body, Vol. 1: Components Design, MES, pp. 1–2.
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should be completely understood with respect to shortening the body development time without jeopardizing the style features that are defined during the phase of creative activity.

The computer aided systems used to verify the geometrical compatibility between the body shell and the constituent parts, and issues relating to the feasibility of the assembly process in the production plant and the disassembling in the service shop, are also introduced.

The fourth chapter is dedicated to the body shell architecture broken down into components, with particular reference to a sedan body made of steel sheets.

The functions of the assembled body are analyzed together with the related design criteria and testing procedures; materials and technologies applied to permanent joints presently in use are also introduced.

Then the contributions of the different parts in order to attain the performance and desired functional targets are introduced, again with reference to three- and two-volumes sedans.

The last part of this chapter addresses the analysis of the variations of body styles different from the sedan, particularly station wagons, sport utility vehicles, off-road vehicles, coupes, convertibles, commercial and industrial vehicles.

In the following chapter, all components applied to the body shell are introduced, including bumpers and other elements such as grilles, skirts, moldings, weather strips, etc. Considering the large quantity of materials applied and production technologies involved, particular attention is paid to these issues and their consequences on body design.

This chapter includes also glasses, wipers and headlights; despite not being conventionally addressed in books in this field, these issues are considered particularly relevant in light of the tight function and style integration of these parts adopted by most recent cars.

The last chapter addresses the primary components present in the passenger compartment.

The first section regards restraint systems (safety belts) and includes an analysis of the functions performed, a description of the primary components and the design rules concerning the definition of the anchorage points on the body.

The following section describes air-bags, their required functions, their components and, again, the description of design strategies with respect to the protection they must offer.

In the same way, the dash board, interior trimming and seats, functions, components, design options, materials and production technologies are discussed.

Also this chapter considers a part not usually considered to form part of the body, namely the Heating, Ventilation and Air Conditioning system (HVAC). The reason for this choice relates to the tight correlation with body functions, in this case, the climatic comfort within the passenger compartment; also in this case the functions performed and the primary components incorporated are introduced.

2

Historical Evolution

The aim of this chapter should be the description of the evolution path of the car body, as it was defined in the introduction of this Volume, including body shell, interior components and trimming and a number of accessory devices.

The notable complexity of this subject is discouraging an exhaustive approach; we will limit the scope of this chapter to the body shell (with the chassis frame), including its closures (doors, hood and trunk lid) and the accessories for external lighting.

This decision is motivated by the higher relevance of these parts to the car and also by the complexity of their evolution.

However some remark about the evolution of interiors is reported in related chapters.

In the following sections the initial organization of the automobile production will be described, to supply the reader with a reference frame; afterwards the historical evolution of chassis frame and body shell will be presented according to three historical periods, partly overlapping, including respectively:

- Non-unitized chassis frames;
- Partially unitized chassis frames;
- Unitized chassis frames or unitized bodies.

A dedicated section will outline the external shape evolution and its consequence on the aerodynamic drag.

The last section is dedicated to the electric system and has the aim to offer a scenario on the evolution of many body accessories, as for example the headlights that used different source of lighting before arriving to electricity.

L. Morello et al.: The Automotive Body, Vol. 1: Components Design, MES, pp. 3–32.
springerlink.com

2.1 Industrial Organization

The body structure includes chassis frame and body shell. The first supplies all mounts for mechanical components, such as engine, transmission, suspensions and steering system, characterized by relevant and concentrated reaction forces. The body shell is the container hosting passenger and useful loads; it can be mounted on the chassis frame or be unitized with it, as in modern cars.

The term chassis, not to be confused with the same word, indicating in this case the chassis frame or structure, implies that part of the vehicle including all mechanical elements useful for vehicle motion and their supporting frame; this assembly of parts might be really available at a certain stage of the production cycle, as happened till about the end of the '940s on most cars, or might be considered as a virtual subassembly that cannot be separated from the rest of the vehicle.

At the downing of the motoring era, the inventors who dedicated their intellectual and financial efforts to develop this product preferred to concentrate on the aspects that are most peculiar and essential to mobility, as engine, transmission, suspension and steering.

In other words, they became designer and producer of chassis, a French name for frame.

The technology for the body as it appeared on cars of the end of the 19th Century was not considered to be crucial and was imported from horse carriages; many coach builders became, therefore, also car body makers.

This situation determined also an initial clear-cut separation between the chassis and body industry.

Car manufacturers worked primarily on metallic materials and had tooling suitable for casting, stamping, welding and turning; in consideration of the complexity of matching parts, they had to rely on drawings and work on small production lots.

On the other side, body manufacturers used primarily structures of pure wood or wood reinforced or covered with steel; they had tooling for carpentry or for cutting and shaping sheets; they produced without drawings, because each body was often one of a kind, to satisfy individual customer desires.

This tradition derived from the fact that wood was easier than steel, to be shaped in curved surfaces, according to the fashion rules of that time.

Varnishing, essential to obtain an aspect pleasant to the eye and to the touch and to protect surfaces, was again a point in favor of wood, in consideration of existing oil varnishes and caused a separation of chassis from body production cycle, to avoid damages to the body varnish, during the complex chassis assembly.

It should be remembered that a complete surface treatment cycle requested hundreds of work hours to apply a number of coatings; the drying time of each coating had to be added, to obtain a figure in the range of 400 hours to finish a complete body.

The existence of a chassis physically available was therefore caused by the available technology and related industrial organization. It allowed car manufacturers to present a finished product to the customer or to the body manufacturer; the chassis could, therefore, be driven, tested and transferred easily.

This is why we find a 'test body' among the body styles, listed in Fig. 2.3 (detail 8).

Usually the final customer bought a chassis, which was then delivered to a coach builder to obtain a car at customer's specification; nevertheless there were examples of body makers who bought chassis on their own, to sell finished cars or of car manufacturers who had permanent agreements with body manufacturers or who set up their own body shop.

This situation was widespread in Europe till the beginning of the first World War. The first series productions were made with their body produced at the car manufacturer premises and manufacturers had to develop their own capability to design and produce bodies.

This last point favored a gradual transition from wood to steel technology, including what we could call hybrid bodies made with wooden skeletons covered by steel sheets.

The development of synthetic enamels shortened, in addition, the paintwork of an order of magnitude and made possible a tighter integration between chassis and body assembly cycles.

This new work organization was developed in the United States and imitated by major European manufacturers, starting from the end of the '920s. About twenty years later the first unitized bodies were developed in Europe.

2.2 Non Unitized Bodies and Chassis

The chassis frame, the bearing structure of the vehicle, had to provide all mounting points for mechanical components and to carry on the complete body, that could be considered at that time as a dead weight. In addition, the chassis frame had to favor a sound organization of the assembly work.

First chassis frames were made of wood or steel; steel was more widely diffused than wood. Steel frames were made either by bent and cut sheets, or by tubes, according to the already existing cycle technology.

A wooden chassis frame is shown by a picture of the 1907 Sizaire Naudin, shown in Fig. 2.1; this car is characterized by two massive wooden side beams and by a body made with cut and bent steel panels.

We do not have points to explain this choice. We could argue that the manufacturer did not have a suitable tooling to bend thick sheets and preferred using wood, notwithstanding the lesser resistance of this material; on the contrary the body panels could be easily bent by beating steel sheets on wooden open face stamps.

The most diffused technology for the chassis frame could be explained by Fig. 2.2, showing a sample of the beginning of the last Century.

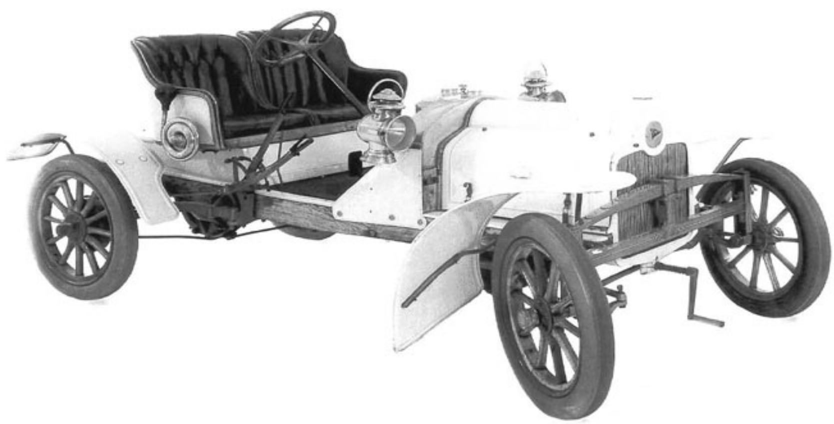

Fig. 2.1. 1907 Sizaire Naudin; this car shows a very seldom combination of technologies: a wooden chassis frame with steel sheet body.

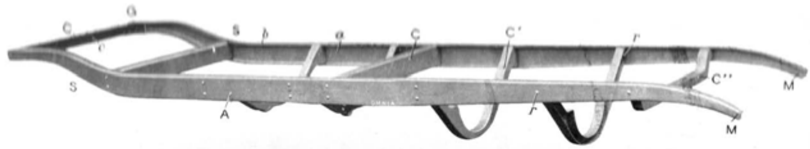

Fig. 2.2. Grillage chassis frame of the beginning of the last century. The frame is made by two side beams and many cross beams. Cross beams are located where major loads are applied, typically at the leaf spring ends and powertrain mounts. Joints between parts are obtained by hot riveting.

It is made by two side beams made by bent steel sheets, with a 'C' cross section. In the front of the vehicle the beams track is reduced, to allow space for front wheel steering motion, while in the rear is enlarged to better cope with the body width; in this area the width of the chassis frame is determined by the rear wheels track and by the transmission bulk. This shape variation was obtained by bending side beams or by putting them according to a trapezoidal layout.

The front and rear ends are curved, in the side view, to better match with the semi-elliptical shape of leaf springs and are tapered to take into account the reduction of bending torque. On younger cars this curvatures were increased in order to reduce the chassis height from the ground in the mid of the car.

The two side beams are connected by a number of cross beams, building-up a ladder-like structure, called, again from French, grillage; cross beams are curved under the engine and the gearbox, to reduce vehicle height. They are usually located near the points of application of concentrated loads, such as leaf springs end and powertrain mounts.

The joints between side and cross beams are made, in this case, by hot pressed rivets; in other applications screwed bolts were used and only later welds.

This kind of structure remained unchanged for years and is still in use on modern industrial vehicles; also for them, rivets and bolts are used for joining, because frame dimensions are such as to make thermal deformations and internal stress caused by welding heat dangerous.

The bodies adopted in connection with these frames were, as we already said, similar to those of horse carriages as shape and technology.

We will refer mainly to sedans or salons as they are called in Fig. 2.3, showing the main body styles in use at the end of the '930s; body styles were many and mirrored the existing situation of horse carriages.

The very first cars, those of Daimler or Benz in Germany, were open, according to the scheme of spiders and phaetons, but already in 1899 Renault introduced the first sedan. Open cars represented till 1920 the 80% of sales; but this percentage reduced to 20% few year later and closed bodies maintained a predominant position till yesterday. Body styles have been proliferating again during last years, but still with majority for closed cars.

To better understand horse carriage technology, we can look at Fig. 2.4, representing a landau of the beginning of past Century, during its fabrication; the picture was taken before the installation of the external panels.

A very complex wooden skeleton can be noticed; beams are cut from solid wood and are assembled with complex dovetail joints to reach a curved shape and adequate resistance.

Interior panels are already pasted and are made by thin plywood sheets, curved in place. External panels will be applied according to the same technology.

This technology allowed obtaining sturdy and light structures with shapes suitable to the aesthetic tastes of that time; the solid wood skeleton had not only the job of bearing loads but also was used as a tool to shape covering panels that were nailed and glued wet.

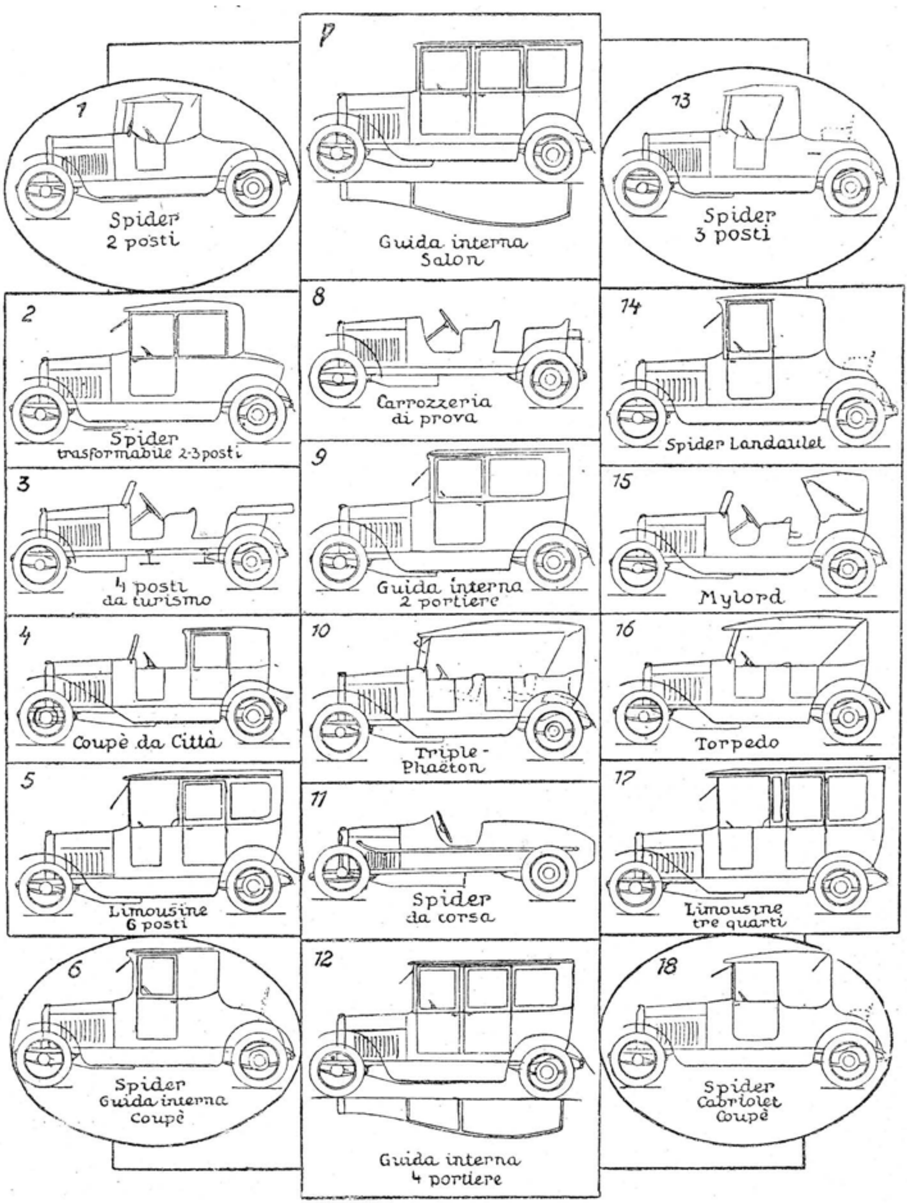

Fig. 2.3. Body styles classified at the beginning of the 20th Century in an Italian engineering manual. The corresponding names in other languages refer to different traditions; for example sedan is called saloon in the UK and 'berline' in France and Germany, this name coming from the city cabs of Berlin. To favour foreign trade an international numerical coding system was also proposed.

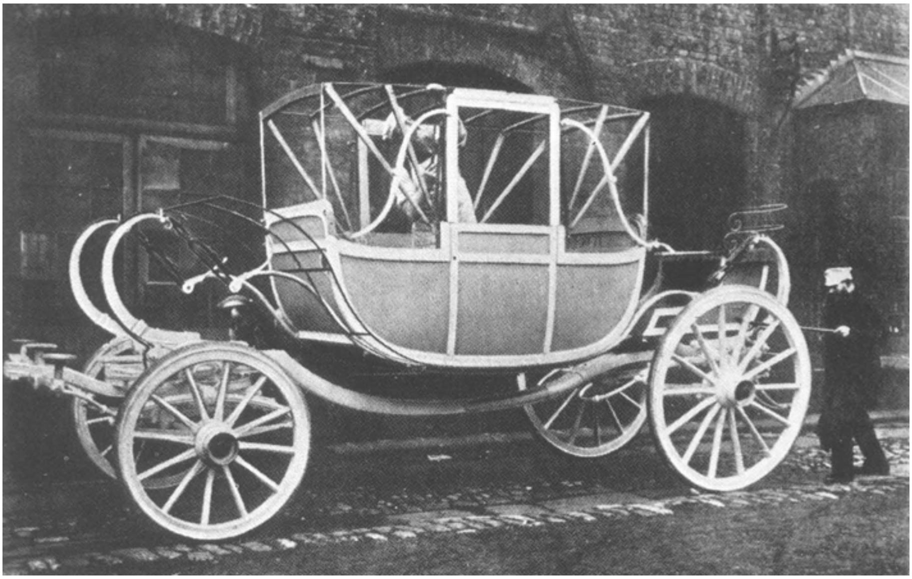

Fig. 2.4. Photography of the Coronation Landau of Edward VII of England in 1902. The picture was taken during the fabrication of the horse carriage, before the installation of covering panels. The wooden skeleton is visible; it will be covered by wooden panels to be shaped in place.

Fig. 2.5. Picture of a car body shop at the beginning of the 20th Century; in foreground a partially assembled phaeton. The similarity with the horse carriage of the previous picture can be noticed.

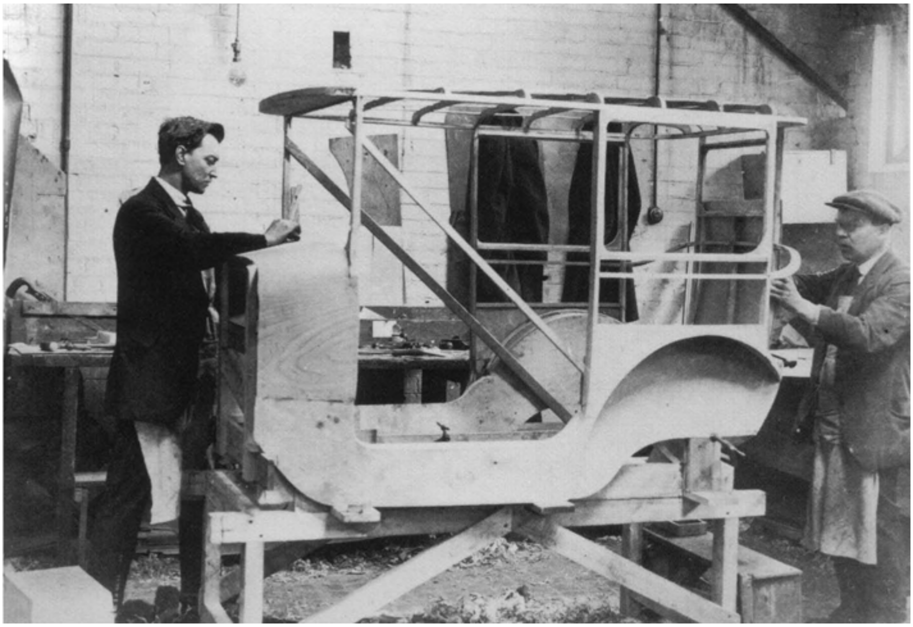

Fig. 2.6. The wooden skeleton was made with beams, along the body edges, and with ribs and formers, spaced in the areas of higher curvature, as for example the roof, the area below the windshield or the back of the body that was used also as back rest of the rear seat. The roof cover was made of waterproof synthetic fabric.

A good similarity with the horse carriage structure can be noticed on a car body of the same years, in Fig. 2.5, in the shop during assembly.

The most complicated shapes could also be obtained; they were made with a number of wooden splints that were subsequently smoothed to the final shape, after nailing them on the skeleton (the body style was called bateau, after the wooden boats fabrication process).

The wooden skeleton was made with beams, along the body edges, and with ribs and formers, spaced in the areas of higher curvature, as for example the roof, the area below the windshield or the back of the body that was used also as back rest of the rear seat, as shown in Fig. 2.6. The roof cover was made of waterproof synthetic fabric.

We should now recall that the torsional stiffness of a grillage type frame is low, because it is determined by the sum of the torsional stiffness of the two side beams, considering the low bending stiffness of cross beams bolted or riveted joints.

In addition, the side beam cross section, almost always of open type because of the easier manufacturing and assembling process this shape implies, entails a low torsional stiffness. Also the bending stiffness is reduced because of the limited height allowed to the side beams.

Looking into the engineering manuals of that time, we have the impression that a higher attention was paid to the bending than to the torsional stiffness; today, the second looks more critical. As a matter of fact, torsion stress is more frequent, due to the non symmetric nature of road obstacles, wheels must afford and the presence of lateral acceleration.

Bending and torsion deformations of the chassis frame became later a major concern, because of their effect on the body shell; this aspect increased in importance as car speed increased.

The body shell was made, as we have said, by a wooden skeleton of notable stiffness, in consideration of the mortise and tenon or dovetail joints between the different parts. This high stiffness induced premature deformations and ruptures.

Body shell and chassis frame, in fact, are two elastic structures that work in parallel, because they are subject to same displacements in their joining points; the stiffer element absorbs, therefore, the higher torque, in proportion of the ratio between stiffness values.

Wooden structures were certainly unsuitable to bear high loads and, after a short period of use, joints became loose, reducing the structure stiffness significantly.

Chassis frame deformations, imposed to the body shell, implied mutual displacements between parts concurring in the same joints. These displacements caused squeaks and plays between parts caused rattles. Sometimes the deformation of the body shell when the car was stopped made opening and closing doors difficult.

For this purpose, metallic joints were studied to improve the behavior of structure. Two different philosophies were followed: increasing the body shell stiffness or decreasing it to a level of insensitivity to squeaks and rattles.

Fig. 2.7 shows the characteristics of these two solutions. On the right side (at top) we see the cross section developed according to the first school; the body shell is mounted on a second steel frame of ‘L’ shape cross section. This frame is firmly joined to body sides and floor.

On the other side the joints with the chassis frame are made with rubber elastic bearing; in this way the body can be stiff and does not follow the deformable chassis frame displacements.

The opposite is accomplished by the second engineering school, as proposed by Weymann, the most important body maker that introduced this approach. This structure concept was derived by the aeronautical technology of the ‘920s, Weymann experienced in field.

The body skeleton, as we can see in the left side of Fig. 2.7, is again made of wood beams, following the scheme of ribs and formers, but the joining elements between them are flexible steel brackets, screwed in wood.

Attention is paid to keep wooden parts at a distance to avoid any contact following deformations and the consequent noise; the flexibility of steel brackets does not allow to transfer chassis deformation to the body with significant stress on wood parts.

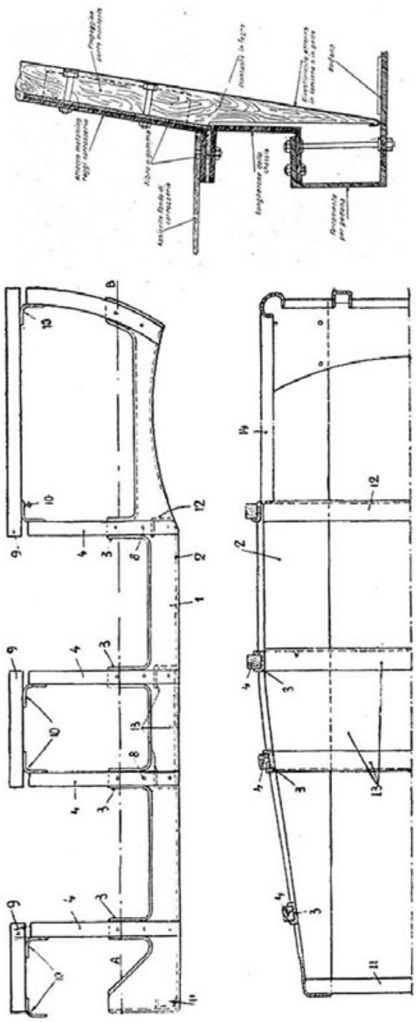

Fig. 2.7. On the right side of the picture (on top) a wooden body is shown which is mounted on ‘L’ cross section stiffening steel frame; this frame is joined to the chassis frame using elastic bearing. The effect is to not impose chassis deformation to body shell structure, with squeaks and rattles reduction. On the left the same effect is reached in the opposite way, according to a technology developed by Weymann; the wooden skeleton joints are made by elastic metallic brackets that can bend without noise. The covering of the body shell is made by waterproof fabric that can also receive significant deformation without damage.

The external covering is insensitive to skeleton deformation because is made with waterproof fabric with a surface finishing similar to natural leather.

This fashion lasted about a decade; the most significant disadvantages were found on the limited endurance and on the possibility of obtaining only polyhedral shapes.

This situation may refer to the end of the '920s; steel sheet became to be largely used in the following decade, even if some all steel application is present in advance as the Lancia Lambda we will describe in the following section.

2.3 Partially Unitized Bodies and Chassis

Some chassis frame of the '930s received a different, more elaborate shape; in particular 'X' cross beams were developed, as Fig. 2.8 shows.

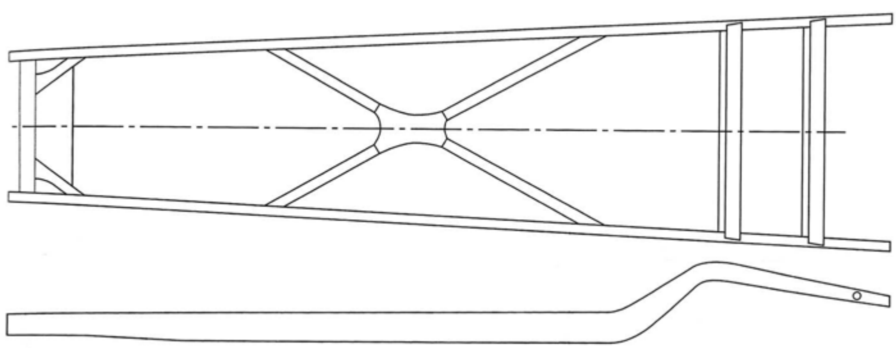

Fig. 2.8. Chassis frame with 'X' cross beam; this kind of cross beam is also riveted to the side beams but is interested by their torsion by means of shear forces applied to the joining points. The consequent bending stress is very well absorbed even by the open section of cross beams. The overall torsion stiffness of the frame is significantly improved.

The 'X' cross beam nailed with the side beams reacts to their torsion with shear forces applied to the joints; the cross beam works therefore by bending; this kind of stress can be very well absorbed even by its open section. The overall torsion stiffness of the frame is significantly improved.

A new step forward may be shown by Fig. 2.9, relating to the chassis frame of the 1935 FIAT 1500; this car is an example of the most modern technologies available in those years, not only as the structure is concerned by also as the aerodynamic performance, as we will discuss later.

We can notice, at first, that part of the chassis frame beams are made with closed section elements; they are produced with stamped and welded parts; in previous examples, beams were made by open stamp bent profiles, cut to their final length.

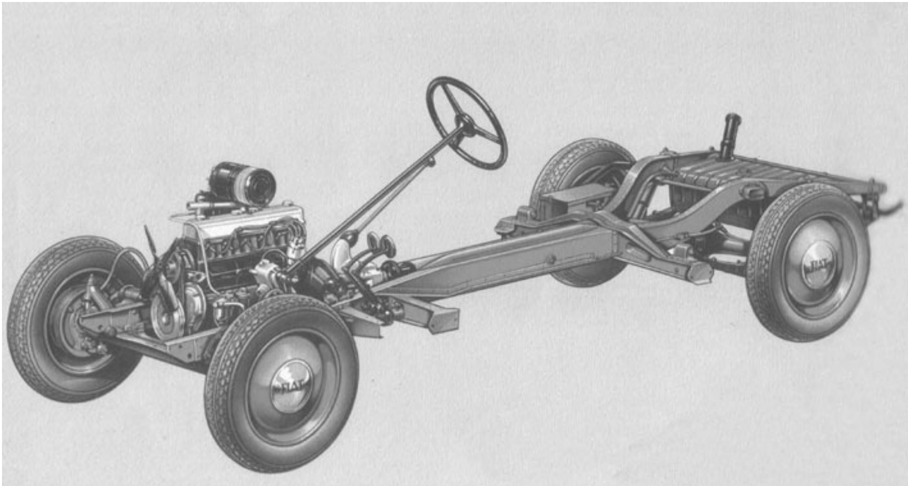

Fig. 2.9. Chassis frame of the FIAT 1500 of 1935; the different parts are made by steel sheets formed in closed stamps and they are welded. The shapes that can be obtained have closed section and allow weight reduction at an increased stiffness; it is possible now to design different sections for their local stress. The two side beams are joined together to obtain a stiff tubular structure. Crossbeams are changed to cantilevers.

The advantage of this innovation is in an improved control of the structure weight, because each cross section can be now designed to its local stress; disadvantages are to be found in most significant capital investments for the production process.

The chassis frame structure reuses the ‘X’ shape of the previous example but goes over the grillage lay-out; the two side beams, in their central area between the cross beams, join to shape up a tubular beam, which is very stiff to torsion; it contains also the propeller shaft. The cross beams became cantilevers and have also closed section.

A further advantage of this structure architecture is that the side part of the chassis frame is free from the bulk of beams; the floor can be made by two lowered sinks and the height of passenger compartment and centre of gravity is reduced.

This kind of chassis frame was bolted to the steel body shell and not welded; this is the reason why we defined this arrangement as partially unitized. Even with a flexible joint a contribution of the body could be given to the overall torsional stiffness of the car.

These new engineering concepts are also consequence of the fact that big presses for steel stamping are starting to diffuse at the car manufacturers in this period of time.

The body of this car, as many of this period of time, is made with stamped steel panels, still reinforced with a wooden skeleton with joining screws, as we saw in previous section.

These wooden elements have the job of offering easy fixation to the interior trimming and to avoid local instability of relatively thin sheets.

Fig. 2.10 shows a drawing of the mid of the body, in the passenger compartment area. We can notice many wooden ribs along the roof sheet and at the edges of the windshield and of the rear windows; many wooden formers reinforced the roof, the tail of the body and the doors.

Wooden screws were certainly unsuitable to exchange significant forces, but reduced the shape instability of panels. Their shear resistance contributed a superior torsional stiffness to the entire body, as compared with previous solutions.

Floor and body are bolted to the chassis frame; this is not an unitized body yet, but we can guess an improved behavior.

Again in Fig. 2.10 some cross sections are marked, whose drawings are shown in Fig. 2.11.

Notice the wooden skeleton and how panels are joined to it; door panels (sections E-E, D-D, B-B, H-H) are also framed by wood.

A more modern and functional solution is shown in Fig. 2.12, where the same cross sections corresponding to those of the previous figure are sketched, for an almost contemporary car with similar style, the 1937 FIAT 1100.

The wood has disappeared and the skeleton itself is made by welded steel elements, shaping up tubular beams. Let us compare, for example, the C-C cross section, showing the frame of the two wardrobe doors near the upper latch, in Fig. 2.11 with the similar section of Fig. 2.12, or section G-G of Fig. 2.11 and section E-E of Fig. 2.12, showing the rear area of the door near the hinge.

Also this all-steel body shell is bolted to the chassis frame in the floor area.

It looks difficult today to understand the reasons why two so different architectures existed by the same manufacturer in the same period of time and why the most advanced was applied to the cheaper model.

We should argue that the lower volumes of the larger model have discouraged the engineers in proposing, also for this car, the capital investments necessary to the higher complication and number of stamped parts.

On the other side, the higher assembly cost was not considered to have a too negative economic impact, considering the availability of a significant number of skilled carpenters and their cheap hourly rate.

By the FIAT 1500 and other cars of the same generation, fenders are no more a pure add-on, as by previous cars (see for instance the first two pictures in Fig. 2.18); they are made by two parts: The inside part, integral with the body shell side, is bolted to the chassis frame and cooperates effectively with side beams to torsional and bending rigidity; to the outside part, structural tasks are instead not assigned, as it can be seen in Fig. 2.13.

Structures of this kind were also applied by many other car manufacturers till the end of the ‘950s and sometimes even further.

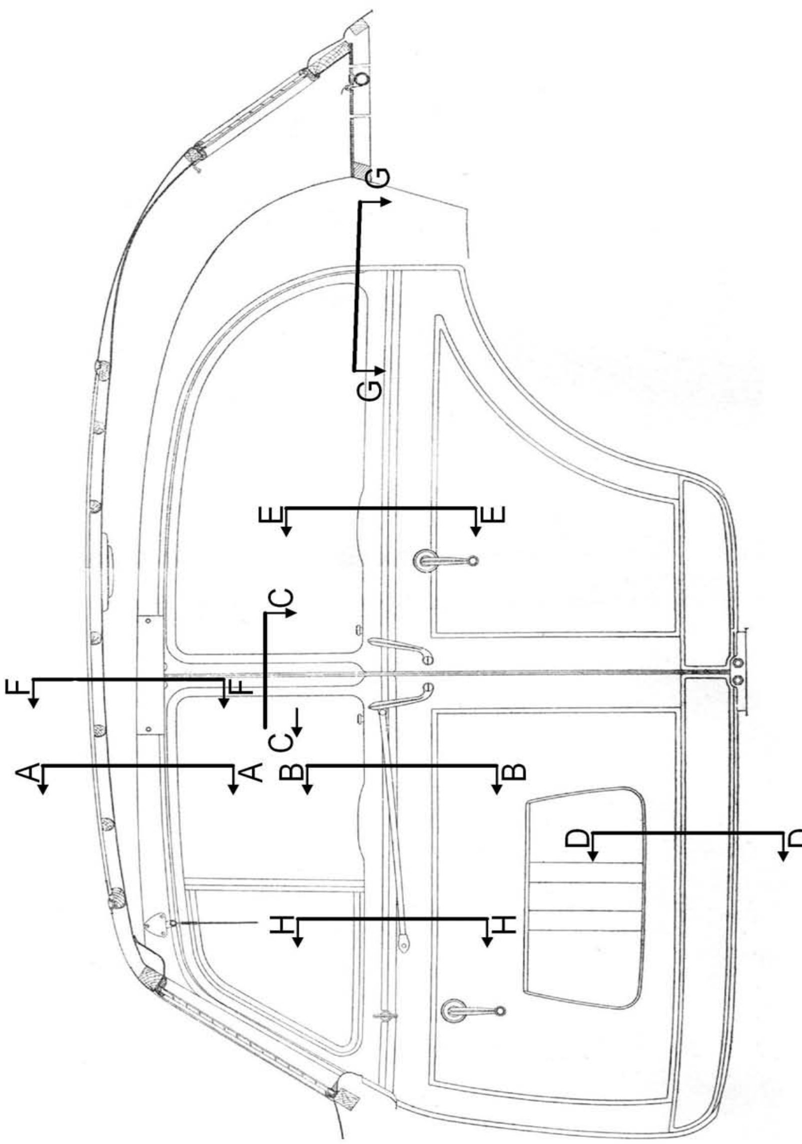

Fig. 2.10. Longitudinal cross section of the FIAT 1500, with a side view of the interior side covers of the passenger compartment. We can notice many wooden ribs along the roof sheet and at the edges of windshield and rear windows; many wooden formers reinforced the roof and the tail of the body. The fixation between wooden and steel parts was made by wood screws.

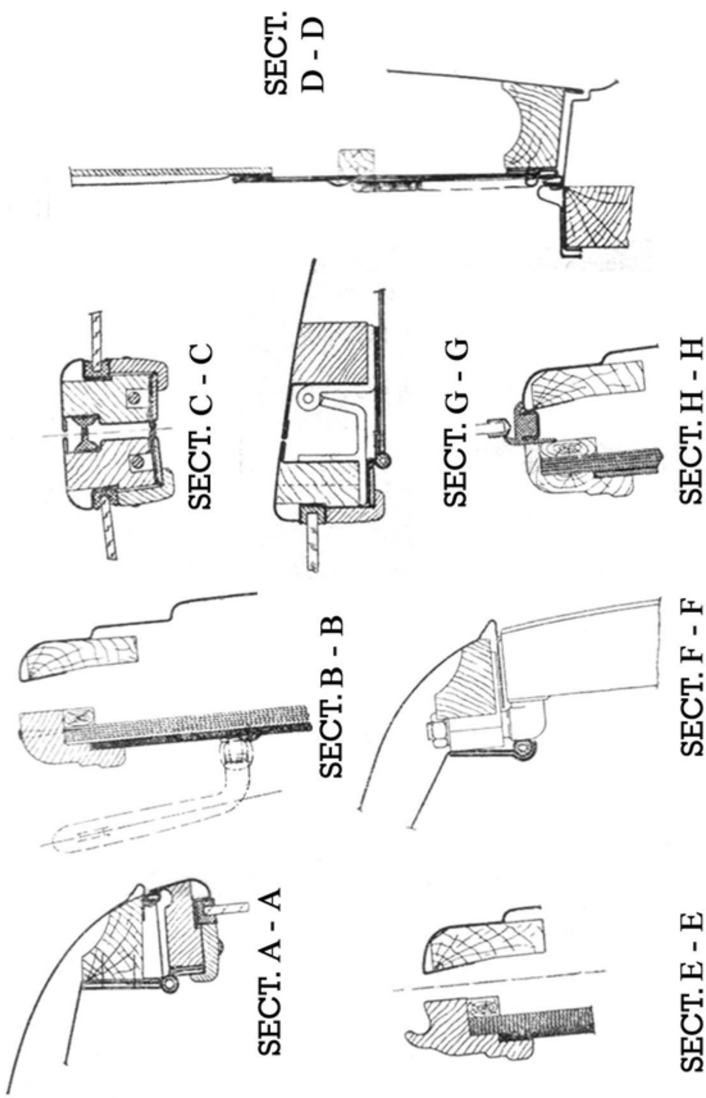

Fig. 2.11. The perimetral skeleton of the body covering panels is completely made by wood (cross sections are referenced to previous figure); door panels (sections E-E, D-D, B-B, H-H) are also framed by wood. Sections A-A and G-G show the hinge mount of front and rear doors with wardrobe opening. Sections C-C and F-F show latch locks.

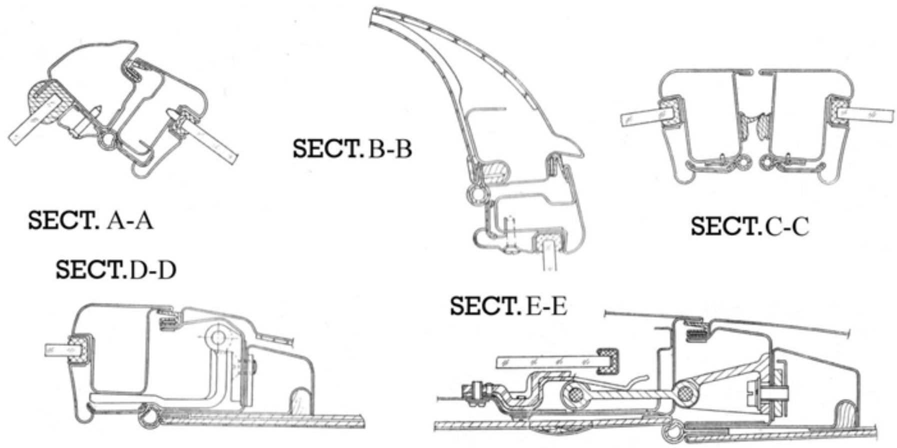

Fig. 2.12. Body shell cross sections of the 1937 FIAT 1100: The wood has disappeared and the skeleton is made by welded panels that are shaping up closed sections. A comparison can be made between section C-C of this figure and the same of the previous.

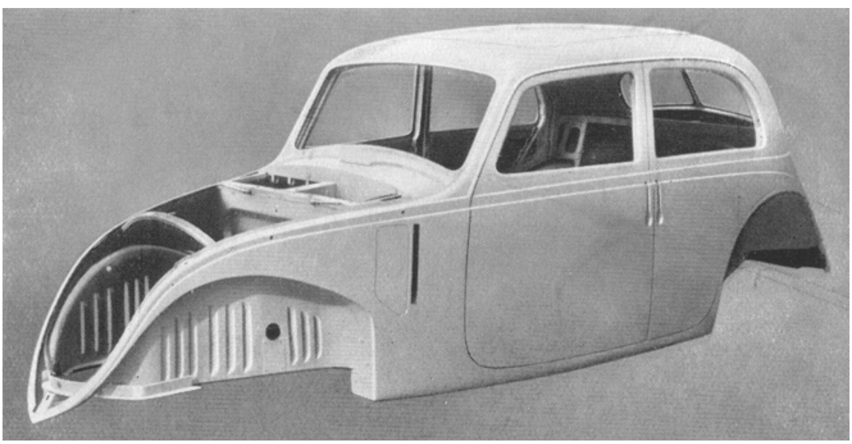

Fig. 2.13. Fenders are no more a pure add-on, as by previous cars; they are made by two parts: The inside part, integral with the body shell side is bolted to the chassis frame and cooperates effectively with side beams to torsional and bending rigidity.

This intermediate solution in parallel with already existing unitized bodies can be justified also by the existing assembly work organization, with separation between body and chassis; in addition, this solution allowed to install different body kinds on the same chassis, also with satisfaction for those customers who still looked for more elaborated styles, as custom built cars.

2.4 Unitized Body and Chassis

Structural integration of body shell and chassis frame is considered as a mean to obtain good performance at a reduced weight; in a sedan car, the notable distance between chassis frame side beams and side roof rails allows, in fact, to obtain a very stiff assembly, if these elements are well joined to very stiff pillars, connecting them as to work as a single body.

In addition, panels covering the body, if suitably shaped, can further increase structure stiffness, by limiting angular displacements between longitudinal beams and pillars.

The first car applying this concept, even if not completely, was the 1922 Lancia Lambda, whose unitized body, with mechanical components installed, is shown in Fig. 2.14.

The body shell is made by a number of welded or riveted steel panels that shape-up a reticular space frame; lower body elements are higher than conventional side beams and increase the torsional stiffness of the assembly in comparison with previous solutions of that time.

A further increase comes from the limited size of the doors, that makes sills height more important, and from some stiff cross panels, as dash board, seat back rests and tail closure. Similar purpose has the portal frame, surrounding the radiator and integrating the independent suspension sliding elements.

Also without taking into consideration the improved structural performance, we cannot demonstrate objectively, we can see at a glance the result on car shape, consistently slimmer and lower than contemporary cars; the reduced height had a positive impact on dynamic behavior.

The sedan version did not take profit of the possibility of exploiting roof elements. It applied the phaeton structure with a flexible add-on top of Weymann style.

A further step was made, years later, when spot welds became practical and deeply stamped steel sheets available; it can be noticed, by the way, that all steel panels of the Lambda are flat pieces of steel sheet with very simple bendings. They could be produced with very basic tools.

One of the first example of fully unitized body is offered in Europe by the 1934 Citröen 11 CV, shown in Fig. 2.15. We can notice the presence of two robust longitudinal beams integrating sills at the floor level; they provide also engine, gearbox and front suspension mounts and are rigidly integrated with the three door pillars.

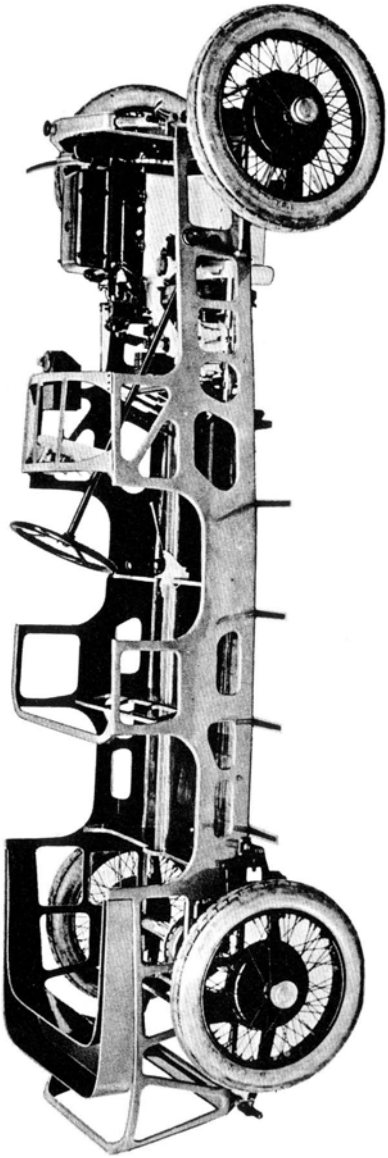

Fig. 2.14. Phaeton body of the 1922 Lancia Lambda, complete with mechanical components. The body shell is made by a set of panels joined by welds and rivets, shaping up a reticular space frame. The torsional stiffness is significantly increased by the contribution of cross panels, corresponding to dash board, seat back rests and tail closure. The front suspension is connected to a portal frame, surrounding the radiator and bearing the vertical sliding elements of the independent suspensions.

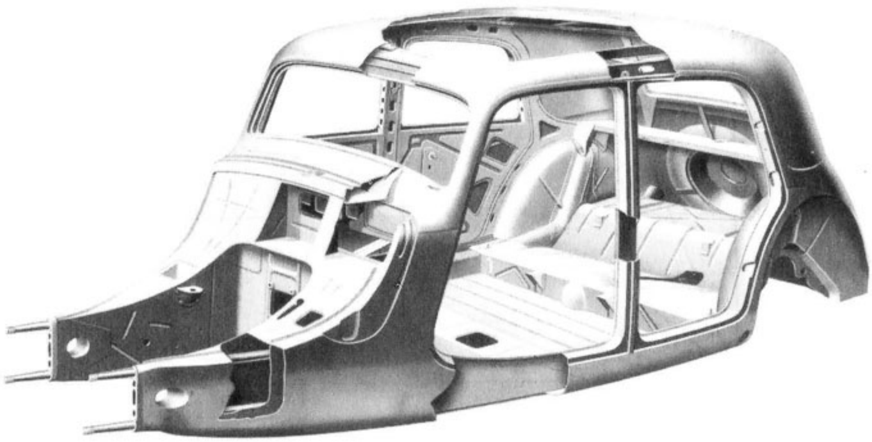

Fig. 2.15. Unitized body of the 1934 Citröen 11 CV, produced till 1956. We can notice two robust longitudinal beams integrating sills at the floor level; they surround also the engine compartment and offer the mounts for the front suspension. This car is also a first example of high volume application of front wheel drive.

The Citröen 11 CV is also an example of the first application of front wheel drive to mass production.

A more conventional example of this concept, was the 1950 FIAT 1400, shown in Fig. 2.16.

All steel panels shape along the junction lines beams organized as a space frame represented in dark in the picture.

The chassis, as a physical assembly, is no more existing and cannot be separated from the rest of the car. The assembly cycle of the car and the production plant lay-out is completely changed; the unitized body shell is produced at first, by welding panels and by receiving paint. Afterward it goes to the assembly plant for mechanical part installation and application of body trimming.

2.5 Body Shape Evolution

The body style evolution has had a strong impact on aerodynamic performance, and therefore maximum speed.

We must avoid, first of all, the prejudice that aerodynamic performance was neglected on the first cars, as the squared shapes of older vehicles seam to suggest.

The problem of reducing aerodynamic drag was already studied by ship engineers; as a matter of fact the first experiments were not made in wind tunnels but in water channels. The shapes developed were very ingenuous for the lack of suitable experiments.

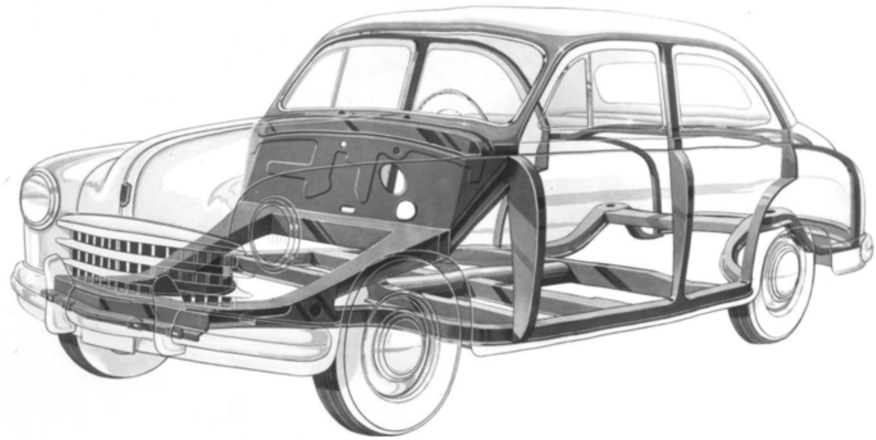

Fig. 2.16. A more conventional example of unitized body is the 1950 FIAT 1400. All steel panels are shaped in such a way as to build a rigid beam at all junctions, surrounding doors, floor and trunk. All these beams, darkened in the picture, build-up a space frame.

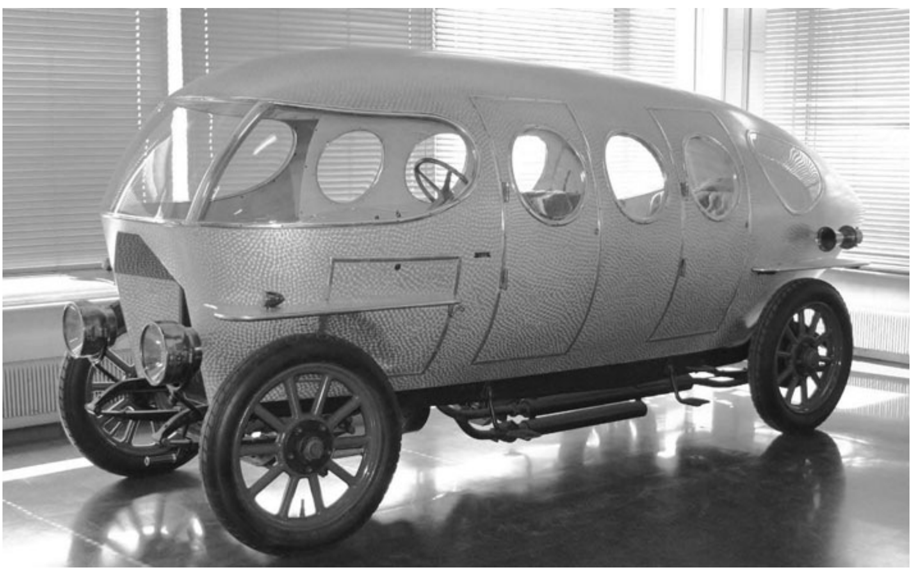

Fig. 2.17. 1914 Alfa Romeo 40/60 HP with body made by Castagna, after a design of Earl Ricotti; the symmetric slender shape proves to have very low resistance only if positioned far from the ground.

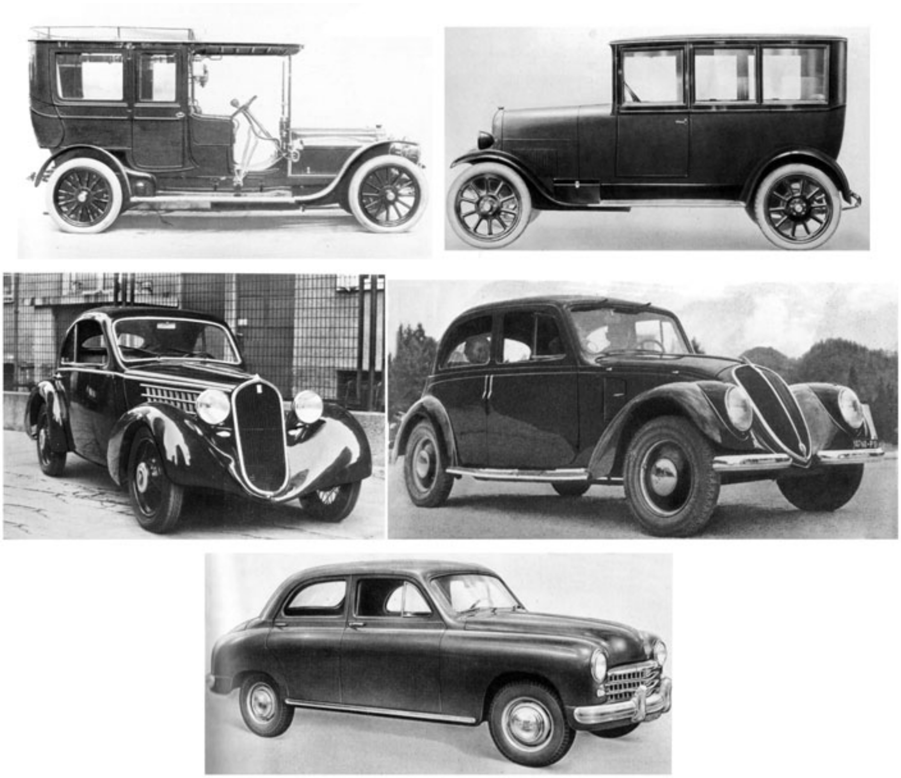

Fig. 2.18. Fiat's cars showing the fundamental evolution of the shape of bodies. Upper left: the 1908 25/45 HP. Upper right: the 1910 501. In the middle row, at left, the 1934 508 Sport: this might be considered as the first body shape of this company developed as a result of aerodynamic experiments. In the same row, the 1500 of 1935. Bottom: the 1400 of 1950.

Many old cars witness attention to aerodynamic drag; among them the Jamais Contente (speed record of 106 km/h in 1899) and the Alfa Romeo 40/60 HP of Earl Ricotti, shown in Fig. 2.17.

Both bodies were designed according to the slender body shape that presents minimum drag at a large distance from the ground. Later it was demonstrated that ground proximity requires the body shape to be slightly curved.

These shapes were premature, in consideration of effective needs and aesthetic tastes of those times; in addition they were completely unsuitable to build-up a vehicle and were not followed by similar examples.

To document the evolution of shapes we will refer for simplicity to a single manufacturer, looking at different sedans produced by FIAT.

A first period of time may be identified at the beginning of the motoring era, from 1899 to 1915, where shapes were squared, especially in the front area, where the hood joined with a flat dash board and windshield without any kind of rounding; an example of this form is the 35/45 HP of 1908, in Fig. 2.18 at upper left.

This form is partly influenced by the fashion, coming from horse driven coaches and existing fabrication technologies, that did not allow very rounded shapes; in addition, a fully functional approach did not consider yet the integration of engineering solution and technologies.

The next period may be set between 1915 and 1930 and the 501 of 1919 can be assumed as its emblem; this car is shown in the same figure at upper right.

Shapes are notably more rounded and show an evolution coming from the adoption of steel sheets worked essentially with roll or bending press. A 'torpedo' shape provides for uninterrupted lines, connecting the radiator with the car back.

Fenders assume an esthetic value and are made with round shapes integral with running boards; in addition, they are used to cover mechanical parts under the floor, still positioned at a notable height. Fenders are produced by beating steel sheets on open wooden stamps manually.

The hood is part of the same surface of the body sides; the radiator also is rounded at its edges.

Frameworks surrounding body panels have also disappeared because of the abandonment of the wood.

The overall aspect still recalls the horse driven coach, but details do not.

This style is still present at the beginning of the '930s; a break point might be represented by the 1934 508 Sport; this body is the result of the first aerodynamic experiments, partly performed in a airplanes wind tunnel, partly on the road directly. It was determined, for example, that a slight inclination of the windshield could increase vehicle top speed by 5%, around a value of 100 km/h.

Similar studies were performed in other parts of the world during this period; we remember in particular the experimental studies of Lay, published in 1933 in Germany, about the influence of different shapes on aerodynamic drag.

The famous, but unsuccessful, 1934 Chrysler Airflow is the starting point of this new style.

We see in the middle of Fig. 2.18 at left the appearance of the 508 Sport. Hood, passenger compartment and trunk are integrated in a single volume; windshield and radiator grille are inclined. Also windshield frame is rounded. The body is tapered in the side and upper view and shows a very long tail; fenders start merging with body sides.

For the first time the drag coefficient is well below 1.0.

This is also one of the first examples of the integration of trunk with body; in previous cars it was an add-on attached to the back of the body.

A further evolution of styling rules developed for this sport car, was their application to a series produced car, the 1500 sedan of 1935, in Fig. 2.18 in the middle right. To stylistic features of the 508 more details were added, as head lights built into fenders and rounded disc wheels. The drag coefficient of this car was about 0.5, less than 0.7, the average value obtained with former more traditional shapes.

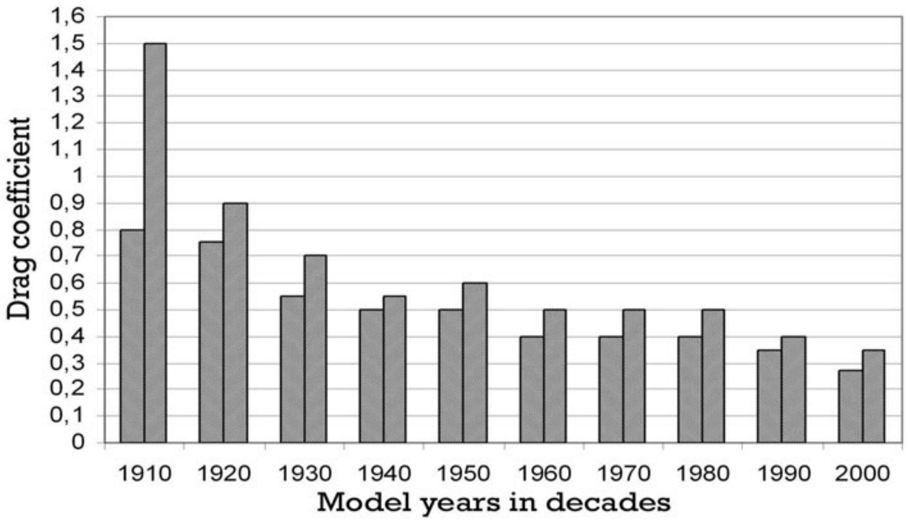

Fig. 2.19. The reduction of drag coefficient in connection with the evolution of body style is documented by this diagram, where the best and worst measured values are reported as function of the model year. The measurement was made recently on full-scale cars in the same wind tunnel.

The passenger compartment is wider and has replaced part of the space previously taken by running boards, that now are a style decoration only; they are no more necessary, because the adoption of central beam chassis frames and independent front suspension have notably lowered the floor height.

Lowering the body has also made the body more vulnerable; the increased traffic density suggests introducing bumpers at the front and rear ends.

We can identify the 'ponton' body shape in the 1400 of 1950, at the bottom in Fig. 2.18, still in use on present bodies.

Characteristics of this new style are the disappearing of separated fenders and running boards and the full integration of head lights.

The passenger compartment takes all the space available between the wheels and the very rounded shapes conceal a highly efficient space frame structure; the reduction of drag coefficient is not so high as for the previous generation.

The reduction of drag coefficient in connection with evolution of the body style is documented by the diagram in Fig. 2.19, where the best and worst measured values are reported as function of the model year decade. The measurement was made recently on full-scale cars in the same wind tunnel.

The following body styles have not always brought big reductions. The '970s oil energy crisis has renewed the interest about more stream lined forms; the performance increase is not only caused by an evolution of the base form of the body but to the optimization of many small details of the external surface and of the underbody.

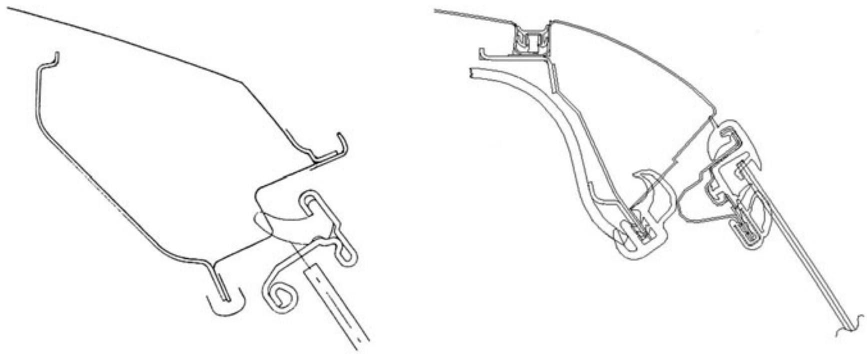

Fig. 2.20. At left: roof cross section of a sedan at the beginning of ‘960s; roof and body sides are flanged and welded in a surface shaping up a drip molding. At right: the same cross section for a ‘990s sedan; the roof is interrupted more inside and glass surface can be better aligned with the body side.

The most showy feature of new styles is the integration of bumpers and the alignment of the glass surface of side windows with the body surface; this last feature is the result of a totally different organization of body shell components in the roof area.

Fig. 2.20 puts in evidence what we said. At left, we can see the roof cross section of a sedan of the ‘960; the roof and the side sheets are flanged and welded together shaping up a drip molding. Together with them, a roof reinforcement is also joined.

The door is cut in the body side and the shape of weather strips causes the glass surface to be positioned inside. The discontinuities on the side surface affect drag coefficient negatively.

A notable improvement was introduced in the ‘970s and diffused gradually on all sedan bodies; it is still adopted in contemporary cars. It is shown on the right of the figure above.

The roof is welded along a section more inside of the body side surface; the reinforcement is welded along the same section and the wending is concealed by an esthetic coverage.

The door side is now aligned to the roof without discontinuity.

The glass weather strip is completely modified (please notice that weather strips are represented with their natural shape, not deformed by the closure of door or side window glass) and allows the glass to be almost aligned with the body side surface.

2.6 Electric Components

Electric energy application on cars was introduced by gasoline internal combustion engines ignition systems, that were applied also to the very first cars; nevertheless, this practice was not universally accepted because of the cost and the limited reliability of those systems, more similar to laboratory instruments than industrial products. Many examples are in fact available of open flame or hot spot ignition systems.

However electricity prevailed at the beginning of the 20th Century.

Electric energy was initially made available by dry cells; they produced electricity through an irreversible electrochemical reaction that made the cell no more reusable at the end of its discharge.

The limited energy density and the high cost of these accumulators did not allow to use this source for other application but the ignition.

A more rational choice, later available, consisted in applying the electric energy already available in homes to charge lead batteries to be used on cars.

Lead batteries, that were reusable after a limited discharge, were invented by Plante in 1859.

They were made by rolling-up thin sheets of lead, between separators of porous insulating material. The roll that was obtained from this process was put in a tight jar, containing a diluted sulfuric acid solution in distilled water.

The final product had to be charged and discharged many times before that porous separators contained a sufficient quantity of lead oxide, to accumulate an energy quantity of practical interest; this technology was therefore expensive and not productive.

The idea was perfected by Faure in 1881, by building-up a battery where electrodes were made by lead grids with meshes filled-up with lead oxide paste; these plates were piled with insulating separators in a sufficient number to produce the desired voltage. The production time of the battery was notably shortened because it was ready to charge.

Each couple of lead plates was able to produce a voltage of 2.25 V; many plates in parallel were sufficient to reach the desired quantity of energy. A typical energy density was about 60 Ah per battery.

A set of these batteries in series could reach a suitable value of voltage. The nominal values of about 6, 12, 24 V became almost immediately an international standard; 6 V batteries disappeared in the ‘970s and 24 V batteries were reserved for industrial vehicles.

This kind of battery, after many improvements, is still in use today as a service battery for internal combustion engines.

The crucial stimulus to the adoption of lead acid batteries and to the application of electricity to body appliances was given by the introduction of a starter motor; this contribution to the car evolution was probably merit of Kettering who already invented the breaker ignition and founded DELCO Company.

He was in fact spurred by Durand, at that time CEO of Cadillac, to introduce electric starter into those luxury cars, starting from 1912. The car history passed on that Durand was struck by the death of a friend killed by injuries after a hand crank.

Before of this event engines were started manually, by a handle, connected to the crankshaft; the clutch between handle and crankshaft was made by non symmetrical teeth. This design was aimed to avoid that the hand of the man could be dragged by the engine, when rotating at higher speed after start.

The maneuver was quite complex and hat to be made after other operations, as gasoline enrichments and spark advance adaptation; it required a lot of effort from a strong and skilled person, especially to start big displacement engines.

Many would-be drivers were prevented by their practice. In addition this operation could became dangerous and induce injuries when the cranking clutch was not working properly or the engine started in the opposite direction, because of a wrong choice of the spark advance.

The introduction of electric starter motors brought an important contribution to car diffusion; this practice introduced into the car electric generators and a battery size that was also suitable for additional applications.

The solution that was developed by Kettering was inspired to the principle of using a single electrical machine, both for cranking and for electricity generation; this option is in fact available because electric motors and generators are quite similar.

This solution had to take into account that cranking required high torque and current, at a low speed, lower than idle speed, while generation required lower current and torque but at higher engine rotation speed.

This problem was solved, as Fig. 2.21 shows, with a two speed gearbox, connecting the machine with the internal combustion engine; two ratios were available: about 1:1, through the water pump, and about 1:100, through the engine flywheel.

This assembly, as long as the engine, included the breaker and the distributor also; the reduced speed gear was shifted by a starting pedal, while the direct drive was shifted by a free-wheel at the end of cranking, when the engine accelerated.

Two different windings were available on the machine: one in parallel for generation and one in series for starting.

Later, two different machines were introduced for these two functions; the cost increase was paid with advantage by the gearbox elimination.

A relay regulator allowed the charge voltage to be kept constant.

But we will concentrate on lighting, the purpose of this section.

Headlights were an heritage of horse driven coaches, where they were applied, to make driving at night easier and to warn other road users.

They were lanterns with rudimental projectors, made by inside thin-plated case; sometimes they had lenses to better direct the lighting beam.

The praxis consisted in applying two big lanterns for lighting in the front of the vehicle and two smaller at vehicle sides to light the doors of the coach.

Fig. 2.22 shows two different lanterns, one for head lighting, one for side lighting.

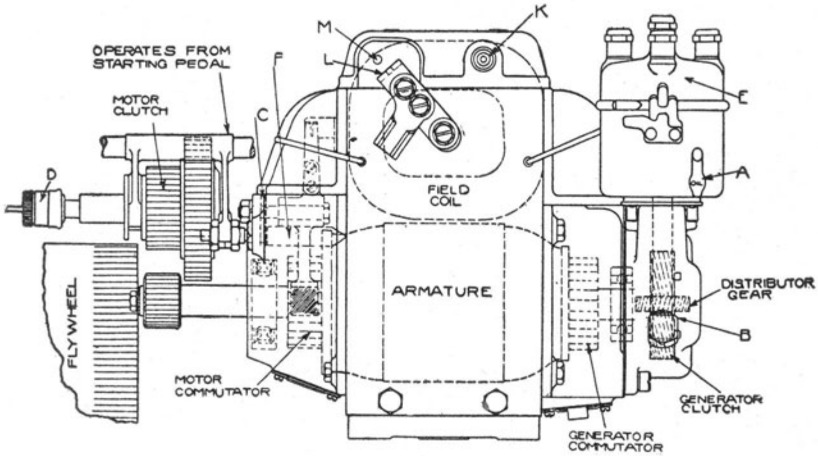

Fig. 2.21. Sketch of the Kettering's starter-generator machine, for the 1912 Cadillac. The electrical machine rotor could be joined to the engine with two very different transmission ratios; an almost direct drive through the water pump, almost directly connected to the crankshaft and at about 1:100 through the engine flywheel. The assembly included the high tension distributor and contact breaker also.

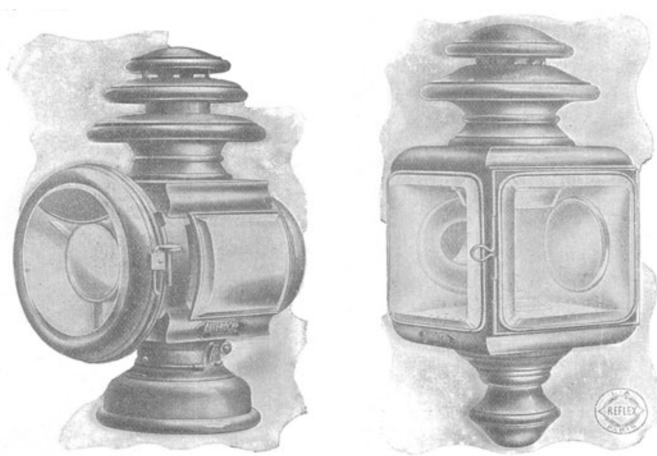

Fig. 2.22. Car lanterns at the beginning of the '910s. The left is suitable for front installation; the shape recalls a paraffin lamp with oil reservoir at the bottom; lens and parabolic mirror are already applied. The right is suitable for lateral lighting and was applied at the lower rim of the windshield as a position and courtesy lamp. We can notice on both the air vents.

Fig. 2.23. Acetylene gas generator. A certain quantity of water in the reservoir A is reacting with granular calcium carbide, in room B, producing a quantity of acetylene; the gas pressure, built up by the faucet M, could stop water flow and chemical reaction, switching off light in a very easy way. By faucet opening the pressure decrease allowed new water to enter the reactor and restarted gas generation.

The energy source was given by burning paraffin or similar liquid fuels that soaked a wick; light was modest but acceptable, in consideration of speed and traffic intensity.

A first improvement came from using acetylene as fuel; the combustion of this gas in the air produces a very sharp and bright flame, very suitable for lighting.

Acetylene was produced with a simple gas generator on the car running board, similar to that advertised in Fig. 2.23. A certain amount of water, introduced into the reservoir A, reacts with a quantity of calcium carbide, in room B, generating acetylene at ambient temperature; the gas pressure, built-up at the faucet M, could stop the water stream and interrupt the chemical reaction and gas generation in a very simple way.

Lighting-on headlights required to get out of the car, to open faucets and to ignite acetylene with a match.

The higher brightness and concentration of the flame could take advantage of parabolic mirrors and lenses and generated a more effective lighting.

Electric lighting, introduced in the American homes by Edison already in 1879, could not be applied to the first automobiles because of the mentioned problems of electricity availability.

The first patent for an electric car lighting system was filed in Paris by Bassée in 1899, with reduced practical results.

Again the 1912 Cadillac received the first practical application of electric lighting, together with electric starter; Fig. 2.24 shows a pictorial view of the entire electric system.

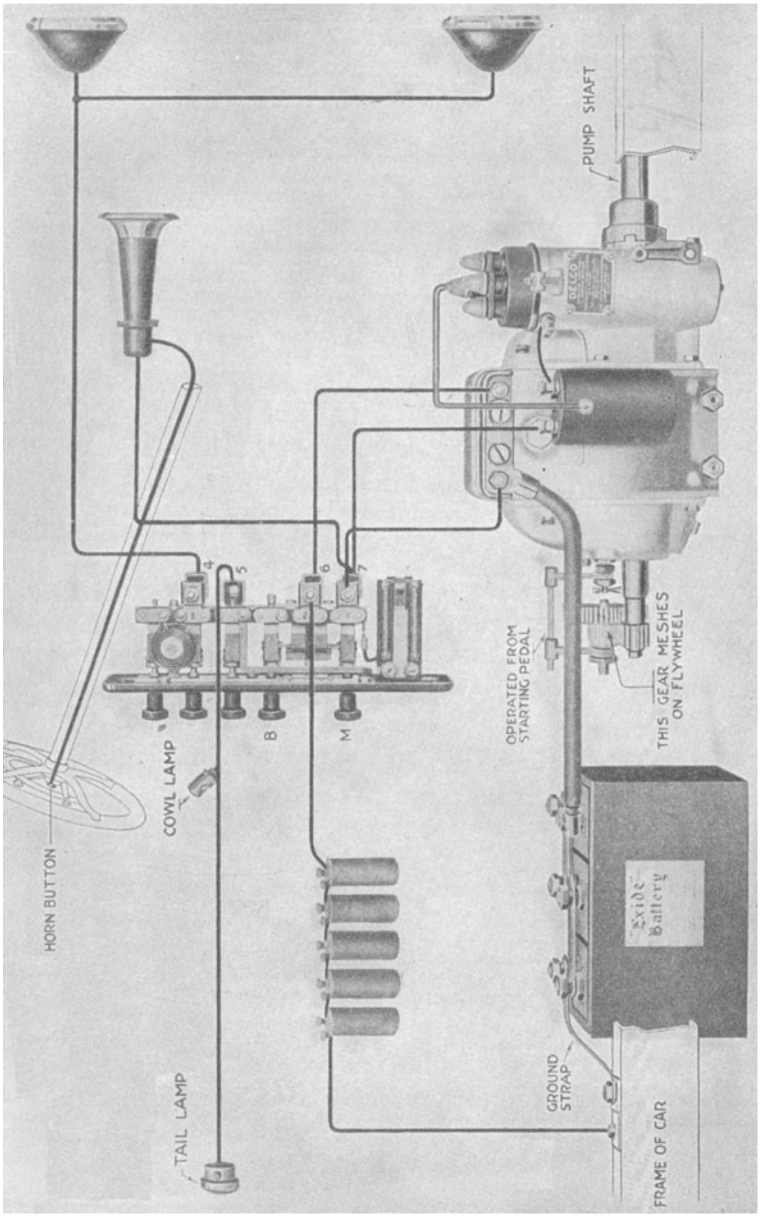

Fig. 2.24. Scheme of the electric system of the 1912 Cadillac. We can notice the starter-generator connected to an Exide 6 V battery. It is very interesting to outline the availability of four dry cells to be used, in case of need, in connection with a spare hand crank starter. Lighting includes two front headlamps, with simple filament bulbs, a single tail light and a lamp for the instrument panel. An electric Klaxon horn is also applied.

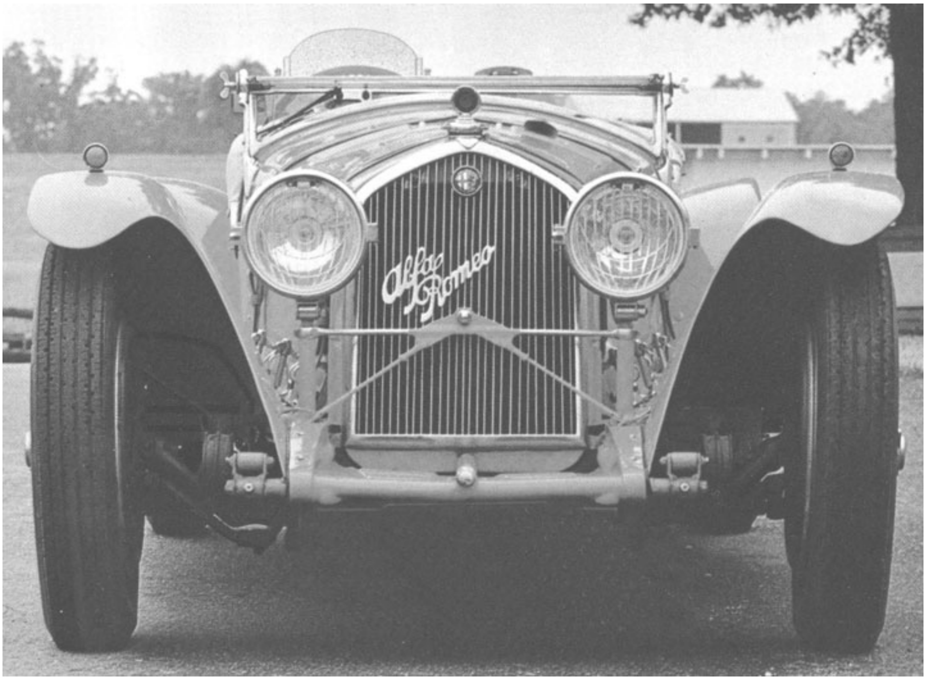

Fig. 2.25. The headlight appearance became one of the peculiar style features of the front of the car, as shown by this 1931 Alfa Romeo 8C Le Mans.

We can notice on this scheme the starter-generator connected to an Exide 6 V battery. It is very interesting to outline how designers did not completely rely on this system, having made provision for four dry cells, to be used, in case of need, in connection with a spare hand crank starter.

Lighting included two front headlamps, with simple filament bulbs, a single tail light and a lamp for the instrument panel. An electric Klaxon horn was also applied. Switches on the dashboard control lighting; dimmed headlights are obtained inserting in the circuit an additional electric resistance.

The headlight appearance became one of the peculiar style features of the front of the car, as shown by this 1931 Alfa Romeo 8C Le Mans, in Fig. 2.25.

3
Graphic Representation Systems

3.1 Introduction

A drawing of an automotive body has some aspects and features that make it different from those of other industrial products, deriving not only from its technical characteristics and production technology, but also from the aesthetic appearance of its shape which plays a fundamental role in determining the commercial success of a car.

From a technical standpoint, the body includes the body shell and trimming which are primarily made by elements of reduced thickness, where the external surface performs usually aesthetic functions; this fact justifies particular development techniques.

In addition, these elements of reduced thickness and complex shape have required the study of particular representation rules, that are different from those used for mechanical components (engine, transmission, suspension, etc.), that require, instead, a limited number of views and sections considering their relative simplicity.

A further specific characteristic is related to the high economic cost of capital investments necessary to produce a body in series, with respect to its useful life, usually limited to few years; contrary to many other components, invisible to the customer, that may be reused with only incremental improvements on next generation models, the body shell and trimming are totally revised at each new model launch, i.e. every $5 \div 7$ years on average.

The reason for this short life may be justified by the accepted tradition of transmitting the image of new product contents through a new shape, which

L. Morello et al.: The Automotive Body, Vol. 1: Components Design, MES, pp. 33–89.
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is supposed to correspond better to the aesthetic tastes and style trends of the moment.

The simultaneous needs for careful management of costs and cash flows for new investments on one hand, and for developing aesthetic forms coherent with the customer demand at the time of the commercial launch on the other, result in considerable pressure to compress the time allocated to development to a minimum; although this requirement is shared also by other car components, it is a critical issue as concerns the car body.

When considering product representation, it should be remembered that these drawings have also different applications with respect to car production and assembling; they also provide the starting point for the development of other drawings that are just as important. With respect to a body shell stamped panel drawing, for example, it is necessary that the following items are mutually coherent:

- Stamp set for production.
- Positioning and fixing tools for welding with the neighboring parts.
- Working robots for painting and assembling (usually applied for many model generations).
- Spare parts catalogues.
- Disassembling and assembling schemes for servicing and repairing.

The development of these items also includes activities which rely on body drawings, often comprising tests on actual or virtual prototypes, the latter being performed using mathematical models describing completely the component geometry, such as Finite Elements (FE) analysis or Digital Mock-up (DMU) used to verify the geometrical compatibility between parts or to verify their kinematic behavior (e.g. : doors opening, wiper motion, side glasses opening, etc.).

3.1.1 Typical Activity Planning

Body drawings should be available sufficiently in advance with respect to the start of production in order to enable all related activities to be conducted; therefore project has to be organized is such a way as to enable many activities are performed in parallel; to accomplish this, the minimum amount of information necessary for performing each of these activities must be determined.

So-called simultaneous engineering or concurrent engineering provides a means for organizing each elementary operation in such a way so as to produce results consistent with the need to initiate the related successive operations with minimum delay.

For instance, in order to start the design of a stamp of a positioning tool, it may be sufficient to determine the overall dimensions of the steel sheet rather than the details of its aesthetic shape; therefore tool drafting can be commenced before the body shell panel has been defined in detail.

This way of organizing the activities increases the number of modifications to be introduced considerably, either for completing drawings with additional detail, or for correcting mistakes that arise due to lack of information when previously executed.

Correspondingly the rate of modification becomes just as important as drafting speed; in addition, a critical factor for success becomes the knowledge and know-how of those involved in the development process, and of those who perform subsequent activities. Consequently each of those involved in the process must aim for final customer satisfaction while effectively working also for an internal client who will apply the results to other equally important activities from the perspective of production or commercialisation.

In the case of the body, the organization of the development work is further complicated by the fact that each design engineer is not only supplier to an internal client but is, at the same time, the customer of activities performed by designers developing the aesthetic shapes; in fact, body engineering must be considered to be in parallel with style development.

Today an overall development time in the order of 24 months, from style model choice to start of production, represents the best performance level achieved by major car manufacturers, although this is only possible thanks to the wide-ranging application of computers regularly utilized for:

- Computer Aided Styling (CAS) applied to develop visible shapes.
- Computer Aided Drafting (CAD) applied to engineering activities related to final product or production tools.
- Computer Aided Manufacturing (CAM) applied to the design of some aspects of the production process.
- Digital Mock-Up (DMU) applied to represent complex assemblies for virtual testing or develop production and assembly plant lay-out.

In addition, computer codes and simulation models, recognized to be essential for shortening development time, should be considered.

Computers have not only reduced the time needed for drafting and the implementation of modifications, but have made it possible to set up a unique data base that enables all the operations necessary to keep product development aligned and updated.

In fact the outside surface of a body panel, the result of the body style development, part of the component drawing, stamp drawing, etc. may be unique, avoiding replication for the different working environments and the risk of error and delay.

The development process may be outlined as in Fig. 3.1.

The scheme demonstrates that a high project development speed (here engineering activities are divided in planning and engineering) can be justified by the

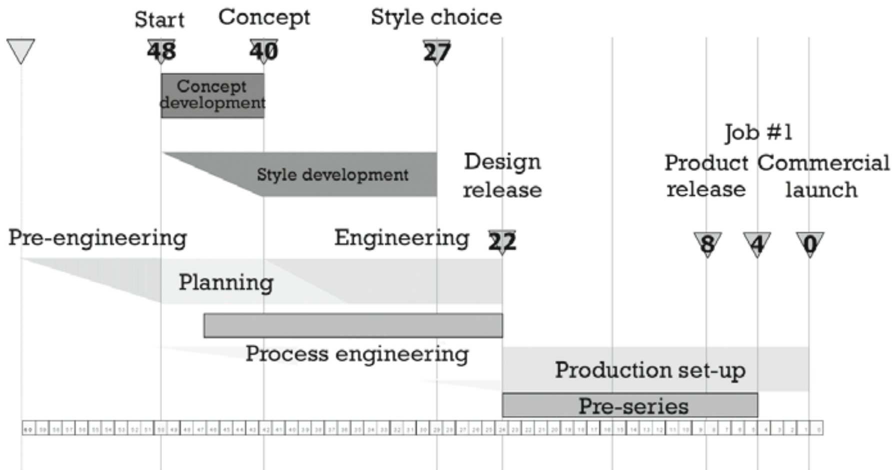


Fig. 3.1. The logical scheme of the main phases of the development process, with specific reference to the body. The time scale, at bottom, is measured in months and the elapsed time is highlighted with respect to major milestones.

existence of a phase, here termed pre-engineering (or shelf-engineering), where alternative solutions are studied and validated experimentally, without a real finalization; these activities contribute to filling an ideal shelf where good ideas are stored for their future application.

The concept development phase, or feasibility study, is performed with the cooperation of engineers, marketing experts and stylists, who arrive to define a product specification (concept) by examining alternative solutions in parallel; this concept specification must simultaneously satisfy customer's aesthetic and functional expectations and achieve technical and economical feasibility.

The manufacturing of prototypes is started at almost the same time as the engineering activities; consequently, prototypes relate to partial aspects only that allow design features to be validated one at a time. Only at the end, prototypes similar to the final product will be available to be used for design approval (or design release), to certify that each specification defined by the concept has been respected.

The so-called pre-series are other prototypes that, as opposed to the first prototypes, are built using mass production tools and plants; the positive conclusion of their tests is used for product approval (product release), i.e. providing certification that the adopted production means and organization are adequate to obtain a product complying with specifications.

The Job #1 vehicle is the first that can be delivered to final customers.

During the interval between concept definition to product definition (from 40 to 22 months before the commercial launch) many activities are performed in parallel such as planning, engineering, style definition, planning and development of stamping, welding and assembling processes, economical evaluation and optimization, in addition to the manufacturing of prototypes that are increasingly complete and closer to the final product.

Many activities that, logically, would be executed in sequence are instead performed in parallel and as a consequence are based upon provisional and continually changing information. This organization of activities, apparently nonlogical, can provide advantages in term of cost and time assuming that design tools, in this case CAS, CAD and CAM, enable rapid modification and reutilization of models for different purposes.

This procedure enables a product solution coherent with production processes, that will not require major changes during the following industrialization phase, to be developed 22 months before the commercial launch; it is therefore possible to start building production tools in time for validation 8 months before the commercial launch at the supplier's premises. Subsequently the production tools are transferred to the plant of the car manufacturer in order to initiate producing pre-series vehicles and accumulate the necessary numbers for commercial launch.

The advantages of CAD in terms of shortening the time for engineering activities have been widely described; correspondingly the significant compression of timescales have only been possible through the pervasive application of computers to all development activities.

Fig. 3.2 illustrates the existing links between engineering activities and corresponding informatics tools.

- Style development applies CAS tools with two different outcomes: Improving style architect productivity and generating an output (mathematical style model) that can be reused as it is by body engineers.
- Virtual reality as an informatics tool that enables the representation of exterior visible surfaces with enhanced realism in context; this makes it possible to evaluate the forms and light reflections they will have in a real environment and enable their visualization from any point of view or in motion; this technique enables those not familiar with drawings or informatics to be involved also in the decision process.
- Structural analysis is one of the major tools included in the CAE that enables the evaluation, not only of the body structural integrity, but also many other aspects, from weight to drag coefficient. The body mesh, the starting point of any FE analysis, is performed by computers almost automatically, starting from CAD mathematical models.
- A particular FE analysis, performed by considering the elasto-plastic material behavior, can be applied to the design of stamps, again using CAE tools; the same body panel mathematical model, defined by product engineers, can be reused by process engineers to verify that sheets can be stamped to their

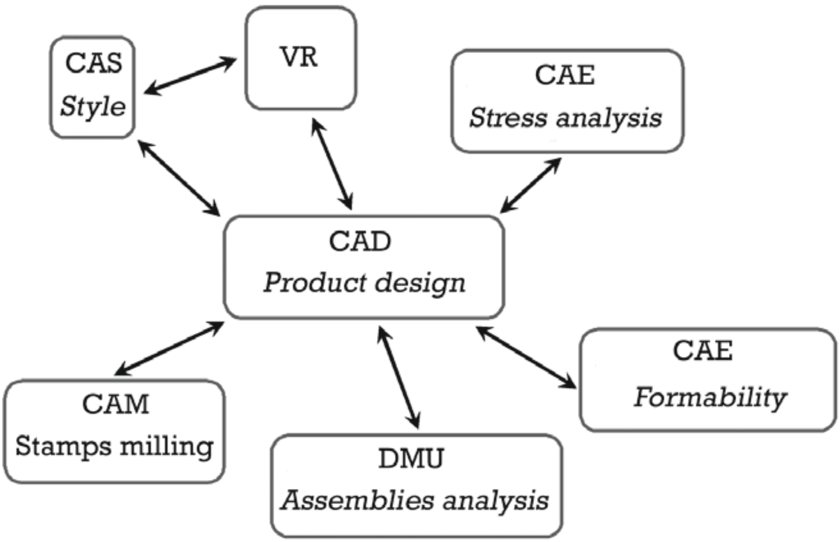


Fig. 3.2. Scheme showing the links between product development activities and dedicated informatics tools.

shape, without risk of rips and wrinkles; similar tools are also used to assess plastic parts formability.

- CAM enables the definition of the cutting tool path for milling machines that will manufacture the stamps; again the same body panel mathematical model that has been used for stamp design can be used also for stamp manufacturing.
- The calculation power of modern computers enables the preparation of complete assemblies renderings with simplified surfaces, including also related production tools, applying DMU techniques, that also take advantage from virtual reality.

Such renderings offer many potential applications by:

- Style architects: evaluating aesthetic results obtained by joining different panels taking into account gaps or profile errors.
- Product engineers: evaluating kinematic mechanisms or interference between neighboring parts.
- Production engineers: assessing the motion of parts along the production line while checking for collisions.
- Service engineers: evaluating assembling and disassembling operation for repairs.

3.2 CAS, Computer Aided Styling

When a new model development is started, a series of general vehicle specifications are defined, essentially consisting in the following information:

- The type of car, market segment and expected production volumes.
- Relevant exterior and interior dimensions.
- Engines, gearboxes and tires to be adopted.
- Parts to be carried-over from previously developed models.
- Manufacturing and assembling technologies to be adopted in connection with the production plant selected.
- Performance and cost targets.

A preliminary car lay-out sketch of the car can be drafted from the first five items; from this preliminary sketch, style and body structure developments are initiated. An example of a preliminary car lay-out sketch is shown in Fig. 3.3.

Usually, each new car is born as a replacement or part of an existing car family; this fact determines constrictions regarding the utilization of an existing platform[1], including car floor, chassis components and powertrain.

To consider only the constrictions to be the starting point of style development is an over-simplification; in fact the crucial objective is to generate a form that can excite positive emotions on future customers which is coherent with the commercial target of the model to be developed and with the existing boundary conditions (i.e. production plant, suppliers, cost, etc.).

In this context two distinct phases in style development can be identified:

- Form generation.
- Mathematical model generation.

3.2.1 Form Generation

The scope of this section is to identify a series of relevant facts without trying to analyze or rationalize the creative process behind them.

In developing cars, or industrial products of similar complexity, designers and engineers have to cooperate closely in order to define the form of the product.

[1] The term platform indicates the virtual assembly of chassis (complete under body) and powertrain common to a given car family; the same term is sometimes used to call the interfunctional organization dedicated to the development of a car family.

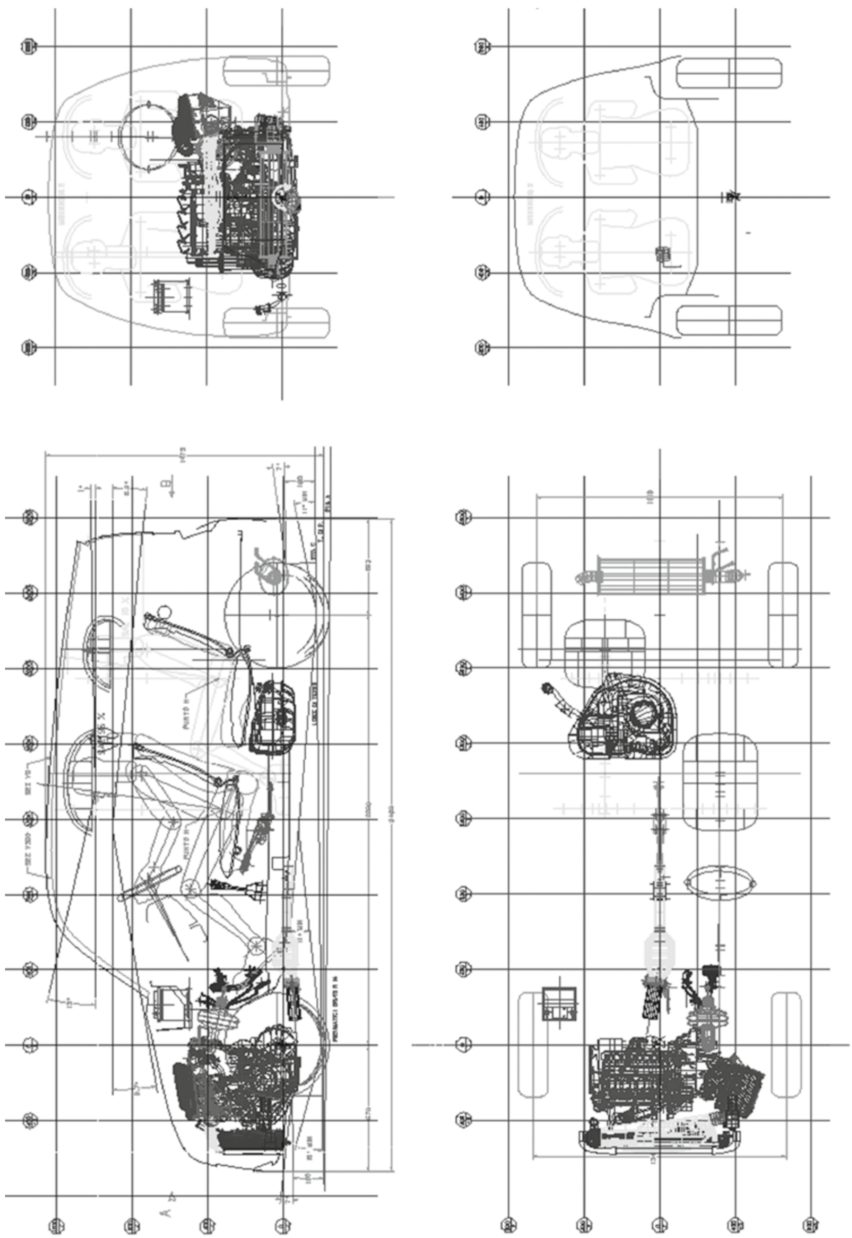


Fig. 3.3. Example of preliminary car lay-out sketch, suitable to demonstrate packaging, roominess and visibility; this is the starting point of style and body structure development.

The designer conveys his insight through graphical elements, while the engineer brings this insight to conclusion, transforming these graphical elements into a technologically feasible object.

To ensure continuity, it is necessary that part of the creative background of designers is available to engineers and vice versa.

In principle there could be two different approaches to product design: develop an idea, a solution to a problem, with the assistance of scientific analyses, or alternatively use scientific analyses to define an idea.

This second approach, even if desirable from certain perspective, yields limited results and is in general only useful to solve relatively simple problems; instead the most fruitful approach is usually the first.

Style development is a balanced mix of intuition and scientific approach, where the success of the development process requires an appropriate equilibrium between creative and structured activities.

What is important, therefore, is full comprehension between two different thought processes: while it is true that the best idea without engineering development cannot become a viable product, it is also clear that the best engineering method without insight will not translate into an interesting product.

During form generation, the product appearance will summarize designer's comprehension of model targets; this comprehension will materialize through partial sketches that only later will be integrated into a coherent form.

Fig. 3.4 shows some sketches of this phase of style development, freezing on a physical support the ideas generated while capturing product targets to be integrated successively. These sketches do not have all the characteristics required for an objective representation, but rather represent the idea as interpreted by the designer.

Still only very immediate tools as a sheet of paper and a pencil for a freehand sketch can materialize insights and make them available for further processing. Indeed no software tool is yet available for creative activity which is quite as effective as freehand sketching, and in general few designers are capable of materializing their ideas with draft and paint software tools available; only when key ideas are conceived they can be integrated into a detailed digital model. This is already a rationalization phase that very seldom will receive further creative contributions.

Fig. 3.5 represents the digitalization of the initial sketches, according to the coordinate lines in the xz and yz planes, which enables the creation of a complete sketch of the car body to initiate discussions between designers and engineers.

Once, designers and engineers could discuss only on scaled clay models, available later in the style development process; now, rapid sketching and paint software tools enable the early interaction between these two different cultures.

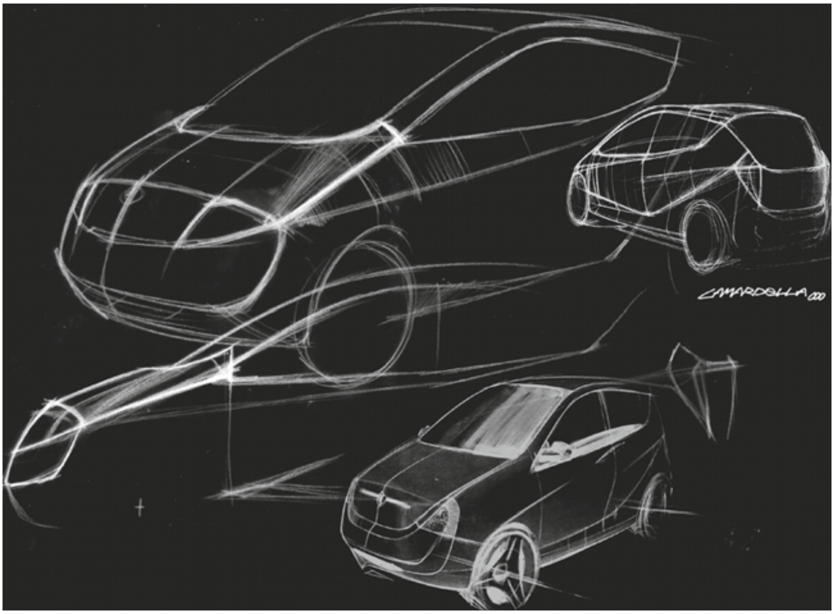


Fig. 3.4. Hand drafted sketches representing the designer's perception of product objectives.

3.2.2 Mathematical Model Generation

It looks unlikely, at least for the time being, that a CAD system designed to provide a complete and very detailed description of the body surface can be also used for a creation process that concentrates only on more specific aspects.

Nevertheless CAD systems are useful immediately after form generation in order to investigate the compatibility of what has been conceived with performance and the technologies involved with its production; product and process engineering require, in fact, a very complete and sharp representation.

The few lines, initially defined, are now converted into spatial coordinate surfaces with the help of software tools, as Fig. 3.6 shows. Missing details are added; this operation is performed almost routinely since it does not require conceiving new forms but just coherence with the previous insight.

Image processing and rendering systems allow results to be verified regularly and the necessary corrections to be introduced; Fig. 3.7 shows one such representation. At this stage, these surfaces are used as an input for a CAD system to enable further details to be added.

At this point, many shape details are added to complete the surfaces; Fig. 3.8 represents the transformation into mathematical lines of the detail of door handles.

During the engineering development of the style shape many problems may arise that require a new reinterpretation or redefinition of the initial form. These

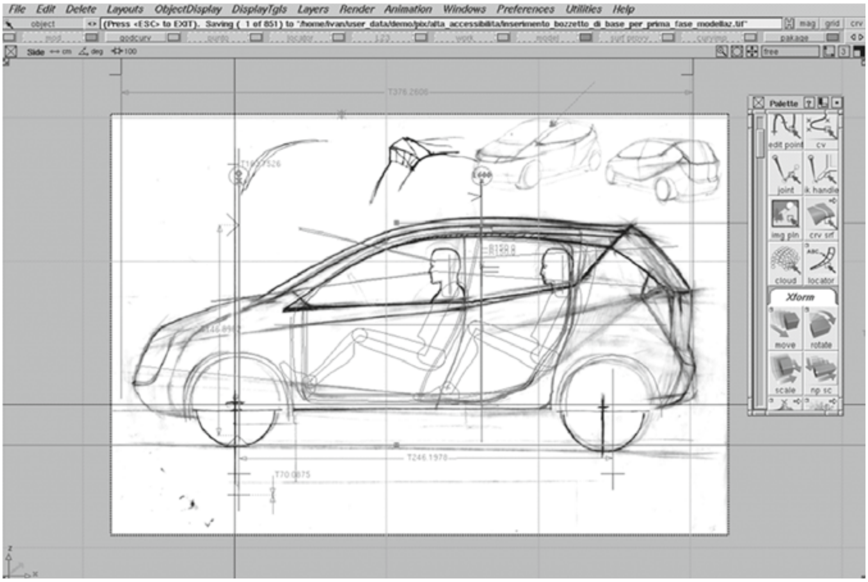


Fig. 3.5. Transforming sketches into coordinate lines (on the xz and yz planes) will allow to arrive to a style sketch that will start discussions between designers and engineers.

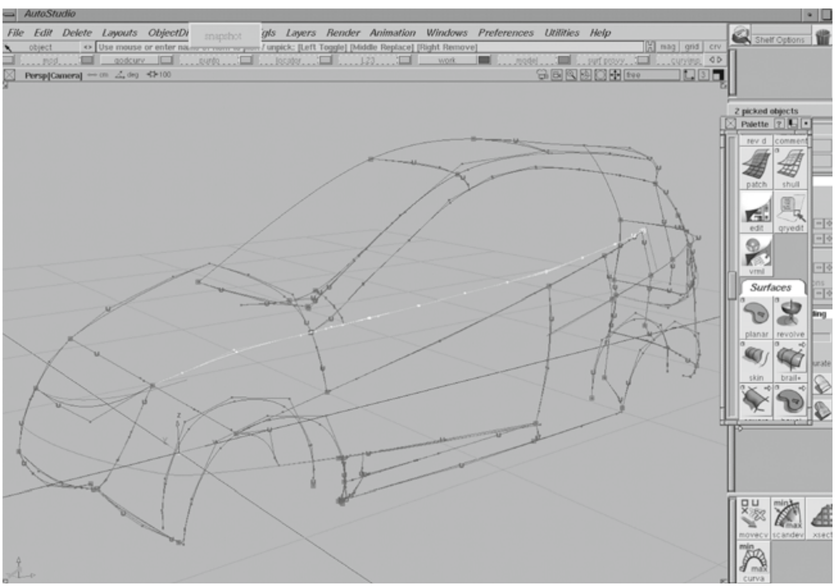


Fig. 3.6. The few lines, initially defined, are digitalized and converted into coordinate spatial surfaces by means of dedicated software tools.

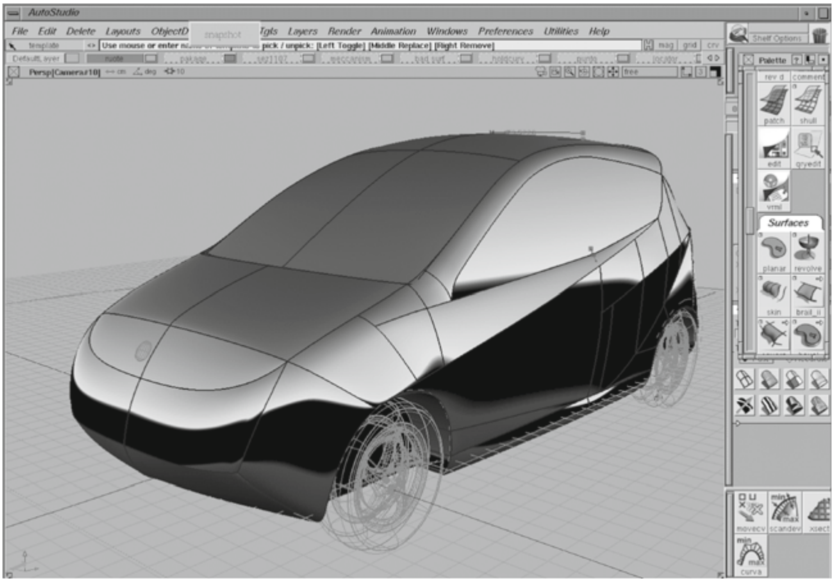


Fig. 3.7. Three-dimensional rendering of initial sketches allows correction of added elements, according to their coherence with the initial insight.

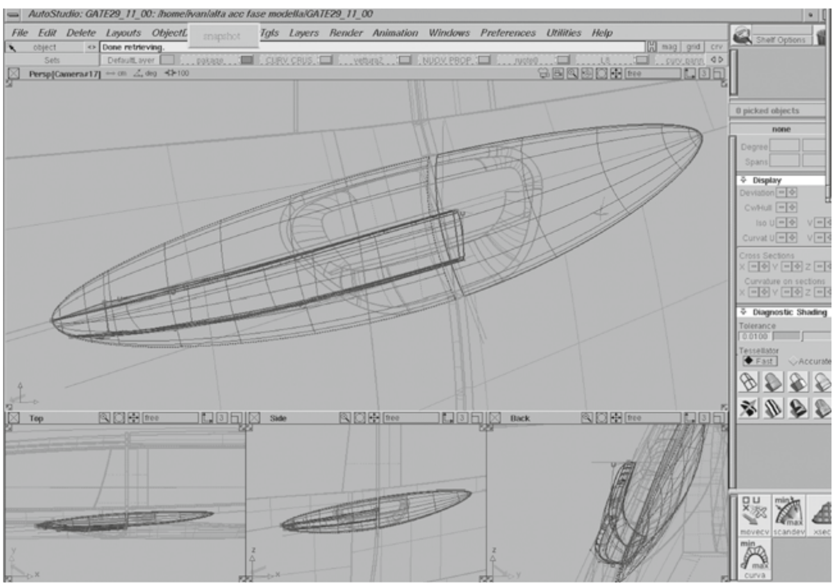


Fig. 3.8. Transformation into mathematical lines of details, as door handles.

Fig. 3.9. Milled surface cut from a sawdust and epoxy resin block (epowood), treated with plaster and paint, to simulate the final appearance.

problems do not regard the body taken as a whole, but more often single details or the transitions between different surface elements.

A CAD mathematical model usually enables the effective evaluation of the car exterior shape, using for instance virtual reality. Nevertheless, improvements in these systems are still necessary to allow each person involved in decisions regarding the appearance of the car to be familiar with them; this is why physical models are still in use to confirm decisions taken on virtual models. Sometimes direct viewing, and the sense of touch on a full scale object, are useful to perceive the correct impression.

Fig. 3.9 shows one of these models. These models are built automatically by means of computer aided milling of an epowood block (a mixture of wood saw dust and epoxy resin), starting from the CAD mathematical model directly. These milled blocks can achieve a highly realistic aspect by finishing, painting and polishing by hand.

Sometimes, corrections are introduced by designers on the model directly, to improve the appearance or to visualize and discuss possible modifications. In this case the mathematical model will be updated by digitalizing the new surface directly.

3.3 CAD, Computer Aided Design

The adoption of informatics instruments simplifies enormously the detailed and exhaustive representation of the surface geometry that is now represented by continuous mathematical equations; nevertheless it introduces new issues depending on the type of CAD system in use.

We should in fact consider that the CAD systems currently available on the market have comparable modeling capacity, but not identical techniques for representing surfaces mathematically; therefore the use of different CAD systems implies the use of so called universal translators such as STEP or IGES, which are two of the most diffused, to convert data generated on one system to enable use in a different one.

In certain cases dedicated translators have to be developed. In any case additional time must be spent to convert, repair and complete data, with consequent costs that could have been avoided by choosing a single CAD system at least for the development of a given model.

In addition, every CAD system, under continuous improvement and modification, as with any informatics product, require significant training time of those expected to use these instruments.

Different systems imply different procedure to create the same geometric entities and the skills acquired by an engineer on a certain system can be applied to a different one but with some difficulty.

A decision about the adoption of a given CAD system receives strategic contents, because of the capital investments involved for software acquisition and training, which has amplified effect on partners and suppliers, and the cost of reusing drawings developed in the past. Despite the inconvenience, in the recent history of car design, it is relatively easy to find instances of major car manufacturers using different CAD systems (e.g. body engineering and powertrain engineering) at the same time.

The mathematical models transfer from CAS to CAD system usually does not require reworking because surfaces are simple (only the visible part is represented) without comments, dimensions and tolerance information; the effective communication between these two systems is a major advantage of these informatics tools: the same mathematical model applied to represent the aesthetic surface is also used to represent part of the component and to program the milling machine cutting stamps.

Aesthetic surfaces contain not only information about their shape, but must define also their contour, including the gaps between different panels of the body skin or play between fixed parts and parts that can be opened or replaced, or between body panels and glasses. The definition of these details is consequence of the compromise between aesthetic concepts and engineering requirements, posed by part function and manufacturability.

In the next section the development of a car body is described, with particular reference to the body shell. The example adopted refers to a new body development, starting from an existing platform, which represents the most frequent case. In fact, the development of any major part of the platform (engine, gearbox, suspensions, etc.) requires a significant development effort; for this reason, such parts are applied for more than 10 years, also on very different cars.

3.3.1 Body Modelling

The most important steps of body modelling are typically the following:

- Breakdown structure definition, as function of expected production volumes, adopted technologies and materials.
- Definition of main sections of the skeleton, partly independent of the style model.
- First approximation modelling of body exterior panels.
- Detailed analysis of junctions, between side members, cross members and pillars.
- Trade-off between aesthetic, structural and manufacturing requirements.

Breakdown structure

The first step is the definition of technological and design solutions that will be adopted for the body under development.

To shorten development times, including modelling, virtual and physical validation, solutions are preferred that have already been applied on other cars or validated in previous non-finalized development activities (the so-called pre-engineering): these solutions are usually conceived as archetypes, meaning a generalized model, useful for subsequent application to an assigned exterior style or shape.

Archetypes are not only the consequence of a structure architecture, but also of the assembling process or materials selected. For instance, on a large production car, the most common body archetype is the unitized one made of stamped steel, while for a small production volume a partly not unitized solution could prove more convenient.

The term archetype is all-embracing because includes many different design aspects such as the impact of aluminium adoption, with the possibility of using extruded or cast parts, or laser welding, with the elimination of welding flanges and electrodes passage holes.

Main sections

According to the selected archetype, including the breakdown structure, architecture, material, applicable forming and assembling technologies, characteristic cross sections of the skeleton are defined (see, for example, Fig. 3.10).

Starting from an archetype, even if not yet applied to an assigned aesthetic surface, many functional parameters are conditioned such as:

- The dimensions of resistant cross sections.
- Thickness and material for each of its parts.

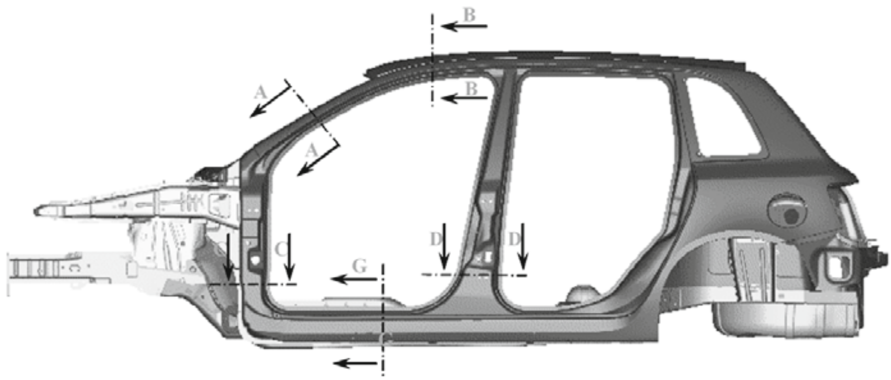


Fig. 3.10. Some typical body cross sections that can be defined starting from an archetype.

- Aesthetic matching with neighboring parts, for instance parts that can be opened or made of glass.
- Assembling solutions for small components such as weather strips, hinges, locks, etc.

To understand how all this information can be focussed in few lines in practice, reference can be made to Fig. 3.11, where section B-B of Fig. 3.10 is shown, corresponding to the part of the roof above the front door: the description will become clearer in the following chapter where each component of the body shell will be analyzed in detail.

Four very different archetypes can be observed:

- Archetype 1, characterized by a longitudinal aesthetic strip covering the welded joint between the roof and the body side, by a sliding glass without visible outside frame and by a weather strip integrated with the guide liner of the glass.
- Archetype 2, characterized by an enveloping roof with no covering strip, framed glasses and weather strip mounted on the welding flange between the roof and the body side.
- Archetype 3, again characterized by a longitudinal cover strip, integrating also the function of weather strip.
- Archetype 4, similar to archetype 2, but with frameless glasses and integrated weather strips and glass guide liner.

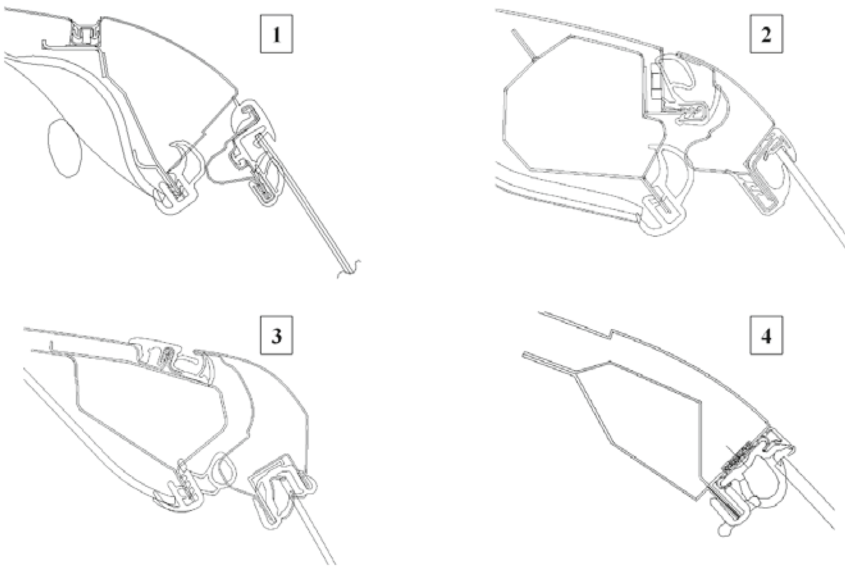


Fig. 3.11. Some different archetypes for joining the roof with body sides, depending on the door archetypes that can be matched.

Different archetypes have different aesthetic contents, also corresponding to different capital investments and procurement and production costs, as a function of the different structure breakdown and materials.

It is important to remember that the represented sections can be applied to the specific body only if they are adapted to the mission to be accomplished and to the specific shape of the car style.

This archetype selection and adaptation process can be performed not only for major components, but also for details such as weather strips and glasses.

To speed-up this process and avoid mistakes, it is very important to access a wide database of already developed in-house or competitor solutions.

This operation consists of repositioning on the new style and resizing already existing elements, corresponding to production cars or pre-engineering results; other components may be used as-is, i.e. without adaptation, e.g. the weather strip section, locks, hinges, etc.

This geometry will be subsequently refined following analysis and virtual or physical prototype testing.

The implications of the adoption of predefined archetypes are discussed again in the following section.

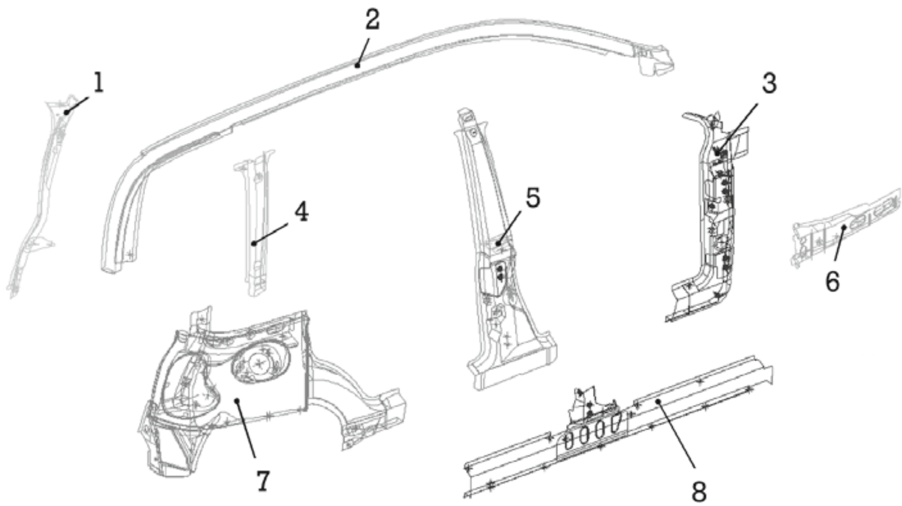


Fig. 3.12. Basic components of the body side of a space frame type body.

Modelling

Once a number of sections have been positioned and sized in sufficient quantity to define the body shell critical areas, engineers proceed with modelling the remaining body shell parts, doors, hood, etc. Critical areas usually include the structural skeleton and doors hinges.

To clarify this process, a body shell conceived as a space frame may be considered, as in the example of Fig. 3.12 and Fig. 3.13, since it is easier to identify beams and junctions on the body side.

For instance in section B-B (Fig. 3.11 and Fig. 3.10), the archetype that better matches the example is 1. Based upon this cross section (and clearly a number of others along the door contour) the upper part of the body side and its upper beam can be modelled in detail. Existing CAD systems enable this operation to be performed almost automatically, thanks to their parametric and associative features.

The upper beam to be modelled is logically connected to the aesthetic surface (it is associated with the surface) and its size is defined by the measurements as a function of a limited number of fundamental dimensions (parameters).

These parametric and associative features also permit the implementation of the many modifications to be expected in short time; for instance, CAD systems with these features allow an entire model to be regenerated, as a consequence of a style modification, maintaining the archetype logical relationships automatically.

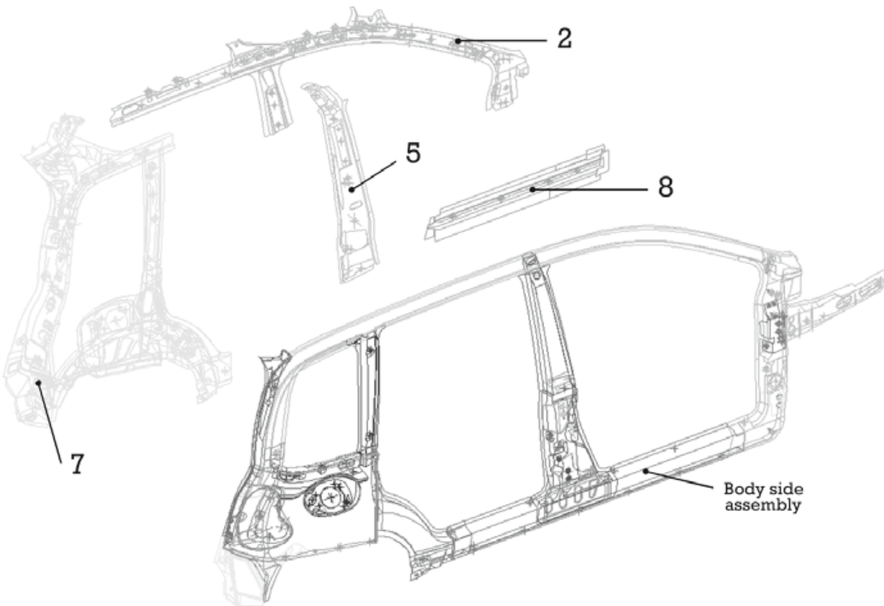


Fig. 3.13. Body side assembly of previous space frame body.

The power of the associative features can be exploited to investigate the effect of a modification also to other geometric entities, such as stamps, milling paths, finite elements analysis models, etc.

This kind of approach can be repeated for all body elements of which the geometry can be assimilated to a cross section extruded along a curved path.

Stamped steel or aluminium body panels may be represented as a portion of solid space included between the aesthetic surface and a similar surface obtained by shifting the previous of the panel thickness. A line obtained on a drawing by cutting the aesthetic surface is called style profile; the other line defining the panel section is obtained with a pure shift.

This process may be applied with some caution to thicker elements, such as plastic components, later introducing completions as ribs, roundings, pins, etc.; also these details may be defined using archetypes.

Some car manufacturers have instead opted to model also surface-like parts with solid bodies, thanks to CAD systems designed for this feature: this procedure involves greater modelling time, but enhances the successive development steps, such as designing stamps for high thickness plastic components.

Junctions modelling

When structural beam elements of the body are modelled, the junctions at beam intersections can be defined in detail.

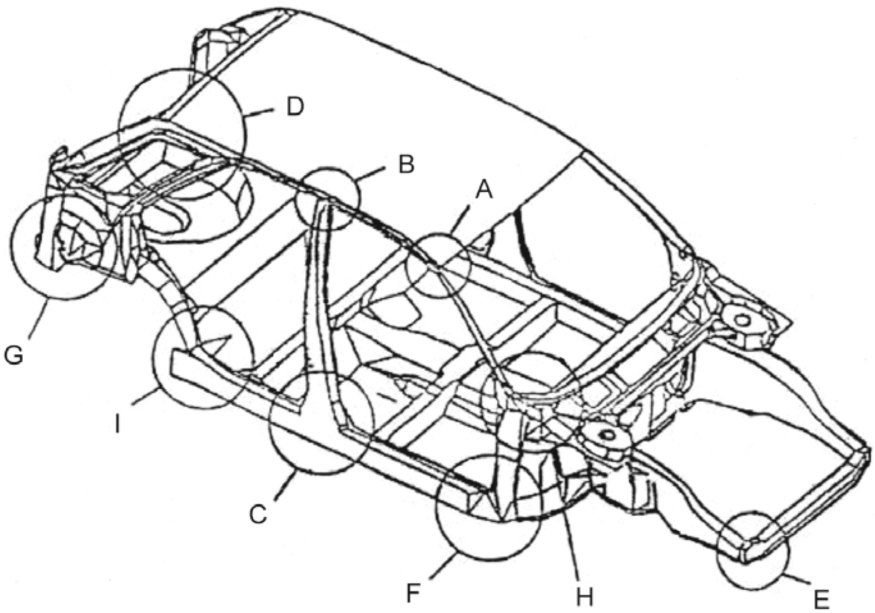


Fig. 3.14. Conventional designation of main body junctions.

To designate these junctions, a standard nomenclature has been defined (see Fig. 3.14): it is interesting to note that the order adopted puts in foreground the areas more bound to style than to structural behavior.

Consider, for instance, junction A, at the intersection of body side with windshield and roof:

The components of the body shell involved (see Fig. 3.15, on left) are the roof, upper windshield cross member, exterior body side, A pillar cross section and reinforcement member.

At this joint also the windshield and its structural adhesive bond contribute, and the geometry of any liner may be involved. The front door and their weather strips are also affected by this geometry, as is the space available for driver and passenger and their visibility.

Together with the space requirements for the installation of these entities, the structural requirements relevant to torsional stiffness, front impact, roll-over should also be considered; the assembly cycle feasibility should also be considered.

If classical spot welding is adopted, also access for the electrodes should be taken into account. For example (see Fig. 3.15, at right), the eyelet surrounded by a dotted line allows access to the electrode of the welding tool from the inside of the body and therefore makes the junction between roof and body side possible.

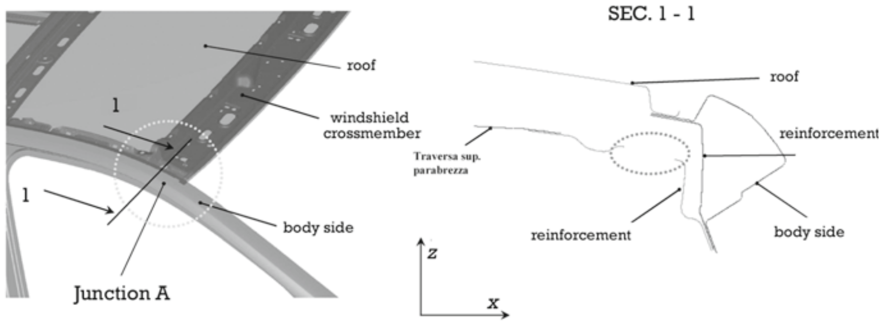


Fig. 3.15. Junction A modelling, at the intersection of body side with windshield and roof.

Also the task of designing different junctions in detail is simplified by CAD systems, enabling 3 D modelling, with a clearer perception of geometrical issues, together with quicker modification or adaptation of existing pre-validated solutions, therefore shortening the development time.

Test validation

Once the body has been defined, including doors, hood, hatch and removable parts, together with all detail interfacing body components (such as weather strips, locks, hinges, etc.), a complete 3 D model is available that can be easily tested with respect to different perspectives. Each virtual test will result in modifications for surfaces or sections; with a parametric associative CAD system, each will be implemented in a very short time, sometimes automatically, and transferred also to associated entities such as stamps, assembly fixtures or other dedicated production tools.

CAD system speed is particularly advantageous when introducing the large number of modifications resulting from potential malfunctions detected during the virtual validation tests.

Some of these validation tests are described in summary in a following section of this chapter; more details are included in the relevant sections on body and interior components.

As far as aesthetics is concerned, mathematical models obtained with this procedure enable the refinement of the exterior surfaces with style architects and certify coherence between shape, performance and manufacturability: for instance, the shape required for the windshield by the style concept is verified in terms of visibility and installation of wipers, or for side glasses again in terms of visibility and sliding motion into the door.

The body mathematical model can be transferred for evaluation in terms of structure analysis, regarding dimensions, local thickness, material choice and welded junctions. Also in this case, informatics tools contribute to shorten development times by generating the calculation mesh almost automatically.

In this way, the mathematical models become an effective communication tool among engineers, stress analysts and, again, style architects in order to be able to negotiate modifications and define trade-offs.

A similar situation enables process engineers to evaluate and analyze formability and the assembling process.

It should be underlined that the mathematical model is built in the ideal hypothesis of nominal dimensions, without taking into account the effect of fabrication tolerances.

Again, using dedicated software tools, mathematical modelling enables investigation into the effect of dimension variations on the assembling process and compatibility with product performance.

3.3.2 Rules and Common-Practice in CAD Modelling

CAD models are the transposition into mathematical parameters of a set of numbers that regard not only the geometric nature of a part, but also its technical and organizational features.

The information regarding geometric nature includes the coordinates of points, surface and lines equations, etc., necessary to define the shape of a part completely.

Part of this geometric information has also some organizational content; for example, the associative features describe, in informatics language, the operations accomplished by the design engineer while modelling a part (design intent) and their relationship with neighboring models (welding and assembling interfaces); this information permits the regeneration of the mathematical model automatically when some of its geometrical parameter are modified.

Technical features cannot directly infer geometric information, containing for example dimensions tolerance, positioning reference points, functional specifications, etc. that are necessary for part operation, manufacturing, or production fixtures.

Nominal dimensions are instead usually inferred of the mathematical model.

Organizational features consist in data necessary to manage the part within the company information system according to usual company practice.

Among the organizational information, the description of the product configuration is the most relevant; product configuration describes the logical relationship between any of the parts composing the vehicle. Product configuration enables the correct identification of any subassembly or elementary part and the preparation of a bill of materials.

Product configuration description allows also the creation of any assembly drawing and the management of material flow along the production line, orders to suppliers and the delivery and storage of spare parts.

A further organizational feature to be recorded on mathematical models is a note concerning their development status; it is necessary to advise any of the potential users of a mathematical model about the level of risk of processing an information not fully validated since many activities are performed in parallel by people with real-time access to a common data base.

Finally, CAD models are classified with reference to their content and to their preparation technique. The following classification is usually applied with regard to the content:

- Outline drawings, essentially useful to the design engineer to develop ideas, define critical matching between parts and solve problems of geometric compatibility.
- Assembly drawings, useful for documenting how parts are assembled together.
- Part drawings, useful for exhaustive documentation of dimensions, materials, specifications of a single part.

The following classification refers, instead, to preparation technique influencing the kind of model used, the principal being:

- Wire frame models.
- Surface models.
- Solid models.
- Conventional drawings.

Wire frame models are 3 D models where solid bodies are represented by spatial curves describing their edges; between one curve and the next, the surface shape is unknown and must be interpolated.

A surface model is again a 3 D model where a part is described through its contour surfaces; the coordinates of each points are fully determined.

A solid model includes a complete description of the space included between the boundaries of the model and can represent every detail of a part, including its physical properties such as mass, moments of inertia, etc.

A conventional drawing is a paper print-out, similar to a pencil drawing, used for communication only and unsuitable for further development.

Reference system

The reference system traditionally adopted by body engineers is different from that suggested by the SAE J670 standard for mathematical models of vehicle dynamics; here a xyz axis system is referred to with its origin set on the body symmetry plane, at the intersection with the front wheels axis of rotation and where:

- the x axis is contained in the symmetry plane and set horizontally, pointing rearwards,

- the y axis is perpendicular to the symmetry plane, pointing to the right with respect to the driving direction,
- the z axis is consequently vertical, pointing upwards.

If the vehicle body were not symmetric, the xz plane would be assumed to be coincident with the vertical plane.

The definition of the origin depends upon the position of the suspension, which determines the centre of the front wheels and the body pitch angle; therefore, this definition must be applied by loading the car with respect to the reference condition, usually corresponding to a full tank of fuel and four passengers of 70 kg of mass each, with 40 kg of luggage in the trunk for cars with four or five seats, or two passengers and their luggage in two-seater cars.

For different kind of payloads (vans, minibuses, trucks, etc.) a load condition near to full load is usually selected.

Considering the body size, and the fact that drawings should be printed at least in full scale, a complete body assembly is rarely represented on the same drawing for sake of clarity.

To enable the correct location of partial assembly drawings or part drawings, a quoted reticule is represented on each drawing, according to the local applicable coordinates, as shown in the Fig. 3.21.

Surface representation

Body part drawings usually contain surface elements that are fully defined by a mathematical model; large surfaces are represented by joining a sufficient number of patches with dimensions depending on local curvature: more curvature requires a higher number of small patches.

Visible parts of the body surface are called aesthetic surfaces and are coincident with the style model[2].

In the case that aesthetic surface is not available as a mathematical model (this was commonplace until just a few years ago) style architects must provide a physical full scale 3 D support representing this surface; this support will be digitalized point by point, for example at the intersections of the surface with the body reference reticule; the lines obtained are joined with interpolated mathematical patches as in the other case.

Each section of the drawing representing a part contoured by the aesthetic surface will contain also the style profile, the intersection of the aesthetic with the section surface.

The concept of style profile applies also to solid models, for instance high thickness plastic parts.

[2] The following indications are not standardized but refer to the praxis of a large car manufacturer and his suppliers. There are no international applicable standard rule for the time being, even if similar rules are widespread.

Skeleton surfaces do not usually contain parts of the aesthetic surface; nevertheless they are represented with the same system, developing a surface mathematical model for the side of the skeleton matching with visible parts, taking care to define a sole style profile for each of its parts.

Where the aesthetic surface is interrupted, for example at a door contour or near a dismountable part, the mathematical surface will be cut by a surface determined by an envelope of constant diameter circles with their centre on the aesthetic surface; this operation enables a constant gap between different parts to be generated.

Subsequently the two parts of surface are rounded to reproduce the effective shape of the part that can be obtained by stamping or bending. Flat surfaces might be added, to join the outside body panel to the skeleton. These are called completion surfaces, for comparison with the aesthetic surface.

Drawing surfaces are usually classified in classes (A, B and C class) with reference to the accuracy of their mathematical model.

The accuracy is measured by comparing the mathematical with the aesthetic surface and measuring continuity between patches.

Classes are useful to speed-up the activity of style architects and body engineers, improving time and manpower efficiency with regard to applying the finishing touches when the style freeze event is still far away and many major modifications could still be necessary.

Class type represents, therefore, not only the accuracy of the mathematical model, but also the maturity of the project: from class C, used for feasibility studies and the first style proposals, drawings are refined up until class A, at the end of the project, to represent the part to be put in production.

Common practice is that:

- at the initial stage, when more alternative style proposals are under evaluation, class C is allowed in each mathematical model;
- when a style alternative is selected, but uncertainties and variants are still present, class B is allowed;
- final drawings, ready for production, must contain class A surfaces only.

Specifications for each class are contained in the following points.

Position continuity

The distance between each point of the edges of two neighboring patches must comply with the following limits:

- For class A: no more than 0.01 mm.
- For class B: no more than 0.02 mm.
- For class C: no more than 0.05 mm.

Tangents continuity

The angle between the tangents to the surface on the edges of two neighboring patches must comply with the following limits:

- For class A: no more than 6' (0.1°).
- For class B: no more than 12' (0.2°).
- For class C: no more than 30' (0.5°).

Curvature continuity

The control parameter is the patch curvature along its contour.

- Class A surfaces must have coincident curvature at least every 100 mm of contour of two neighboring patches.
- Class B and C have no applicable rule.

Points of maximum curvature or inflection are only allowed along patch contours of Class A surfaces.

Completion surfaces

As we have seen, they do not belong to the aesthetic surface (even if part of them is visible and influences the aesthetic evaluation of the body), but are added to represent the part as it can be produced.

- For class C surfaces: completion surfaces are not required; gaps are represented by double lines drafted onto the aesthetic surface.
- For class B surfaces: only rounded contours are represented on the surface that is always fixed to the body.
- For class A surfaces: completion surfaces must be designed in all detail.

Shape tolerance

The shape tolerances are measured by comparison of a surface patch with the counterpart on the aesthetic surface.

- For class A surfaces: no more than ±0.5 mm on body shell surfaces (or large surfaces) and no more than ±0.2 mm for interior trimming (or small surfaces).
- For class B surfaces: no more than ±1.0 mm on body shell surfaces (or large surfaces) and no more than ±0.5 mm for interior trimming (or small surfaces).
- For class C surfaces: shape tolerance is not applied.

The distance between points with maximum and minimum displacement (undulation) between mathematical model and aesthetic surface must be less than 1,000 mm for large surfaces and less then 200 mm for small surfaces.

However class A surfaces could show other unacceptable aesthetic defects; to correct these before stamps milling and finishing, aesthetic surfaces are represented by means of special rendering systems, sometimes available to CAD systems, suitable to represent light reflection on the actual painted body surface.

The lighting system simulated is, traditionally, a linear source lamp (neon tube lighting) that can put highlight each of the defects to be corrected; Fig. 3.16 allows the difference between inaccurate surfaces or class A, well refined surfaces to be perceived. The same procedure is applied also to the interior surface, despite not reflecting light on the actual car, as shown in Fig. 3.17.

3.3.3 Reference Points

Dimension measurement of body stamped parts or even of a complete body shell cannot be made without particular contrivance, because of the complexity of shapes and, in the case of steel stamped parts, for lack of sufficient rigidity that prevent them from positioning on a reference surface univocally, as for other mechanical components.

Similar considerations also apply when trying to position such parts on welding or clamping fixtures during production.

The purpose of reference points, usually flat surfaces or holes, is therefore to enable the correct positioning of a body part or complete body on measuring or positioning fixtures, either during production or in body repair shops.

Reference points are usually classified as:

- Primary,
- Complementary and
- Auxiliary.

If the reference point is a hole, cut on a stamped steel part, if possible its axis should be parallel to the stamping direction or, at least, inclined not more than $\pm 3°$.

Primary reference points

There are generally three primary reference points in the lower part of the body, providing a safe and precise isostatic supporting system for the complete body.

They are used for the dimensional measurement of a complete body.

Welding spots are not allowed on supporting surfaces around primary reference points; on each of these points a load equal to 2/3 of the gross vehicle weight could be applied without major deformation.

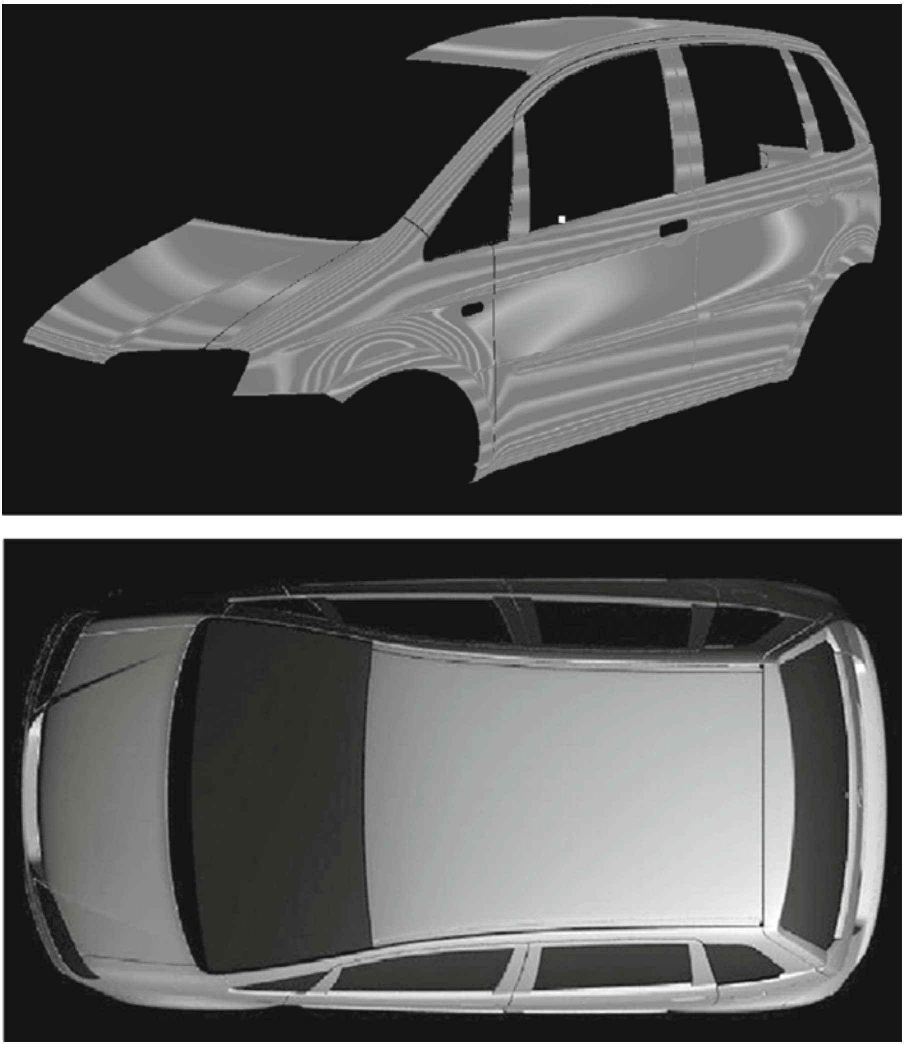


Fig. 3.16. Light reflection representation for a complete body with good (below) and poor (above) quality surfaces.

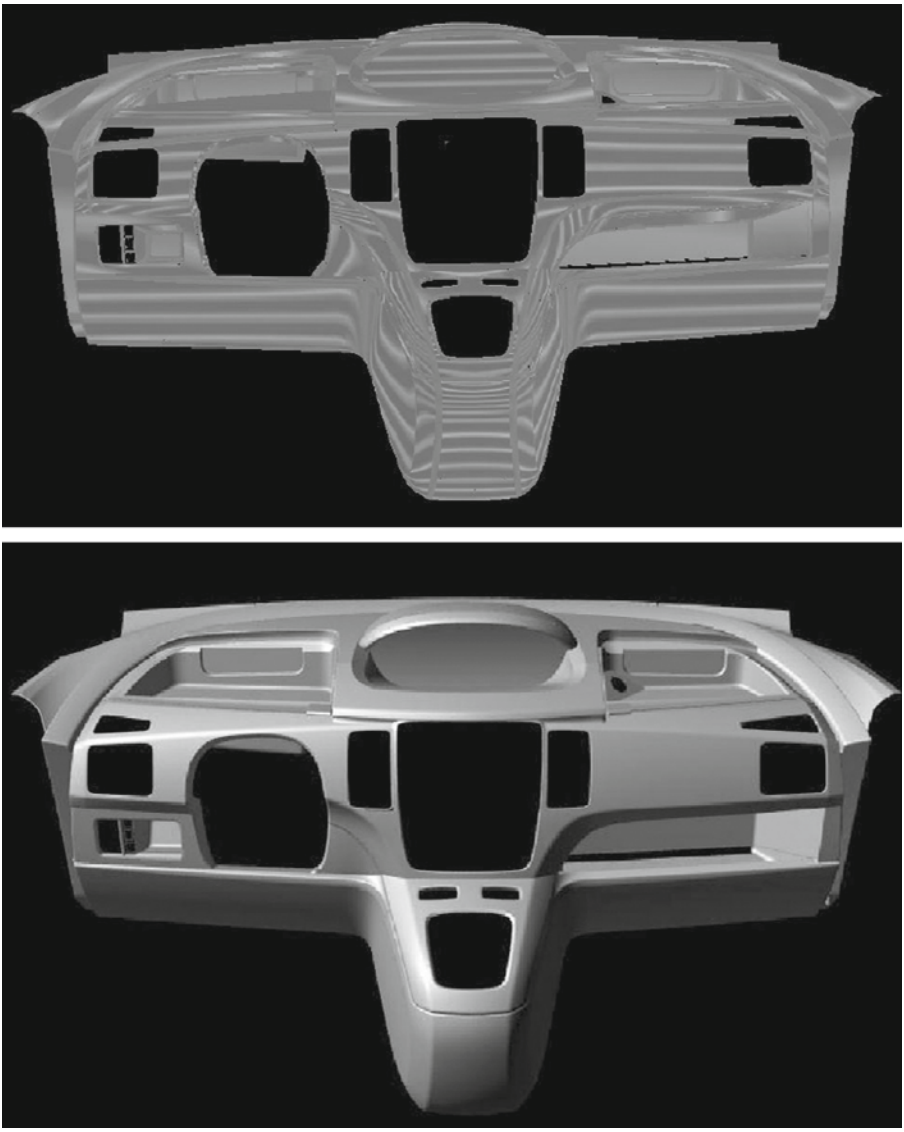


Fig. 3.17. Light reflection representation for a complete dashboard with good (below) and poor (above) quality surfaces.

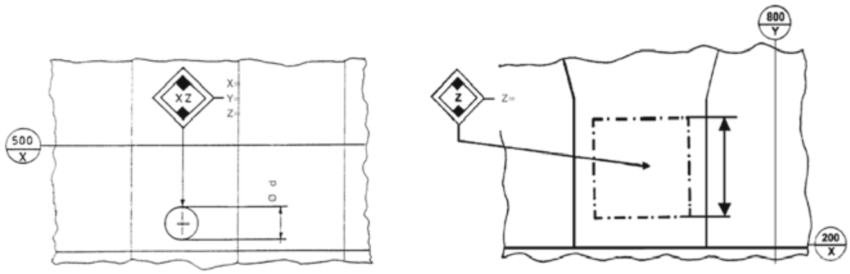


Fig. 3.18. Conventional indication on a drawing of a primary reference point, made with a hole (at left), to control the x and z coordinates and on a surface (at right) to control the z coordinate.

Primary reference points are shown on drawings with symbols in Fig. 3.18; the double square surrounds the name of coordinates determined by that point; outside of the double square the reference point coordinates are reported, with reference to the body reticule. If the reference point is on a flat surface, a dotted rectangle surrounds the points where the dimensions have to be guaranteed.

Complementary reference points

Complementary reference points are used to position a part correctly (a sheet element or a subassembly) on a measuring or welding fixture.

Complementary reference points must be selected while bearing in mind that measurements are made on a partial subassembly in order to verify that they will be suitable for assembling further parts.

Therefore the areas to be controlled are, in most cases, those that correspond to the welding or positioning interfaces in the following operation.

These points are shown on drawings according to the scheme of Fig. 3.19, at top left.

The simple square, referring to a hole or to a surface center, reports the coordinates that are controlled by the positioning point and the reticule coordinate figures of its centre.

Auxiliary reference points

Sometimes complementary reference points designed for a stable isostatic contact with a fixture are not sufficient for positioning a part correctly.

This happens when the weight of the part or subassembly, compared to its stiffness, could affect its shape between the complementary reference points that have been designed.

Auxiliary reference points are shown on the drawing with the symbol on Fig. 3.19, at top right according to the rules that have already been described.

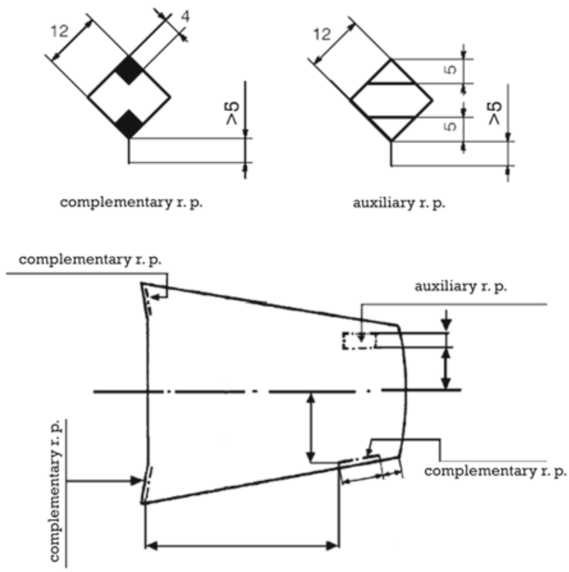


Fig. 3.19. Conventional indication of complementary reference points (at top left) and auxiliary reference points (at top right); position scheme of reference points for a hood (at bottom).

Fig. 3.19, at bottom, can clarify how to organize these reference points on a hood; complementary reference points are positioned on the welding flange on the windshield side to control x and z coordinates position, and on the right side to control y and z coordinates position; the sheet panel flexibility suggests adding an auxiliary reference point on the inside surface of the left front side in order to prevent deformations along the z coordinate.

3.3.4 Part Detailed Drawing Example

To complete this section with some more details, it is appropriate to illustrate a practical drawing example which regards the inside cover of the lower A pillar of a car.

Because it is difficult to show the entire drawing (its actual size is about 110×170 cm) on a book page, one small area of it is seen at a time; an icon on the figure shows, with a darkened area, where this part of the drawing is located.

Fig. 3.20 shows the upper right part of the drawing where general information is shown such as a 3 D scale model useful to refer overall dimensions; when not otherwise shown, dimension tolerances refer to company standards.

The 3 D sketch is made automatically by the CAD system and shows the transition lines between the different surface patches, composing the aesthetic surface. Not all of these lines correspond to actual edges, but only to curvature transitions.

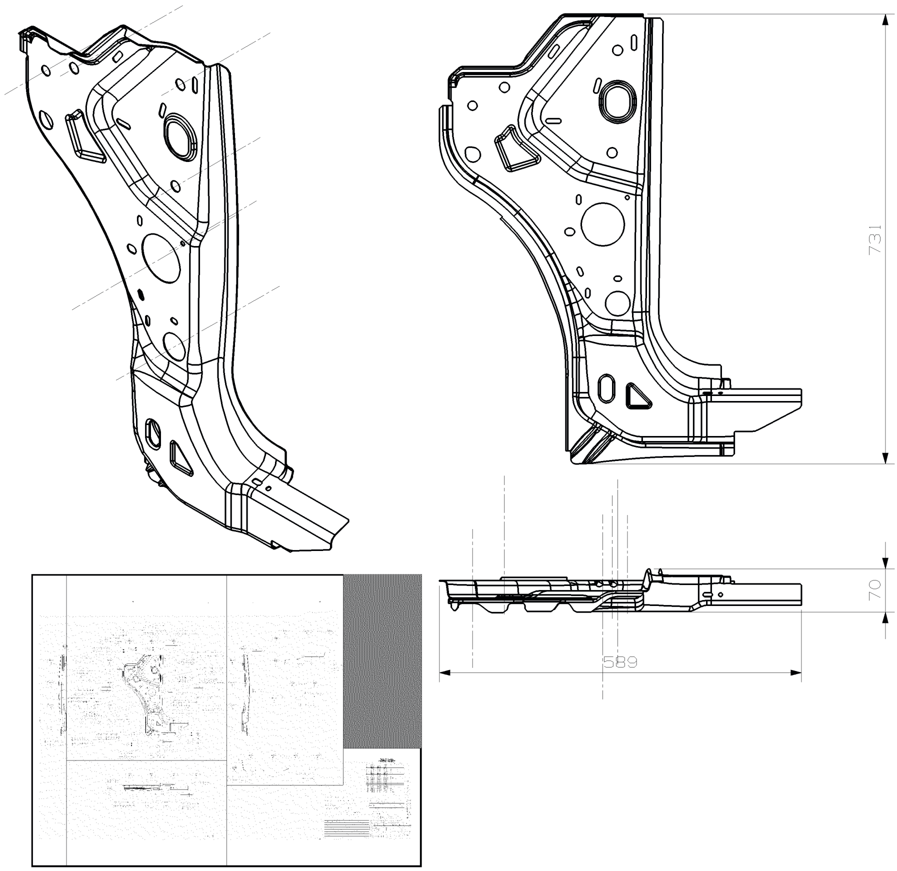


Fig. 3.20. Part of the drawing showing a simplified 3 D sketch, useful to show overall dimensions. The lay-out on the actual drawing is different for the limited space available.

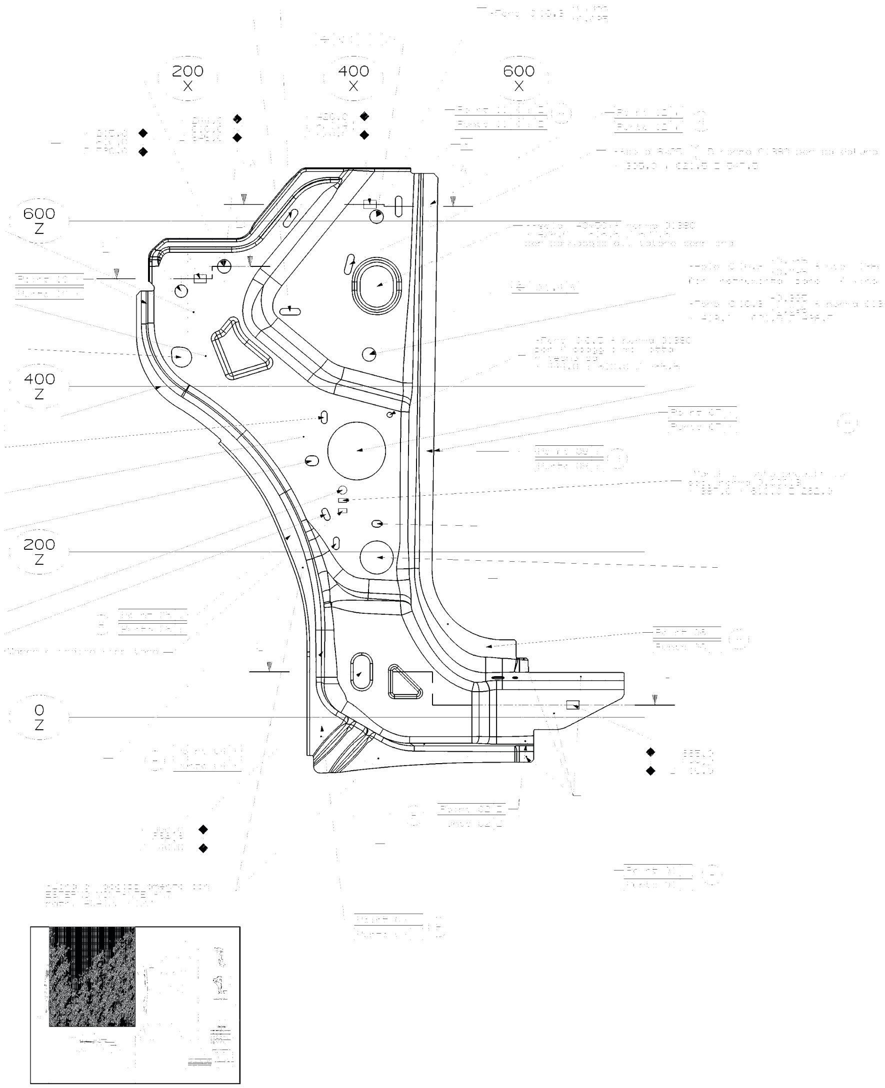


Fig. 3.21. Central part of the drawing showing the main view of this part with the reference body reticule.

Fig. 3.21 shows the central part of the drawing, regarding the main view of this part; in consideration of the position of this part within the body, the point of view is on the y axis.

The following information is reported on this part of the drawing:

- Body reticule with a 200 mm pitch; since the point of view is on the y axis, only the x and z coordinates are shown.
- Hatched areas show matching areas with neighboring parts; joining may be obtained by welding, as in this case, or with bolts, clamps, etc.; each matching area function is commented on the side of the drawing by showing the number of the part to be matched.
- Section lines are identified by letters.
- Complementary reference points are referenced according to the explanation of the previous section.
- Each feature on the drawing (circular or oval hole, stamping, etc.) is identified by its centre coordinates and nominal dimensions; usually is impossible to report all dimensions on the drawing; missing dimensions refer to company standards.
- Q letter with other completion symbols (H, 1) shows dimensions that are crucial for part quality; they must comply with specific rules on tolerances, again reported by company standards.
- Points to be measured in process are referenced with numbered rectangles with the coordinate to be measured; a dedicated table on the drawing shows the results to be obtained for acceptance.

Fig. 3.22 shows two cross section of this part, from an x view; also these sections follow the representation rules previously explained.

Fig. 3.23 shows the legend and comments area of the drawing; the information contained is used for general organization and reporting purposes:

- Part name and number; names and numbers refer to the specific function of the part on the car body and to the car to which they are applied; the bill of materials allows to know how many parts described by this drawing are necessary for a car.
- The name of engineers in charge of developing and checking this drawing.
- The material of the part.
- The scale of the drawing and other accessory information.

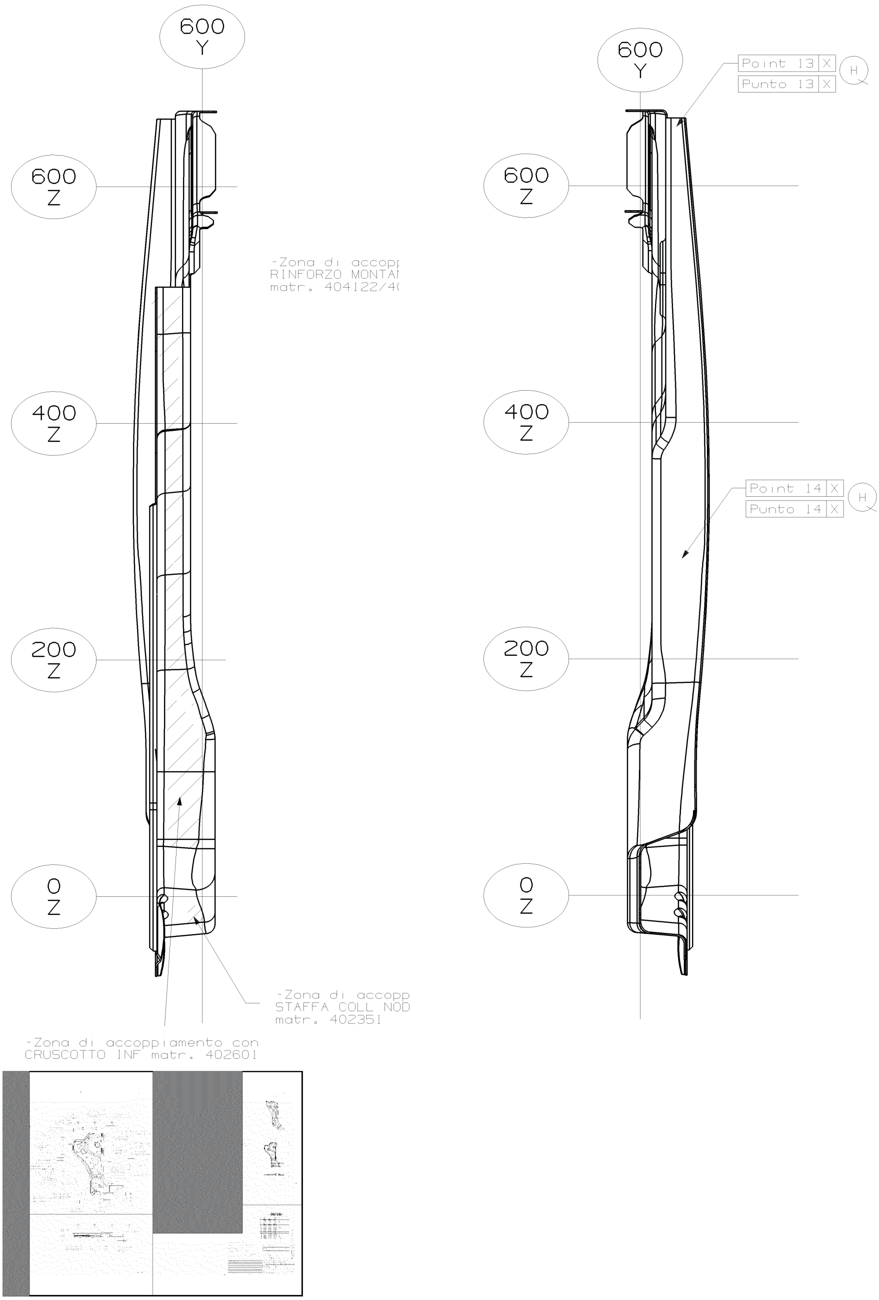
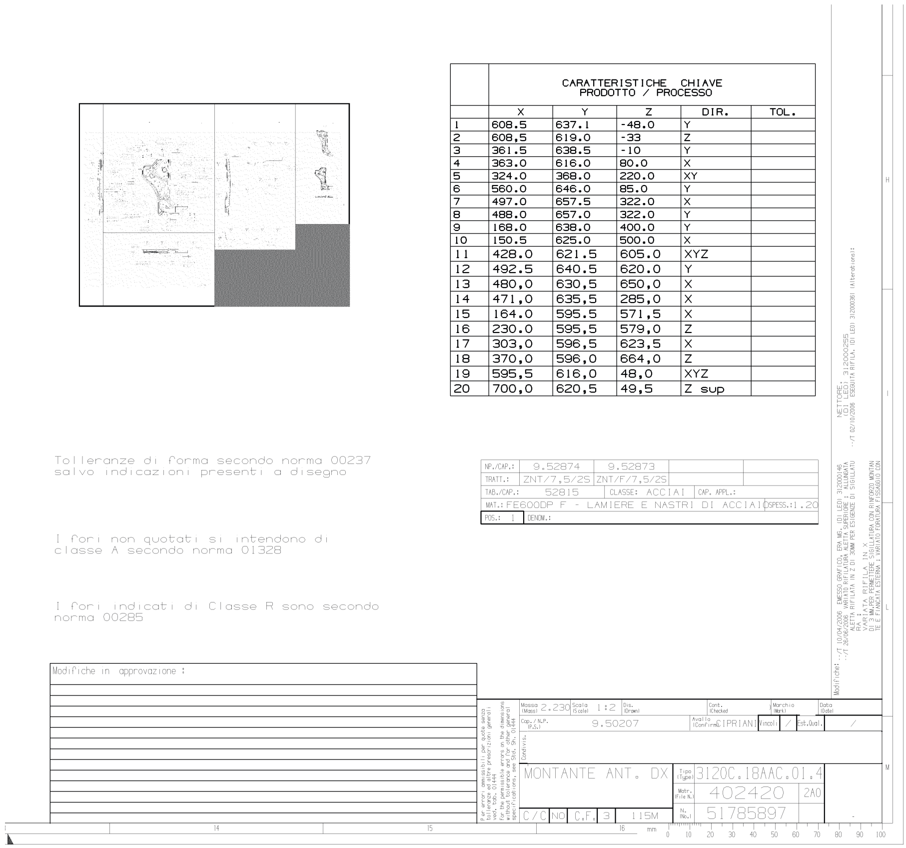


Fig. 3.22. Vertical cross sections of the part; their position on the drawing is altered for sake of simplicity.



	CARATTERISTICHE CHIAVE PRODOTTO / PROCESSO				
	X	Y	Z	DIR.	TOL.
1	608.5	637.1	-48.0	Y	
2	608,5	619.0	-33	Z	
3	361.5	638.5	-10	Y	
4	363.0	616.0	80.0	X	
5	324.0	368.0	220.0	XY	
6	560.0	646.0	85.0	Y	
7	497.0	657.5	322.0	X	
8	488.0	657.0	322.0	Y	
9	168.0	638.0	400.0	Y	
10	150.5	625.0	500.0	X	
11	428.0	621.5	605.0	XYZ	
12	492.5	640.5	620.0	Y	
13	480,0	630,5	650,0	X	
14	471,0	635,5	285,0	X	
15	164.0	595.5	571,5	X	
16	230.0	595,5	579,0	Z	
17	303,0	596,5	623,5	X	
18	370,0	596,0	664,0	Z	
19	595,5	616,0	48,0	XYZ	
20	700,0	620,5	49,5	Z sup	

Fig. 3.23. Representation of the legend and comments area of the drawing.

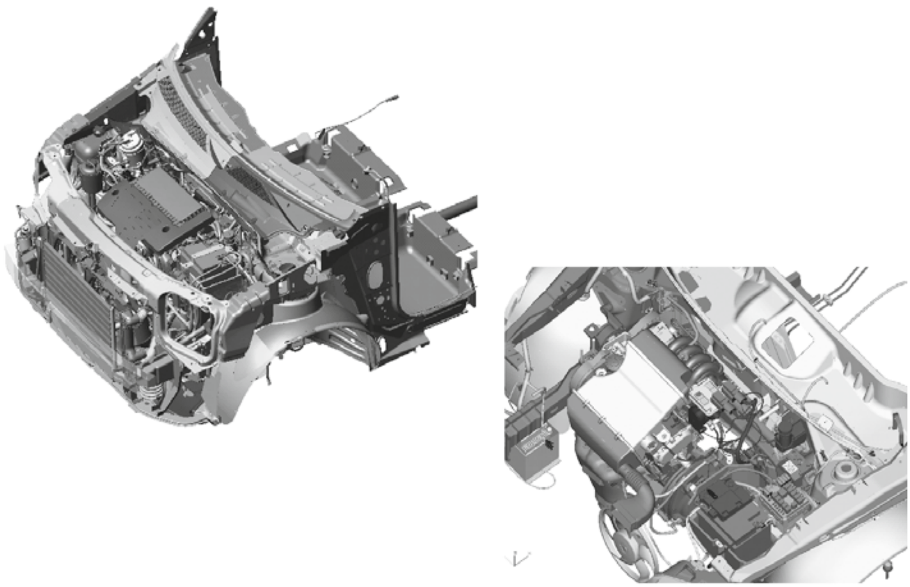


Fig. 3.24. Two examples of a DMU of the complete under-hood environment; the high graphical complexity makes this representation not viable with a traditional CAD system.

A dedicated area of the legend (rotated of 90°) at the top right reports the modifications implemented on this part during its production life (after design release).

A table recalls all numbered complementary reference points with their applicable coordinates. Also in this case tolerances refer to company standards.

3.4 DMU, Digital Mock-Up

A major proportion of the development costs of a new car corresponds to prototype building and testing; newest development projects take advantage of DMU to lighten part of this burden with the so-called virtual prototypes and virtual tests, providing an enormous advantage through the increasingly detailed graphical representation of real parts.

Fig. 3.24 shows an example of two complete under-hood environments. The high graphical complexity makes this kind of representation not viable using a traditional CAD system.

A DMU system enables the assembly, in a suitable application environment, of all parts that should be examined; these parts must be available as independent CAD mathematical models.

A DMU system permits the study of the interaction between each component with the assembly, in order to search for potential interference in their final position or during assembly, disassembly or motion according to their function. It is therefore a virtual representation of objects supporting the development process of both product and production tools.

Virtual reality, although a different informatics technology, can be considered to be an implementation of DMU featuring a higher representation realism.

DMU takes advantage of visualization systems that are able to manage very large assemblies, such as an entire car body, with interior trimming, an engine compartment or a platform, complete with all mechanical components.

These systems approximate the boundary surface of each component with simpler elements, e.g. triangles, obtaining a notable simplification in terms of the information describing the objects to be represented.

This technique is called tessellation or tiling.

To provide a general picture, the file representing the assembly can be reduced by ten times in size in such a way that a complete car body, which usually occupies more than 1 G Byte of memory, can take less than 1 M Byte in the visualization environment.

This reduction is usually performed off-line with suitable translators, interfacing original CAD models with the visualization system; the representation error introduced by this operation can be controlled by the user.

An important further advantage provided by the DMU system is the possibility to manage, in the same representation environment, mathematical models from different CAD systems; their diversity, justified by previous choices or by particular design aspects, is overridden when the models are to be translated in any case to a different common format.

In addition, the reduction in mathematical complexity of these models makes them usable on personal computers; therefore these models are available also to people not directly involved in the design process, providing benefits also as regards wider sharing of information.

The virtual prototype (the entire vehicle or a major part of it) represented by a DMU system can offer each working group a sole and reliable reference, offering the advantage to manage each component in its real environment. Finally DMU systems are capable of storing the product break-down structure, identifying each part included in a given assembly.

A last important implication of DMU is that working in different locations or different companies is facilitated by the existence of a common assembly model of reasonable size than can also be shared through the internet.

Fig. 3.25 shows an example of a complete body shell DMU. This figure illustrates what is displayed by the computer monitor; on the left the work breakdown structure shows part number and name of each component in the assembly.

The product breakdown structure is usually imported from the company information system before initiating DMU implementation, helping to build up a complete assembly from its parts without omitting any.

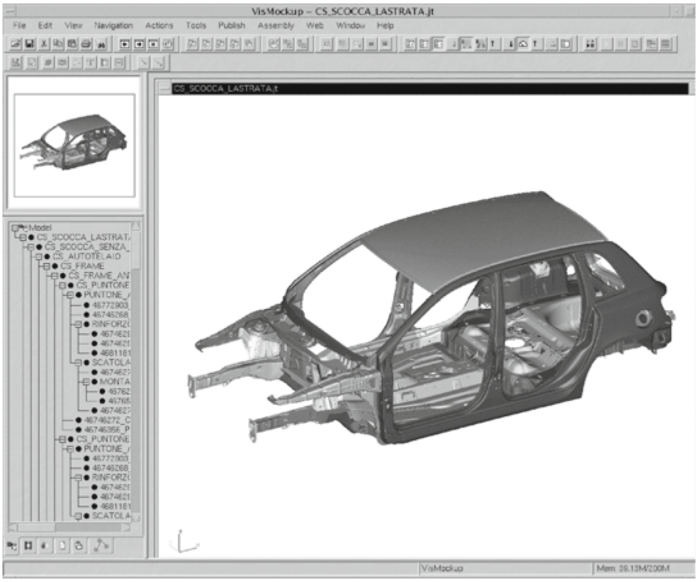


Fig. 3.25. DMU of acomplete body shell. This figure reproduces what displayed by a computer monitor, showing the product breakdown structure on the left, with the names and part numbers of each component or subassembly included in the model.

The same structure is used as a navigation tool to reach easily each of the parts in the assembly or to build and check partial subassemblies, available along the production line, before completion.

DMU not only simulates the final shapes of the body but stores its parts in hierarchical systems capable of simulating the body assembly process, in the same sequence as developed along the production line.

The first application of DMU is composing assemblies, in order to look for errors in their components. In fact, the high complexity of components geometry makes shape errors quite likely.

Assemblies visualizations are usually made by assigning to each component a different color; color is altered when this part is selected (although the grey tones prints of this book are unable to illustrate this).

By examining Fig. 3.26 it is not difficult to realize how flanges or spot welds disappear when assembling a large number of components in a single assembly or discover an evident interpenetration between different elements. This occurrence is more likely during the initial phase of the mathematical model development of body panels or when assembling a trimming element on the body for the first time.

To correct these errors, the following checks can be performed directly within the DMU environment:

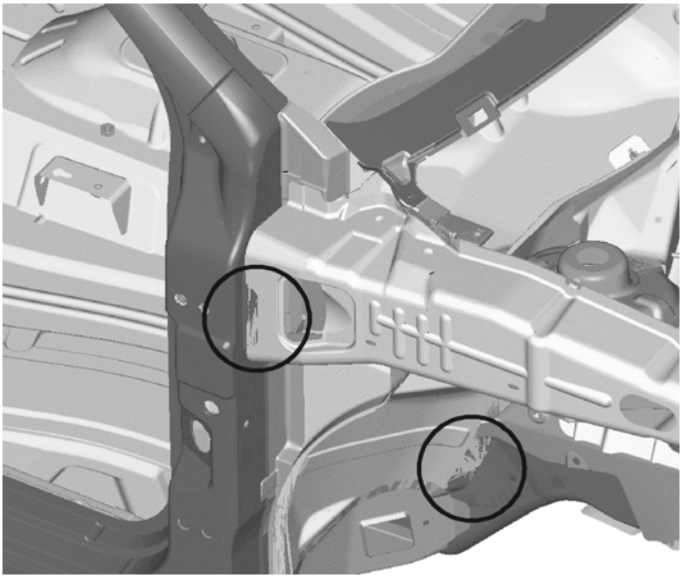


Fig. 3.26. The circled areas in this picture show color changes that indicate interpenetrations of contacting parts due to modeling errors.

- Geometry compatibility between visible elements of different parts.
- Building local cross sections and measurements of distance between parts not immediately visible; this operation can be made in quickly, even on two remote PCs connected on line, during a teleconference for example.
- Potential interference during assembly.
- Geometry compatibility in dynamic conditions, when some element is deformed by external forces.
- Feasibility of kinematic displacements.

Fig. 3.27 illustrates how it is possible to represent the complete body shell with a multi color shadowed model in the DMU environment and to open, in the meantime, a window where a cross section along an assigned plane is quickly made. This plane can be translated in any direction to investigate the entire interface between two parts.

This procedure allows the investigation of a new assembly very easily, how it can occur when an assembly is developed by a supplier or is carried-over from an existing model.

Apart from instantaneous sectioning, the temporary elimination of some part is also possible, in order to enable attention to be concentrated on one element of the assembly.

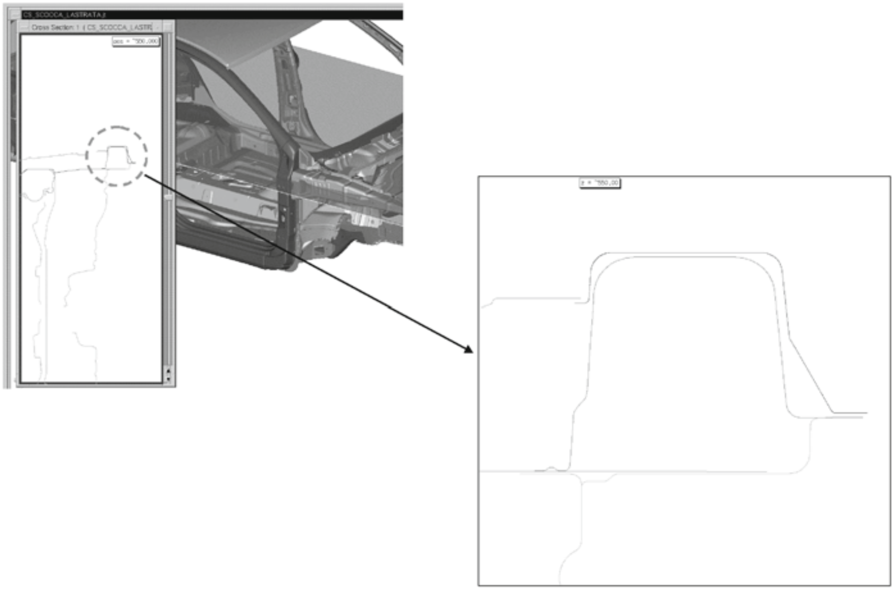


Fig. 3.27. Automatic creation of a cross section to check for body interpenetration.

By looking at the enlargement at the bottom right in Fig. 3.27, the lines that are represented correspond to the style surface of different parts. When actual parts are in contact, section lines of the style surface are separated by the sheet thickness.

This feature must be kept in mind in order to avoid misinterpretations while checking models for gaps and interpenetrations.

Measurements can be taken also on cross sections (see Fig. 3.28): This function enables a quick check of part dimensions or gaps in the welding flanges areas. As mentioned previously, these operations can be performed by people not totally familiar with CAD modeling.

The only virtual tests not performed with DMU systems are those related to dynamic and structural performance, that are investigated by different simulation models.

3.4.1 Examples of DMU Applications

Main examples of DMU applications are:

- Drawings check.
- Cinematic analyses.
- Assembling and disassembling feasibility evaluation.

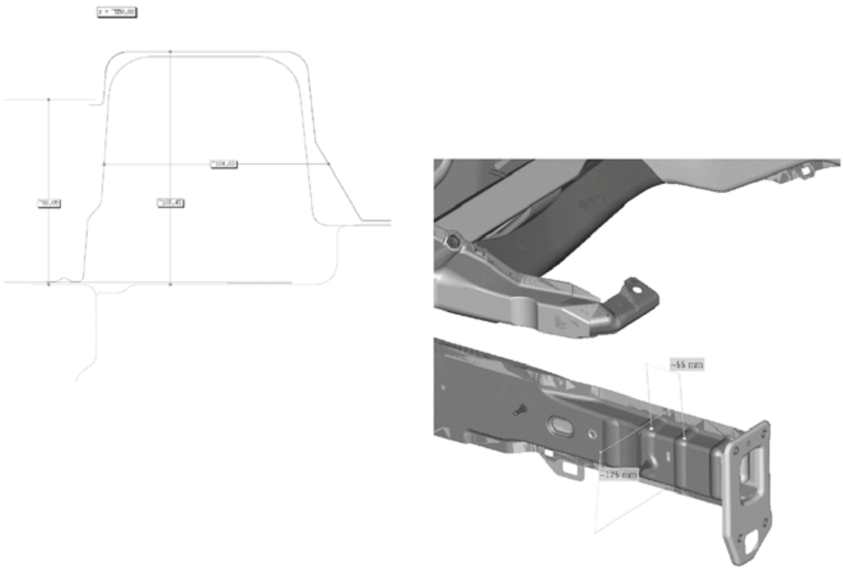


Fig. 3.28. In the DMU environment, dimension measurement is easily made, to check for part geometry or gaps.

Drawings check

Drawings are checked to verify their accuracy and compliance with company's design rules.

DMU assemblies are examined according to dedicated check-lists that enumerate rules to be observed and certify the compliance of related drawings respectively.

The person in charge of this check is not always the person in charge of the drawing and its related modification, and could also be an internal customer of this drawing.

Therefore these check-lists become a tool to enhance a structured discussion between members of the different working groups.

Check-lists of an assigned assembly could consist in, for example, a table reporting, in the rows, the functions to be performed and, in the columns, the components of the assembly involved in these functions. Each of the verifications to be made should refer to a written rule documenting this function objectively.

Table cases, at each intersection between rows and columns should report 'yes', 'no' or 'not applicable' with respect to the question of compliance with relevant design rules.

If during prototype testing a malfunction is detected in an area covered by an item in a check-list, some decision must be taken by all those involved in the design process of the related component or subassembly. It is very important not only to correct this error, but also modify rules that have allowed this error to occur. Thus company rules are modified to avoid this error occurring again in the future or new control items are added to the check list.

A typical list of functions to be verified in a part or subassembly of the body should include the following categories of checks:

- Drawing completeness (dimensions, tolerances, surface finishing, etc.).
- Visibility of stamp split lines (which should never be visible from viewpoints corresponding to the normal positions of driver or passengers or should be concealed by dedicated trimming).
- Assembling and disassembling (these conditions are not equivalent, because assembly shop cycles cannot be reproduced in service shops; for obvious reasons, in principle, each part should be replaced without requiring disassembly of other parts).
- Interference between parts or contacts (if not correctly treated, contact points are a potential source of squeaks and rattles).
- Utilization of parts with dimensions at the limits of the allowed tolerance field.
- Powder and water tightness of passenger compartment and trunk (treatment of junctions between parts separating trunk and passenger compartment from the outside).
- Separation between electric harness and flammable materials (prevention of fires after vehicle crash).
- Separation between hot parts and flammable materials (prevention of fires after vehicle crash).
- Separation between power and signal electric harness (prevention of malfunctions due to electromagnetic interference).

As we have seen, DMU eases the measurement of distances between parts; this can be done by drawing cross sections in the critical areas of the assembly. This procedure looks to be insufficiently productive when verifying large body assemblies, such as the engine compartment, the underbody or the very congested space between dashboard an firewall. Fig. 3.24, illustrating two assemblies of engine compartments, highlights the difficulty with identifying all potential interferences or dangerous proximity points between parts to be checked. In addition, such verifications should be performed not only in static conditions, but also at any position a component can assume during vehicle operation, considering for instance the powertrain motion on its suspension due to road bumps and torque variation.

All DMU systems offer the possibility of automatically looking for points of neighboring parts closer than an assigned set point and sorting out components in the assembly according to their function in the product breakdown structure.

Fig. 3.29. DMU of an extendable hinge of a sliding door.

Movable parts (for instance wheels, during their steering motion) can be introduced in the assembly as an envelope body encompassing all potential positions during vehicle operation.

Kinematic analyses

Kinematic analysis finds important applications in body engineering while designing mechanisms of moving parts, such as doors, hood, trunk lid and other accessory mechanisms as wipers, sliding glasses, locks, outside mirrors, etc.

The objectives of this analysis are:

- Validation of the functioning of the mechanism.
- Interference of moving parts that become closer during their motion.
- Positions of stops limiting the mechanism motion.
- Evaluation of speeds, accelerations and forces during mechanism operation.

Consider, for example, Fig. 3.29 showing the extendable hinge of a lateral sliding rear door of a minivan: the DMU of this subassembly includes the mechanism itself (the extendable hinge), the fixed related components, such as the body side, the sliding rail, the front door and the movable part, such as the sliding door and its interior covering panel.

One highly useful feature of DMU is that each part in the assembly is loaded into the model from the company data base at its present status of development;

once the model is set up, it is possible to repeat any verification as soon as a new element in any of its parts is added or a modification introduced. If new modifications are necessary to allow the operation of mechanisms, they can be introduced in the same working section and checked consequently.

The mechanism is represented by defining the following elements:

- Kinematic couples between mechanism parts, such as cylindrical, spherical or sliding bearings.
- External shape of moving and fixed parts.
- Extension of the rotary or sliding stroke of the elements of the mechanism.

DMU allows only kinematic motion without friction and can only verify geometric compliance; nevertheless DMU can be used to calculate the input functions for a multibody model of system dynamics, suitable for providing a full evaluation of system performance, including dynamic forces.

Assembling and disassembling evaluations

A further design requirement of complex systems (such as the car body) is the compliance of shapes and dimensions of each component with an existing assembling shop and cycle; this compliance is not only related to parts dimensions, but also to the compatibility of these parts with the welding, assembling and transportation fixtures of the production lines.

This problem has already been mentioned when referring to check-lists; in this section the DMU functions involved in this verification are explained.

Considering, for example, the front part or the engine compartment lower rail, in the left part of Fig. 3.30 the complete assembly can be seen that should be obtained as a result of a series of operations defined by the assembling cycle.

In Fig. 3.30 an exploded view of parts involved in the assembling is represented: Without entering into the details involved in this set of operations, it is possible to imagine identifying, through a series of trials, possible operations sequences which achieve the required result. If different sequences obtain the same result, the most convenient should be selected by taking in account:

- The number of loading and unloading operations of parts on the welding and assembling fixture.
- The final dimensions tolerance that can be obtained.
- Possible deformations on the assembly due to thermal expansion caused by the spot welding sequence.

DMU proves to be a very useful tool to initiate working team discussions or topical verifications. Many significant mistakes can be avoided during a free preliminary multidisciplinary discussion. The examples introduced should enable the usefulness of DMU in its main applications to be appreciated.

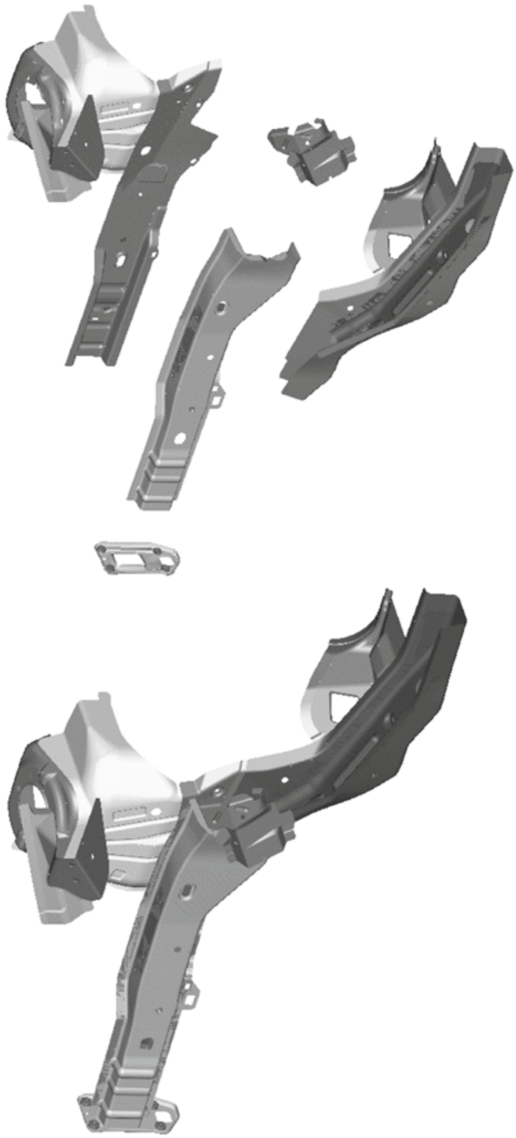


Fig. 3.30. Automatic design of a subassembly made by a DMU system, starting from the CAD mathematical model of each part.

These virtual analyses become increasingly accurate as the informatics tools continuously progress; nevertheless real tests on physical prototypes must be performed, at least for final product validation, that will be achieved with lower expenditure due to the increasing number of errors eliminated at the virtual stage.

3.4.2 Virtual Reality and Body Engineering

This final section is included to highlight the role of virtual reality (VR) in enhancing engineering design, describing this tool in conjunction with DMU since, in fact, VR could be thought as being the most sophisticated tool to represent and navigate a large detailed assembly.

This technique allows one or more user to interact simultaneously in a simulation environment controlled by computers; this simulation can achieve greater realism than that available while interacting with a model by using a conventional monitor and a mouse, making operations more intuitive, effective and rapid.

Due to the fact that these systems are still under evolution, some information regarding hardware is also included, while realizing that new developments will make VR simpler, less expensive and, therefore, more widely applied.

Many interface devices exist that provide the illusion of seeing, touching and manipulating virtual objects; their common characteristic is the property of granting people, working with this simulation, the possibility to view from any direction, providing high levels of visual perception and sense of involvement; visual feeling can be enhanced by hearing and touch.

Virtual reality is a technology that can be used to enhance natural human capabilities or exploit those usual capabilities that appear only in front of a physical prototype of the object under examination. The ultimate target is, again, to reduce development time and costs, bearing in mind that traditional interfaces such as keyboard, mouse and monitor effectively force engineers to work within a limited and unnatural bi-dimensional space, requiring a high capacity for abstraction and imagination which not everyone has.

An ideal virtual reality system should possess at least the following features:

- High resolution stereoscopic visualization; human eyes distinguish punctiform objects seen under an angle of 1’ (i.e. two dots with mutual distance of 0.58 m, at 2 m from the eyes), and full representation of any object in the semi-space containing the optical axis.
- Update of objects in motion with respect to the point of sight, in a time lower than 10 ms and a time lag less than 20 ms; when images are obtained by using multiple projectors, outputs synchronization must be perfect.

In addition, systems possessing also non-optical outputs should provide:

- Full stereo sound output of both environment and object noise, with a frequency response in the field 16÷25,000 Hz, dynamic range of at least 90 dB and background noise lower than 30 dB.
- Tactile and force feed-back, as a function of object displacement suitable for human motion capacity.

The first virtual reality experiments were performed in flight simulators developed by the Massachusetts Institute of Technology in the 1960's; a crucial contribution to this technology came in the 1980's from Silicon Graphics, a company leading the production of powerful and relatively inexpensive computers.

The first applications mostly addressed flight training for pilots.

Virtual reality that was born to better visualize objects simulated by computers received further development.

Thanks to them, the physical properties of a vehicle can be simulated in order to verify different functions, such as internal and external visibility, access to the passenger compartment, space availability while interacting with the vehicle, etc.

In the case of style development, a more complete representation of the object can be obtained, that can be in motion or seen by a moving observer.

Fig. 3.31 can offer an idea of the performance currently available with regard to representing the outside of a car, starting from a CAD surface mathematical model, (despite the relatively poor quality of the black and white picture).

Not only a high resolution representation, but also the interaction with the model are necessary, allowing the operator to manipulate the objects in the virtual environment.

The interaction of the user with the model is possible with a full-immersive environment or by improvement of the current practice.

A simulation environment is considered to be full-immersive if the operator is completely insulated by the real world, independently of the technology applied to the simulation.

An immersive simulation can be, on the other hand, more or less intrusive depending on to what extent the simulation tools available to the user feel natural.

For example a 3 D visualization helmet could be immersive and intrusive at the same time.

Another issue relating to virtual reality simulations is the so-called presence level of the user in the virtual environment. The presence level is high if the user can also see his body during his experience in the virtual environment; on the contrary it is low if his and the body of other operators can only be shown by virtual representation.

The features of an immersive simulation include the following:

- The virtual environment can be observed in a natural way, offering realistic views when the head is rotated.

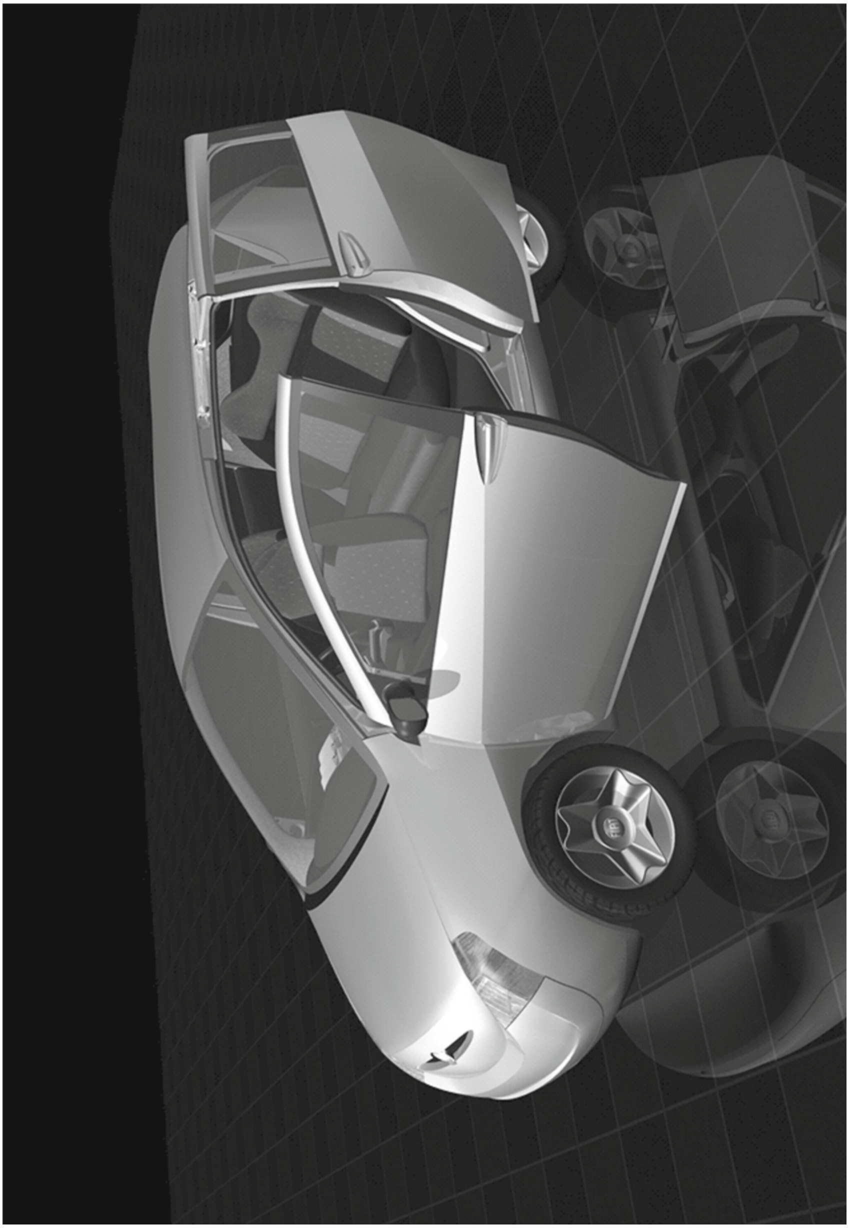


Fig. 3.31. Virtual reality model of the exterior shape of a car obtained by CAD surface mathematical models.

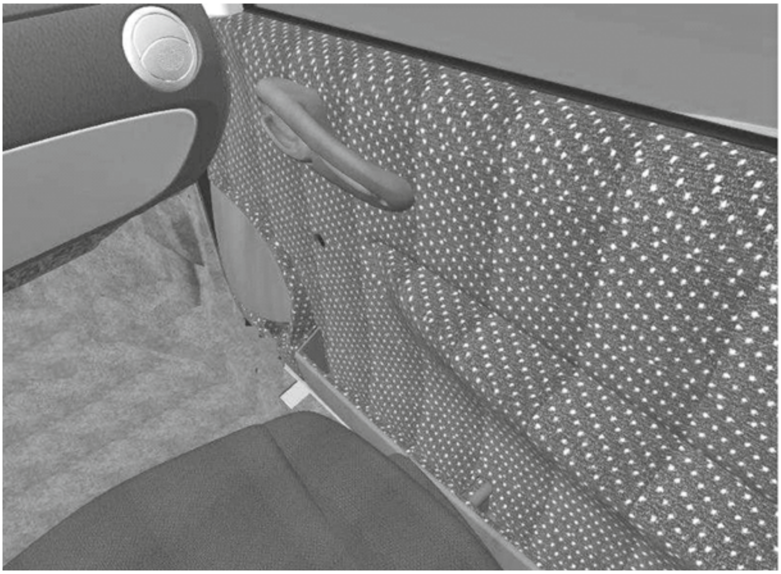


Fig. 3.32. Visualization software multiplies indefinitely an elementary ornamental drawing, taking into account real deformation consequent to the adaptation of cloth on stuffing.

- The view is stereoscopic and allows perception of distances between virtual objects.
- Virtual objects are perceived in their natural size.
- There are devices addressed to the manipulation and control of virtual objects.

The illusion of living in the virtual environment may be enhanced by sound.

Virtual environment

The virtual environment usually consists of a realistic representation of virtual objects (a vehicle and its components) in a related outside scenario (i.e. show room, production shop, repair shop, etc.).

Geometrical accuracy is very important, as is the accurate definition of colors, textures, light spots and their correct reflection on surfaces, according to their gloss.

Texture is, in this case, the repetition of an ornamental drawing on a surface, that can be deformed, e.g. representing a decorated fabric upholstery covering seat stuffing or the grain of a dashboard surface, simulating leather.

Fig. 3.32 can better explain what we have said; the simulation system is supplied with an elementary drawing composing cloth decoration. The simulation software repeats this drawing indefinitely, covering an assigned surface (in this case, the interior side panel of the door), taking into account the deformation of the cloth on stuffing, that is simulated by a full deformable, non-extendable surface.

Virtual objects can be created by a dedicated 3 D modeling tool or can be imported from an existing CAS or CAD model. In any case, the description of these models not only includes the mathematical equations describing their surface, but also information about the aesthetic nature of their visible surface (influencing how investing light is reflected or diffused) and, sometimes, about forces (mass forces, resistance, elasticity) connected to their displacement.

The virtual environment controls object motion with procedures considering dynamic rendering and dynamic simulation; while parts are displaced, potential collisions are controlled by dedicated software.

The environment status is influenced by inputs that are usually the positions of head and hands of operators, while outputs are video, audio and feed-back force.

Some dynamic objects can be defined without any space constriction, while others are physically constrained to move within a set of boundary surfaces. For instance an observer's head evaluating external visibility of car, from the driver's seat, is constrained to stay within the passenger compartments.

When the head is moving outside the allowed space, at least an error signal should be sent to the operator or, for a perfect simulation, a reaction force applied to its head.

Generally speaking, any object is constrained for displacements and rotations with reference to a local reference system. This constrains are chosen as process parameters and they should be controlled to stay within allowable limits.

3 D graphics requires an intensive usage of computer memory storage, considering object size, number and real-time refresh.

Model numerical complexity plays a primary role in determining refresh speed. To keep this speed at high values, different models of the same part, with different number of details, are contemporarily stored in the computer memory.

The operating system selects the most suitable model for the current simulation: detailed models are suitable for close-ups, when few parts are contemporarily present in the visible environment, while coarse details are sufficient for viewing from a larger distance, when many parts are to be described. Models change, therefore, with operators motion.

In addition, for each exterior surface the quantity of reflected and diffused light must be calculated, as function of the surface gloss.

Input signals

Input signals regard position and orientation of head and hands of users inside the virtual environment.

The user's head position determines the point of view with reference to whom the virtual environment must be represented. This input must be detected at a frequency of 100 Hz at least.

There are four kinds of sensors in use to detect position and orientation of an object in a 3 D space.

They are based upon electromechanical, electromagnetic, acoustic and optic techniques respectively.

Electromechanical sensors were the first to be considered; they consist of an articulated arm connected to a helmet worn by the user, leaving adequate freedom to him: The angular displacements of the articulated arm joints allow to calculate head position and orientation.

Electromagnetic monitoring systems are now more frequently applied. A fixed device generates electromagnetic signals that are measured by a set of receivers on the user's head (helmet or stereoscopic glasses). Time delay in receiving signals is used to calculate head position and orientation.

Acoustic sensors determine distances in a similar manner.

Optical systems are under consideration because thanks to the performance improvement of processors. Many kind of sensors are available from video cameras to optical diodes. Infrared light is particularly suitable because it does not interfere with users eyesight.

Position and orientation of user's hand are used in the virtual environment to input commands to the computer in a more efficient way than with a keyboard or mouse; in particular cases (i.e.: assembling and disassembling simulations, ergonomic evaluation of a vehicle control) these signals are used to move parts of the mathematical model.

For these application particular articulated gloves are used to detect fingers motion and to apply the correct force feed-back to them.

Interaction with the virtual environment

The correct feeling, received by touching or moving objects, may be reproduced by suitable devices as joysticks with six degrees of freedom (three displacement and three rotations) or interactive gloves.

This feeling can be enhanced by including user's hands in the representation of the virtual environment.

The system can control if the user's hand can reach and touch any of the virtual objects in the virtual environment.

If there is a contact the system can be programmed to move this part in the coherent direction or to make it integral with the user's hand.

If the glove integrates suitable actuators, it is possible to give the user the tactile feeling by the corresponding forces that this object could apply in the real world.

There is a new science, called haptic technology, referring to what interfaces to the user via the sense of touch, by applying forces, vibrations, and motions to

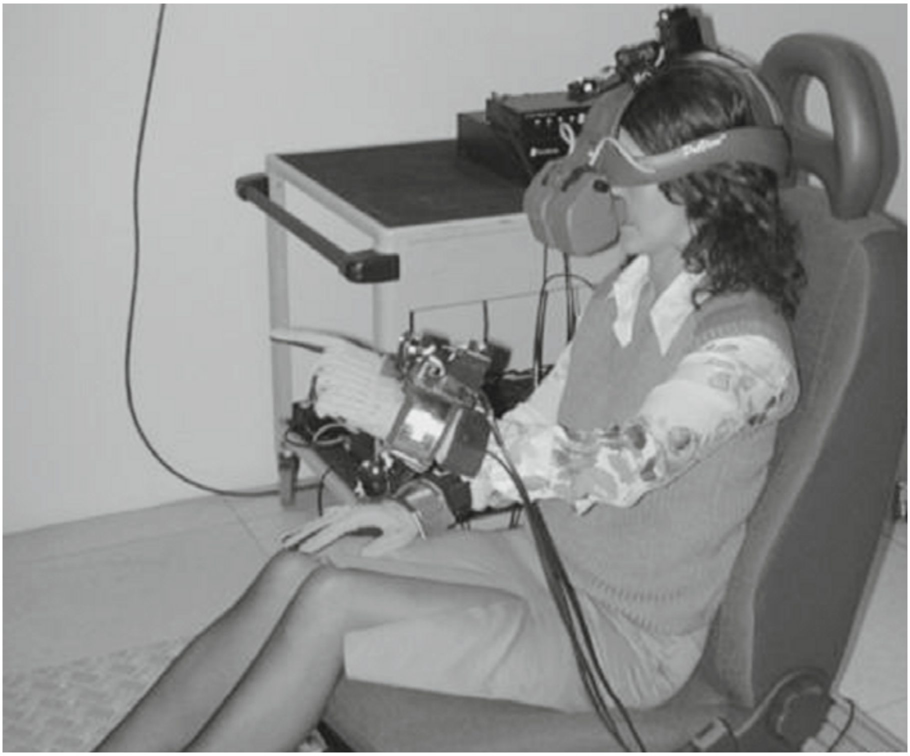


Fig. 3.33. The user observes the virtual world (in this case the interior of a passenger compartment) through a helmet with a binocular display. The seat is a real physical prototype; controls are simulated by means of a haptic glove.

its fingers. The word haptic, from the ancient Greek haptikos, means pertaining to the sense of touch.

This technology contributes to our understanding of how touch and its underlying brain functions work.

An example of what we have said is shown in Fig. 3.33; the user observes the virtual world (in this case the interior of a passenger compartment) through a helmet with a binocular display. The seat is a real physical prototype. Controls are simulated by means of a haptic glove that restores the same feeling the user will have on an actual real control. The scene is showing the user while operating a virtual switch on the dashboard, to evaluate ergonomics of this control.

In the future haptic technologies will study a wider range of touch sensations, including the nature of the surface to be touched (smoothness or roughness, temperature, humidity, viscosity, etc.); for the time being, only reaction and inertia forces can be reasonably considered.

All haptic devices should obviously be connected to a hand tracking system, in order to avoid that hands are penetrating into virtual objects, by increasing contact forces significantly. These devices are particularly suitable to investigate about the characteristics that are expected of an ideal control or are indispensable in drive simulators to restore a realistic feeling on the steering wheel.

Visualization devices

Visualization devices may be divided in two groups in relationship with the technology applied to display the virtual environment: direct vision or projection.

The first group includes:

- Head mounted displays (HMD).
- Binocular omni-orientation monitors (BOOM).

With these two systems, the user observes the virtual scenario directly through the internal monitors of the device. An example of HMD is again reported in Fig. 3.33.

The second group includes the CAVE[3] and the projection backlit walls (Power walls) or tables.

HMD has been the first device able to allow an immersive experience to the user. It includes two miniature displays, like the lenses of a pair of glasses, that simulate the stereoscopic view.

A moving tracer on the HMD measures head position and orientation continuously allowing the computer to calculate coherent views. This device allows more than one user to walk and look around in the virtual environment.

The computer processing speed must be as high as to not produce image slow down or jumps; even if processing speeds have dramatically increased virtual scenes must be simplified to allow the computer to update images in a realistic way (at least ten times in a second).

HMD devices carry on also earpieces for environment sound simulation; also audio signal might be function of head and hand positions.

BOOM devices contain an optical and display system similar to HMD, but this is contained in a box suspended to an articulated arm, equilibrating its weight. The user looks at the virtual environment through two holes and can explore the space by moving or orienting the device. Suitable sensors control any motion.

BOOM and HMD devices may be integrated in test rigs, containing also physical parts, as seats, steering wheel, pedals and shift stick, to study posture comfort, reach of controls, realistic visibility of a car.

Projection based devices apply special stereoscopic glasses used to observe a semi-transparent screen.

The 3 D effect is based upon the fact that each eye see slightly different images under the perspective they should have in the real world. The human

[3] Power Wall is a registered trade mark of BARCO; CAVE is a registered trade mark of Fakespace.

Fig. 3.34. Two pictures of a CAVE including also real elements interfacing the user in a driving simulator.

brain interprets this different coherent views to recognize distances and volumes of objects in the environment (stereoscopic view).

Stereoscopic glasses separate images perceived by the right and left eye using liquid crystals shutters, synchronized with the actual projection. With suitable infrared pulses sent to the glasses, different projections can be triggered to different eyes.

A typical immersive, non-intrusive projector for virtual reality is the CAVE (cave automatic virtual environment), a cubic room build up with backlit projection screens, where users can move and interact with the virtual environment.

Inside this room, many other devices can be used, as haptic gloves or joystick, enhancing user's interaction.

Images are projected on the walls, on the ceiling and sometimes also on the floor.

Fig. 3.34 shows two pictures of a CAVE including also real elements (haptic pedals and steering wheel) interfacing the user in a drive simulator.

If several people are present in a CAVE, or other immersive projection systems, part of them will see the virtual environment from the same point of view as a reference user, irrespective of their actual position. The other problem is that they can cast their shadow on the screen obstructing the view of other users.

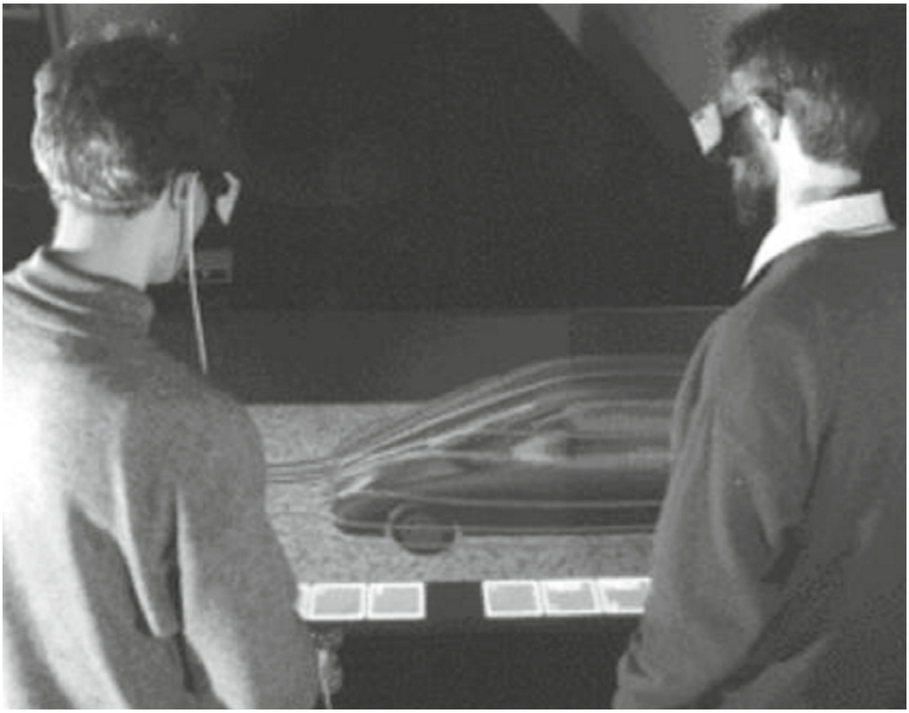


Fig. 3.35. Virtual wind tunnel for scale model of a vehicle.

Also in this case haptic gloves or joysticks can be used.
The main advantages of this device are:

- Ample field of view and high resolution.
- Work environment accessible to more than one user, with some limitation.

Obvious disadvantages are the space and cost investment required. Power walls offer a cheaper compromise by limiting the projection to a single wall of large dimensions with multiple projectors.

Backlit projection tables are suitable to observe spatial phenomena on an object of limited dimensions as a component or a scale model of a vehicle.

Fig. 3.35 shows an example of this device for a virtual wind tunnel, where a computer, solving a mathematical model of the air flow around a vehicle model, can display the shape of the aerodynamic wake. The projection table can be rotated to simulate yaw or pitch in order to observe their effect on the wake.

Applications to product development

The diffusion of virtual reality has launched a process where many engineering applications of mathematical models convert their outputs, from graphs or printouts, to 3 D models that can be explored and discovered by interacting with them more directly.

The success of this approach is in the higher reproduction fidelity of 3 D outputs that can be observed from any point of view, discovering critical issues that sometimes may be hidden in a conventional printout, representing a plane section made in the wrong place.

For the time being and in the short term, it is necessary to adapt existing mathematical models to virtual reality, by developing suitable hardware architectures and visualization software, to enable the simulation and visualization environments to interact correctly at the appropriate synchronization speed.

For this reason the applications more often considered in product development regard the interactive visualization of the car exterior and interior for style evaluation, and the DMU exploration for the purposes described previously.

Successful applications can be also cited regarding exploring DMU of virtually crashed or virtually stressed cars; the virtues of virtual reality enable all critical local issues to be grasped quickly.

The advantages are demonstrated in practice; for example, in style development, virtual reality applications have enable the number of physical models required to be cut dramatically: On occasions they have been reduced from 10 to 2, needed for the final evaluation of two alternatives.

The recent diffusion of virtual reality in product development and research is due to the fact that the best way to evaluate and improve an industrial product is to visualize and use it. This principle also applies to the analysis of performance made by engineers and to perception, acceptance and usability evaluations made by the potential customer.

Virtual reality applications are also starting to diffuse in multi-sensorial analyses, such as acoustic comfort and human reaction to vehicle controls and displays.

4
Body Work

4.1 Body in White

In the usual configuration, a *body in white* is an assembly of a frame and panels, made up of homogeneous materials (for instance, steel or aluminum sheets or composites). As an example, in Fig. 4.1 a 3-door steel body and the frame of a 5-door aluminum body are shown.

Many detachable components are fitted to the body, such as the so-called *movable parts* (eg. doors, decklid, liftgate, hood, fuel filler flap and related locks and hinges), external components (bumpers, windshield, windows, weather strips, grilles, spoilers, moldings, mirrors, lamps, windshield wipers, lamp wipers) and interior trim (instrument panel, seats, carpets, trim panels, safety belts, air bags), together constituting the vehicle body.

The purpose of body design is to achieve the following:

- Aesthetics: to provide a pleasing overall appearance, surface quality and consistent details.
- Structural function: to support the weight of the transported passengers and load as well as the mechanical parts required for vehicle propulsion, control and other system functions, so withstanding mechanical stresses from multiple sources.
- Ergonomy and roominess: to supply easy access and adequate room for the driver, passengers and transported goods.

L. Morello et al.: The Automotive Body, Vol. 1: Components Design, MES, pp. 91–205.
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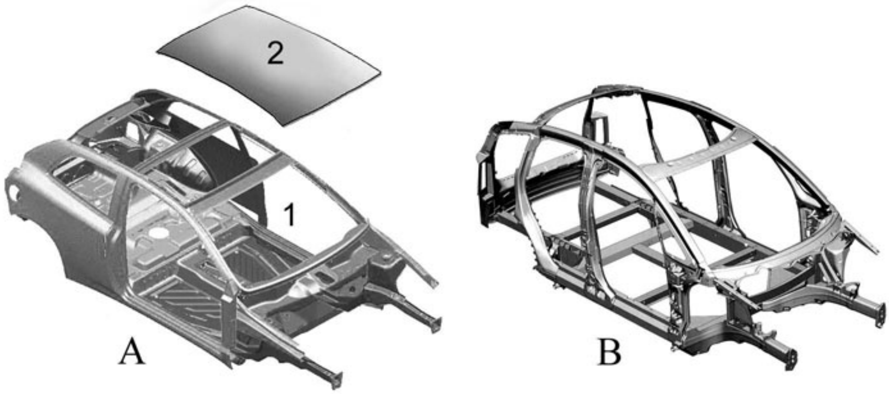


Fig. 4.1. A) Body in white steel sheets (1) and roof panel (2) of Fiat Stilo 3-doors, before their assembly. B) Audi A2 aluminum body frame.

- Safety: to ensure integrity of passenger compartment in the event of a crash, while absorbing the impact energy as well as to reduce injuries to vulnerable road users (pedestrians, wheelers), in case of collision.
- Aerodynamics: to minimize drag due to air impact; to control air flow effects on tyre-road contact and vehicle stability.
- Insulation: to minimize noise, vibration and thermal transmission, generated by body walls, by lack of sealing between compartment and movable parts and by thermal radiation from the surfaces of passengers compartment.
- Visibility: to provide the highest possible day and night visibility on the environment and to host the lighting devices in the most effective way.

Moreover, the body must satisfy a series of prerequisites: high reliability (to maintain design functions vehicle life along), low cost (to minimize production investment, process and material cost), high material recyclability (by rapid disassembling and straightforward division of heterogeneous materials).

These functions ere required by the completely assembled body and are achieved through the individual contribution of body components and several body systems. Correspondingly, a more detailed description is provided in the respective chapter. For some of the functions listed above, a number of different configurations of the underbody can be identified (see Fig. 4.2):

A) *Unitized body* or *unibody*, in which the chassis parts cannot be physically removed from the upper body parts. In this case, suspensions and other mechanical parts are directly fitted (using brackets) to body frame. The main advantage of such solution is relatively low weight, while the main

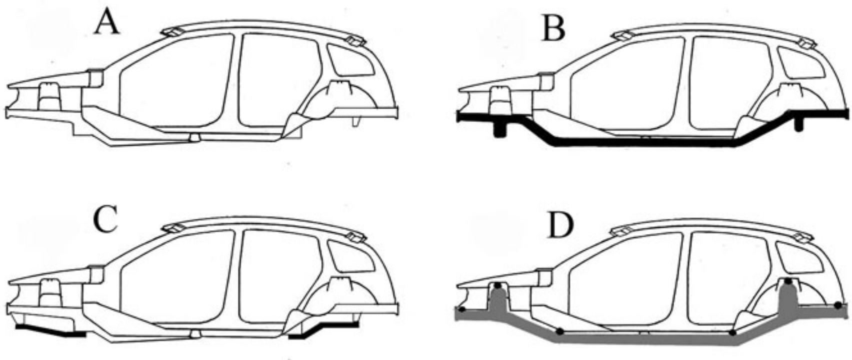


Fig. 4.2. Common body and chassis configurations.

disadvantage is a lower dimensional precision of suspension attachment, due to body tolerance and the lower filtering performance of suspension fittings, reducing the insulation of vibrations due to road-wheel excitation.

B) *Body on frame*, where the chassis frame is connected to upper body frame by bolts with or without the inter-position of rubber bushes. Such a solution offers the main advantage of allowing the adoption of one chassis for different body shapes, providing benefits in terms of mechanical parts standardization and simplification of the assembly process of a mechanical chassis, before being matched to the upper body. This kind of solution is commonly used for cargo vehicles, off-road and SUV. The main disadvantage is the increased weight with respect to configuration A).

C) *Body with ancillary subframes*, for powertrain and suspension systems; connections between the subframe and the body can be either rigid or through elastic bushes. The main advantages are modularity and the division of the assembly process between parallel lines, enabling components to be mounted on the sub-frames. The resulting sub-assemblies can be tested before integration with main body. Moreover, the relative ease in which elastic and damping devices between subframe and body can be inserted, provide an improved insulation from noise and vibration. Again, the main disadvantage is increased weight, but to a lower extent than configuration B).

D) *Dual frame body*, in which body and chassis are separate and connected through elastic and damping bushes. In this configuration, the structural, safety, propulsion and driving functions are concentrated and optimized in the chassis, with priority to front and rear crash absorption, torsional stiffness and resistance to stress induced through the suspension and powertrain attachments. The suspension articulation can be designed to be extremely stiff and precise, since the filtering of road-surface induced excitation is achieved by incorporating elastic connections between chassis and body. The weight of upper body can be reduced, since the structural task is limited to its own inertial stresses and to those induced by transported components, people and load. The same chassis can also be adopted by different bodies of similar inertia properties. Although the increase of chassis weight remains a disadvantage, it is partially counterbalanced by the reduction in the weight of upper body.

Referring to body missions previously listed, the different configurations result in variations of upper body contribution for just a limited number of functions, in which the characteristics of body connection with the chassis is highly relevant: structural function, insulation and isolation, safety and, partially, aerodynamics (due to floor contribution). The remaining functions are not directly affected .

Focusing on the most common body configuration (C), through the example of a 2 box mass production body in white with spot welded steel stamped sheets, it is appropriate to consider the main stamped parts and follow a typical assembling process step-by-step, to gain a deeper understanding of the process used to manufacture the body, widely applied today.

4.1.1 Body Setting

For a better understanding, it is appropriate to consider the split view of a five door *body in white (B.I.W.)* with movable parts (Fig. 4.3): this definition refers to all parts included in the body, except internal and external trim, usually made of plastics, rubber or glass.

The term *movable parts* is commonly used to define macrocomponents that can usually be operated by the customer: side doors, hood, decklid, liftgate. These components, including their hinges that allow relative motion to body, but without trimming (panels, glass, insulation, weather strips) are actually parts of the body.

The body in white with movable parts includes front fenders, which are typically screwed to the body and are thus detachable. In Fig. 4.4, it can be seen that the roof panel is welded to body at a different stage, with respect to body sides and body cross-members, depending on the adopted production process.

Moreover, in Fig. 4.3, the conventional reference system used in body design is indicated, where the abbreviation *RH* (right hand) corresponds to coordinates $Y>0$, the word *upper* refers to a Z coordinate higher than the reference (the opposites being *LH* (left hand) and *lower* respectively). Usually sections are referred to the right side of car, when there is no indication to the contrary.

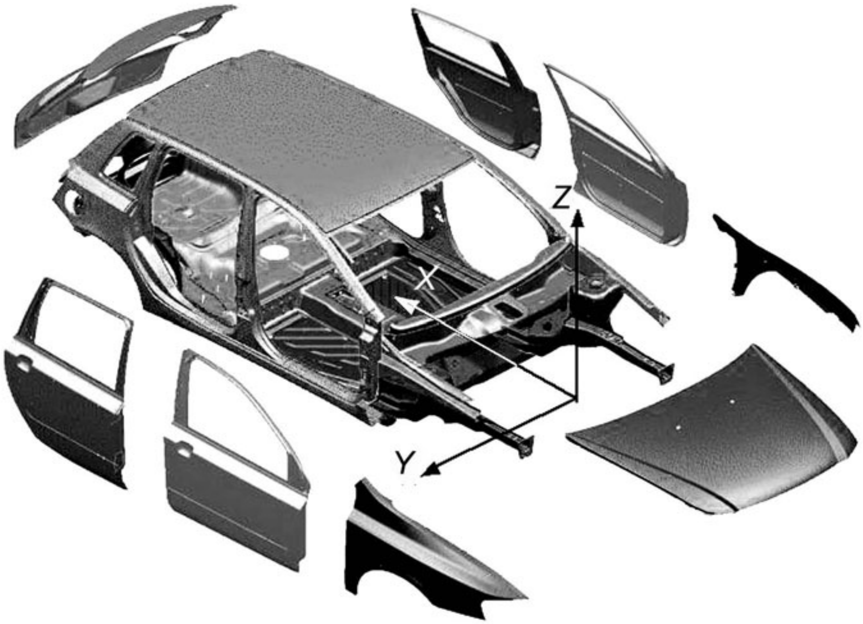


Fig. 4.3. Body in white with movable parts and three dimensional reference system.

Fig. 4.4 shows the simplified set of subassemblies included in the assembly called *body in white with movable parts*, divided to the level of the front rail assy, also called *front strut*.

In each column, sub-assemblies to be joined in the same step are listed: for simplicity, the entire frame has been broken down following only the branch that leads to the front rail. It must be considered that the final assembly is a metal body ready for the paint shop. Therefore, this assembly does not include, for instance, the *front end module*, which is later screwed to body front frame and includes cross-members that connect upper and lower front rails and also headlamps, radiator and hood lock: the front end shall be examined in the chapter related to front body frame.

The lower part of body, usually called *underbody*, is the most important assembly of a unibody, with regard to its structural function and is the part most subject to evolution, over the last decades.

With reference the first column of Fig. 4.4(A) and to Fig. 4.8, it can be noted that underbody comprises a frame (the main structural part), which supports the front and rear floor and some side members connected to the *bodyside* and the upper front rails. It can be observed that preferably the front strut-tower reinforcement, where front shock absorber slot is located, is assembled in this

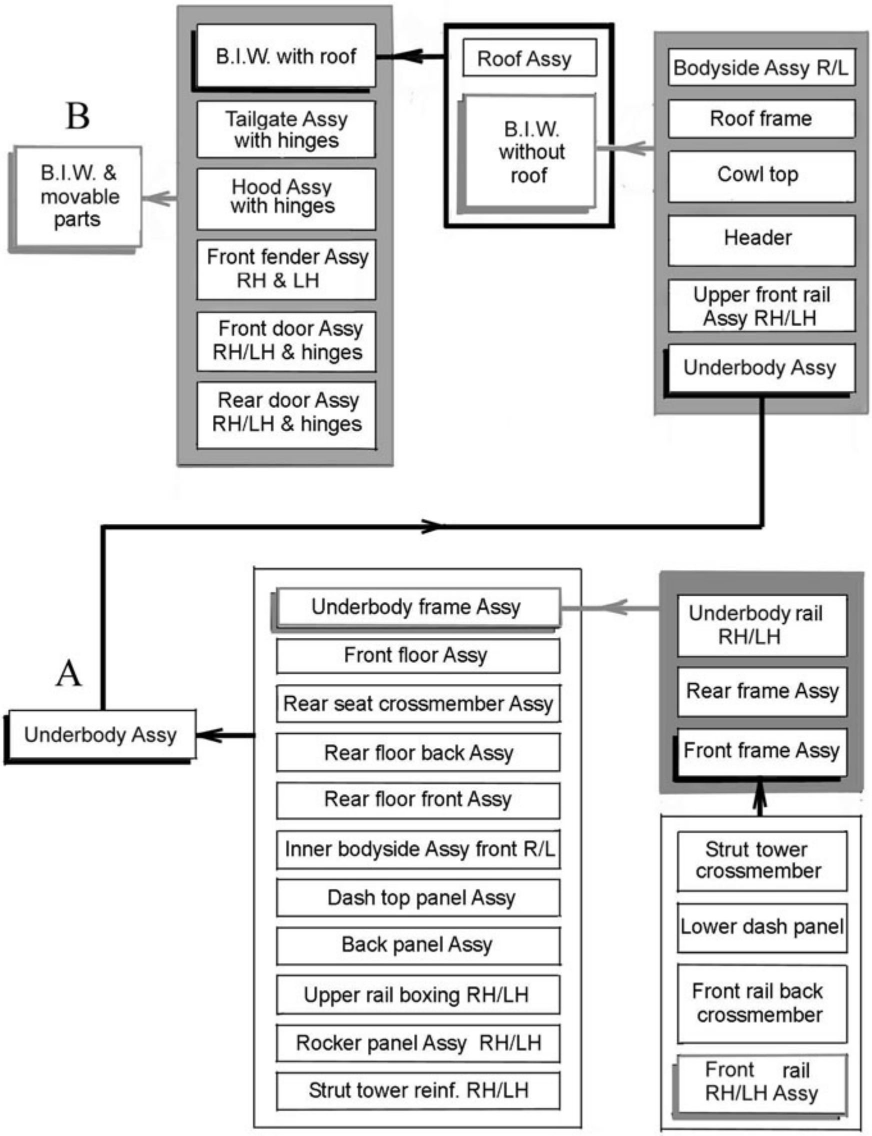


Fig. 4.4. Split set of bodywork sub-assemblies. A: underbody assembly (assy); B: body assy.

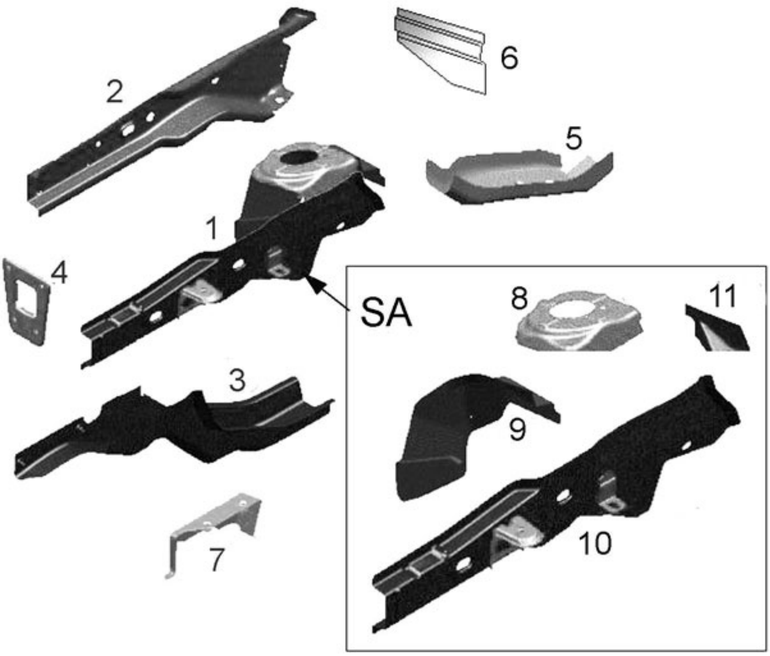


Fig. 4.5. Split scheme of front rail assy; in SA view, the set of rail boxing assy.

step, rather than previously, to the lower frame, because more precise positioning can be guaranteed in this way.

The first step of underbody assembling consists in building the *rail boxing assembly*, starting from the parts shown in Fig. 4.5– SA:

- rail box (10),
- upper front suspension tower (8),
- lower front suspension tower (9),
- tower to cross-member brace (11).

The *front rail assembly* is one of main underbody parts, due to the number of relevant function it performs. In our example, only two steel grades are used: the classification FEP04 refers to a low carbon deep drawing steel, with a low yield strength ($\sigma_y \cong 200$ MPa), the FEE355 is a higher yield strength steel ($\sigma_y > 355$MPa), but with lower formability. Usually, deep drawing steel with higher thickness is used for parts for which high stiffness is the main target or which are subjected to the risk of local buckling (designed in practice for elastic deformation), while high strength steel is used for parts involved in crash resistance and absorption (parts designed for non-elastic deformation).

In the second step of front rail assembly, the following parts, shown in Fig. 4.5, are welded together:

- rail boxing assembly (1),
- front rail (2),
- front-end attachment bracket (4),
- front rail extension (3),
- front rail reinforcement (5),
- cross-member to rail gusset (6),
- powertrain support reinforcement (7).

In front rail assy, the front rail (2) (FEE355, thickness 2.2 mm) and the front rail boxing (1) (FE355, th. 1.8 mm) connected to the front cross-member through two front-end attachment brackets (4) (FEE355,th. 3.0 mm), are designed to enable the section to face a front crash.

Front rail extension (3) (FEE355, th. 2.5) and front rail reinforcement (5) (FEE355, th. 2.5) connect the front longitudinal structure to the floor longitudinal members, the main requirement for this connection being to avoid flexure between the front and floor frames in the event of a crash; also, the front rail extension supports the attachments of front powertrain cross-member.

The lower *front suspension tower* (9) (FEP04, th. 1.8 mm) and upper front suspension tower (8) (FEE355, th. 2.5 mm) provide the attachment to the front shock absorber through the front strut tower reinforcement (see Fig. refesplotel1) and also connect the front rail assy to the upper front rail, exploiting its contribution to energy absorption during a frontal crash.

The tower to cross-member bracket (11) (FEE355, th.2.5) and the cross-member to rail gusset (6) (FEP04, th.1.4) are designed to leave freedom in Y direction, when assembling the RH and LH front rail assy to these cross-members.

Powertrain support reinforcement (7) (FEE355, th. 2.5) is the frame where gear fixing stirrup is fitted; it can be noticed that the vehicle illustrated has a powertrain suspension of the baricentric type and the two upper fitting positions are above the level of the front rail.

The RH front rail assy (1) assembled in this way is then connected (Fig. 4.6) to its twin (2) by: the *front rails back cross-member* (5), the main function of which is to transfer crash loads from the front rails to the floor tunnel; the *strut tower cross-member assembly* (3), providing stiffening to the front shock absorbers attachments in Y direction; the *lower dash panel* or firewall assembly (4). Together, these parts make up the assembly called *front frame assembly*.

Underbody frame comprises the front subframe, the rear subframe and two *underbody rails* (Fig. 4.7). This set is the preferred solution when welded first in the same assembling jig are the front frame subassemblies, related to their reference points (Fig. 4.6) in order to better comply with suspension attachments

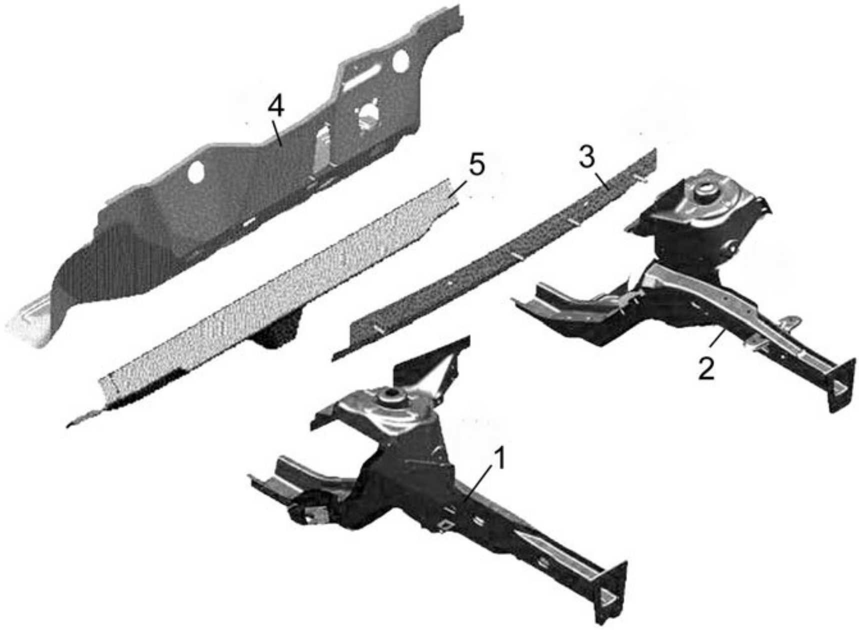


Fig. 4.6. Split view of subassemblies that constitute the *front frame assy.*

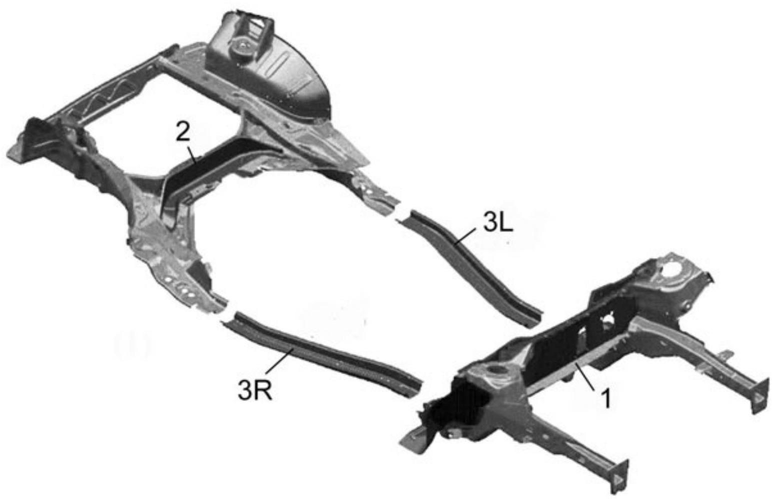


Fig. 4.7. Example of underbody frame and its subframes.

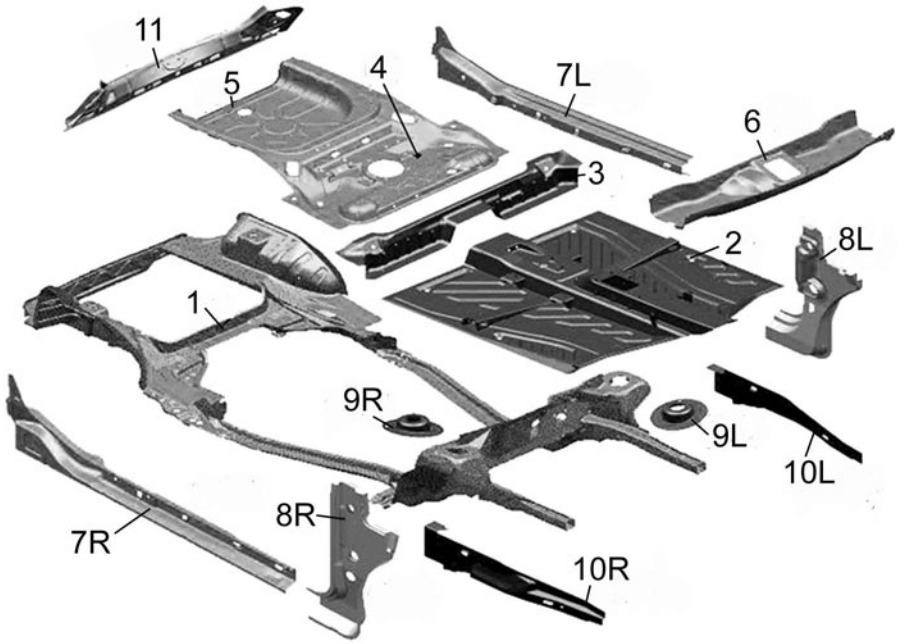


Fig. 4.8. Split set of parts included in the underbody assembly.

tolerances. In the following step (Fig. 4.7), the said assembly (1) is welded to the underbody rails (3R) and (3L) and to rear subframe (2), resulting in the so-called *frame assembly*.

The final step of *underbody assembly* (Fig. 4.8), corresponds to the stage at which the lower frame, completed with floors and boxing elements, is ready to receive the upper body parts.

With reference to Fig. 4.8, parts assembled in this step are:

- underbody frame assy (1),
- front floor assy (2),
- rear seat cross-member assy (3),
- rear floor back assy (5),
- rear floor front assy (4),
- inner body side assy front right (8R) and left (8L),
- dash top panel assy or water box (6),
- back panel assy (11),

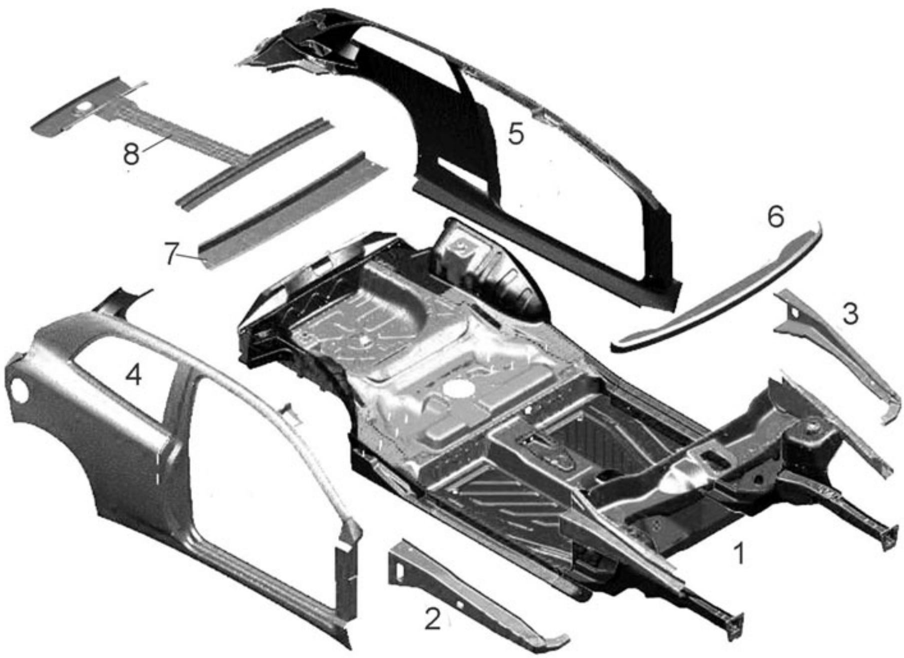


Fig. 4.9. Split scheme of subframes to be assembled to body in white (B.I.W.) assy.

- upper rail boxing right (10R) and left (10L),
- rocker panel assy right (7R) and left (7L),
- strut tower reinforcement right (9R) and left (9L).

The following step is then performed in the final body assembly jig, when the body sub-assemblies are connected by a limited number of spot welds (Fig. 4.9):

- underbody assy (1),
- body side right (4) and left (5),
- cowl top (6) and header (7),
- roof frame (8),
- upper rail right (2) and left (3).

The underbody carries the fittings of front and rear suspension, powertrain, exhaust system, seats, controls; moreover, it is the main sub-system involved in facing front and rear crashes and is also involved in side crash absorption.

Correspondingly, a well designed underbody can be adopted with relatively minor changes in vehicles of different shapes and overall dimensions (tread, wheelbase).

The body side is the assembly most affected by styling and by vehicle functions, as far as front fender and roof panel (the latter being less involved in achieving structural targets, being little more than shells). In addition, a body side must enable the connection of doors, the anchorage of window bag and safety belts as well as resist frontal and side crash and roll over.

The roof frame (usually just *bows*) connect the upper body sides; correspondingly their importance can be understood intuitively by comparing a sedan with a convertible.

Upper rails contribute to stiffness, as they connect the strut tower with body front pillar, help absorbing front crash and support front fenders.

The assembly of these sub-assemblies is then completed with additional spot welding, arc welding seams and *brazing*, included *hard-soldering* of sheet gaps (that means to seal gaps between metal sheets by melting of low temperature alloys).

Having so far examined the composition of body in white (B.I.W.), it is useful to analyze some examples of principal frame sections (Fig. 4.10), in order to determine how the stamped sheet parts can provide structural sections and attachment points; it must be observed that cut sheets are designed as single lines, that represent the trace of one side of sheet surfaces.

Section A–A (Fig. 4.10) is referred to the right A-pillar area, which has interfaces on one side the windshield, to the other side of the front door: it can be noted that the structural section is created by matching the right bodyside outer (1) and windshield pillar rail (3), while the pillar rail reinforcement (2) acts as a partition between the two parts.

B–B section is made in the roof zone, close to central (B) pillar, interfaced with the rear door and the roof central bow (not visible in the section): the resisting section is crated by matching the right outer side (1) and the quarter inner panel (20), with B pillar reinforcement (21) acting as the partition; the roof panel (5) is connected to the body side right assy.

C–C section is referred to the A-pillar zone, where the front door hinges are fitted: the resisting section is defined by the right bodyside outer (1) and inner (15), while the A-pillar reinforcement (10) provides an increase of local thickness; the continuous hinge is fixed to a plate (12), welded to the lower hinge reinforcement (11), while the lower dash (16) is welded to bodyside inner (15), through a flange in Y direction.

D–D section is referred to the B-pillar zone, where the continuous hinges of rear doors and the front seat safety belts (not displayed) are fitted: the structural section is defined by the right body side outer (1) and the quarter inner panel (20), while the central pillar reinforcement (21) increases the local thickness. The lower continuous hinge is fitted to the central pillar using two screws: one of them is screwed into a threaded bush (23), welded to lower hinge reinforcement (22), instead the other to a continuous hinge, acting from the central pillar.

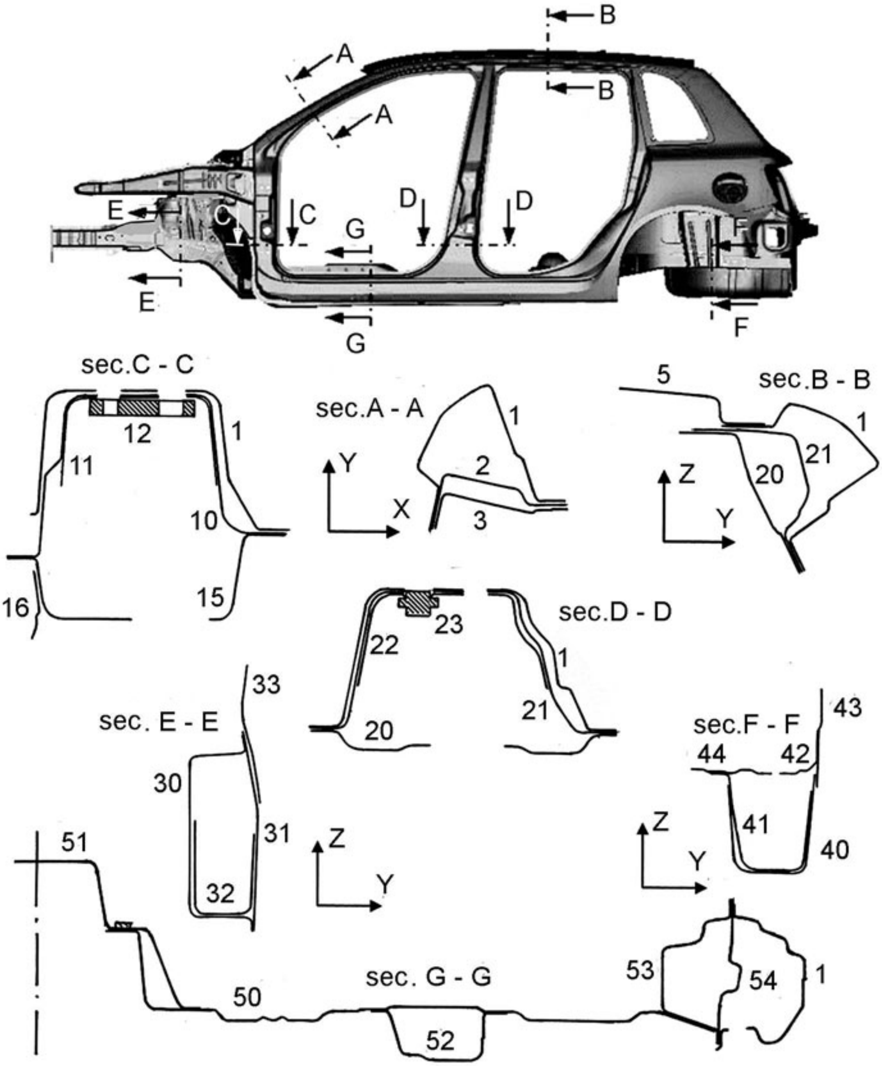


Fig. 4.10. Typical sections of a body in white.

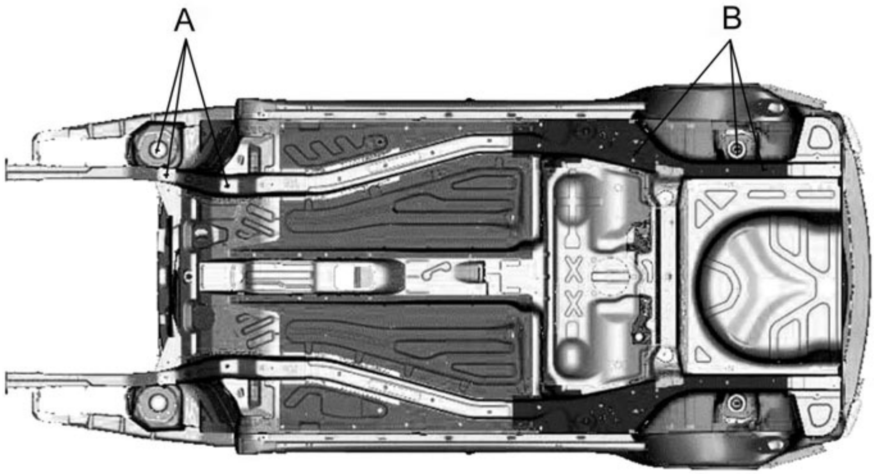


Fig. 4.11. Bottom view of an underbody, in which the longitudinal frames (rails and tunnel) are in evidence.

E–E section (Fig. 4.10) is cut across the front rail: it is possible to see the front rail (30), rail boxing (31), front rail extension (32) and lower front suspension tower (33).

F–F section is on right rear side member, which is connected to rear suspension rod, spring and shock absorber (in this case, with trailing arm suspension). The resisting section is obtained by the rear side member (40) and rear side member box (42), while the rear side member reinforcement (41) improves the rear crash behaviour; the rear wheelhouse (43) is welded to the rear side member (40) and to boxing (42) through two different sewing lines, while the rear floor back (44) is welded to the inner flange of side member, in order to separate the main structural function from other auxiliary functions, such as the spare wheel housing.

Finally, G–G section shows the matching of the underbody and the body in the lower area: the right floor (50) is welded to the tunnel (51) through two sewing lines parallel to the X axis and to the front part of the rocker panel, through another sewing along X; moreover, the underbody longitudinal rail (52), body side outer (1) and inner rocker panel reinforcement (54), which in the assembling process is welded previously to the front pillar reinforcement, can be seen.

Before ending our body analysis, it is appropriate to examine a bottom view of underbody (Fig. 4.11). It can be clearly noticed that the lower longitudinal frame has a lay-out which is as close as possible to being linear, in order to face the risk of bending and collapse in the event of a frontal crash, while depending on how the front and rear subframes are connected to the rocker panels. Moreover, the attachment points of front and rear suspensions (indicated with arrows A and B) are located here.

At this stage of the analysis it is appropriate to examine typical body overall functions in more depth.

4.1.2 Body Functions

Structural function

The mechanical factors of relevance to the structural function are: stiffness, static and dynamic strength, fatigue resistance and impulse reaction. The body is actually stressed by loads applied by the propulsion system and the wheel-road interaction, by its own inertia forces and by the inertia loads of all masses carried on-board, including components, people and goods.

Correspondingly, the common stresses result from both static and dynamic or impulse sources.

When the vehicle is stationary, the static stresses are caused by carried components and masses and by external constraints, i.e. by wheels support conditions: an example of a relevant static stress is that caused with one wheel standing on a step (for instance, a pedestrian platform). Instead common dynamic stresses result from inertia loads, proportional to accelerations due to the wheel-road excitation and to vibrations from the engine and relative subsystems, transmitted to the body through their connections and linkages (suspension and support components).

In the case of the unitized body and body on frame, these vibrations are transmitted through the underbody and body frames, and may be more or less amplified, depending on the dynamic response characteristics of the structure involved (as explained in *chapter Modal analysis* of Volume II).

In Fig. 4.12 some typical acceleration spectra of road surfaces are shown, in terms of *Power Spectral Density* (later on named *P.S.D.*).

P.S.D. is a mathematical function, corresponding to the mean quadratic contribution of a physical parameter (for instance, vertical displacement, velocity or acceleration), referred to a defined frequency range and divided by the reference frequency interval.

The unevenness of the road surface excites the body motion through a mechanism represented by the so-called *transfer function* $H(\omega)$, a function which depends on frequency domain ω. In mathematical terms, the vertical acceleration *P.S.D.* of body center of gravity S_z, for example, is given by the product of road profile vertical acceleration *P.S.D.* S_y times the square of transfer function $H_{yz}(\omega)$, as explained in Volume II.

Fig. 4.13 shows a typical vertical acceleration *P.S.D.* measured at a defined body position (a seat rail attachment): by multiplying this *P.S.D.* by the seat mass involved, we obtain the power spectral density of the inertia load applied by this seat to body at the attachment point. By integration of *P.S.D.* of the seat load, over the entire frequency range, we obtain the *root mean square* of vertical seat load, due to road unevenness. In the case of the body being elastically connected to the chassis (dual frame) or body with ancillary subframes, the

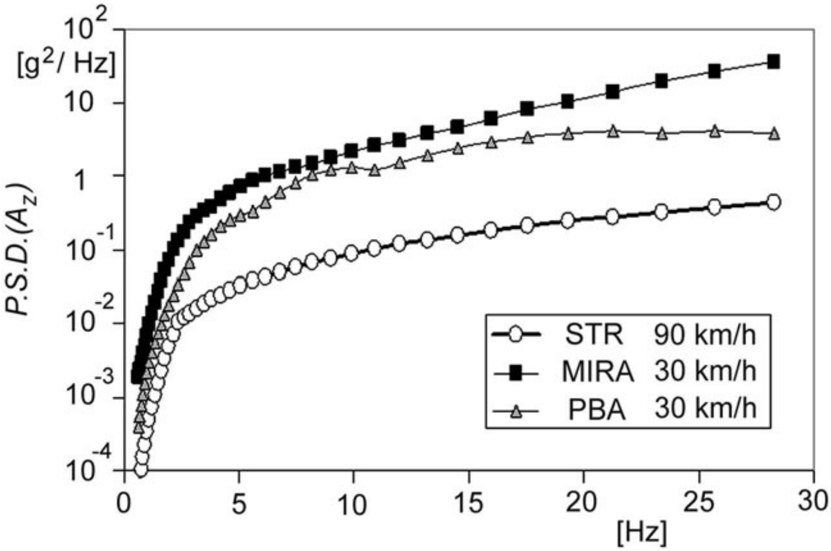


Fig. 4.12. Power Spectral Density *P.S.D.* (A_z) of vertical acceleration for some road uneveness. STR: good asphalt road; MIRA: MIRA paved track; PBA: FIAT-Balocco paved track.

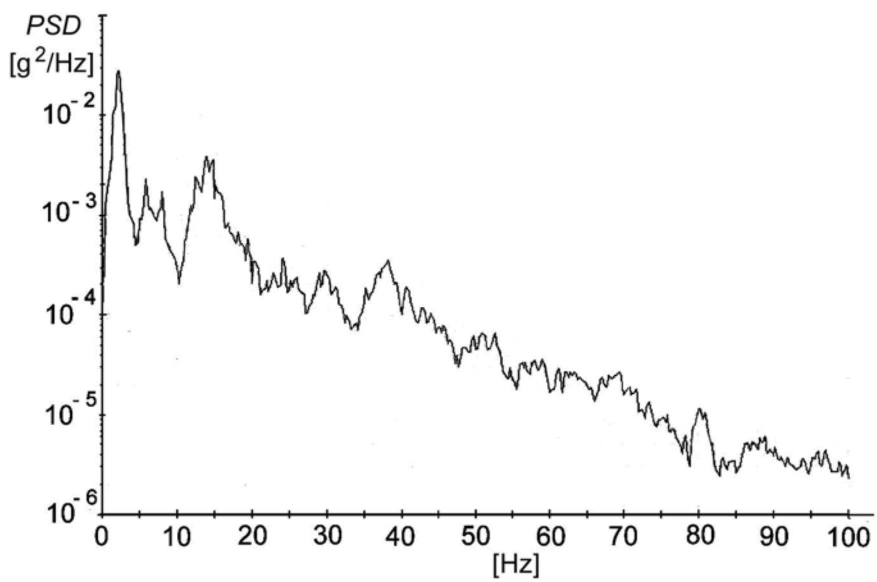


Fig. 4.13. *P.S.D.* of vertical acceleration recorded on a seat rail (uneven road, speed 60 km/h).

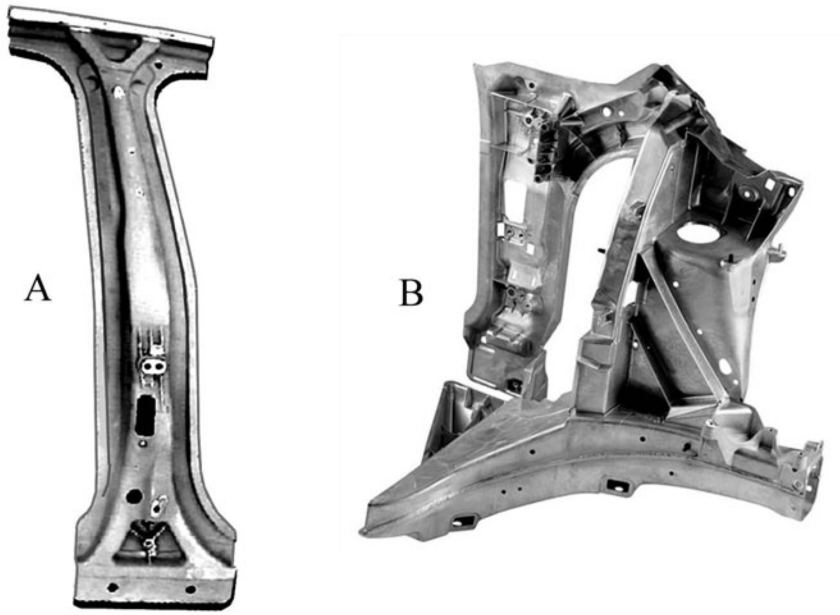


Fig. 4.14. Example of one piece subassemblies cast in aluminum: a central pillar (A) and a suspension tower (B).

accelerations transmitted to body are filtered by viscoelastic bushes and therefore their spectrum is attenuated over the frequency range beyond the body-on-bushes resonance frequencies. This effect causes smaller inertia loads to be transmitted to the body and therefore lower levels of vibrations and less noise transmitted from body to passengers.

A question which may arise at this stage is: which dimensional and functional properties should be given to body elements, in order to comply with their structural function?

Since static and dynamic loads of body mounted components are always transmitted through their fitting points, loads are concentrated in relatively small areas and usually their three axial stress components fluctuate randomly in time, while the vehicle is moving. It is seldom that torsion stresses are generated at the attachment points and therefore the required properties for the hosting structure are principally: a) high local stiffness or high *dynamic impedance* (the ratio between the applied load and induced velocity of the stressed point), as the dynamic phenomena are prevalent; b) adequate sections to carry axial and bending stresses (which means that box section are not strictly requested, as it should be if torsion stresses were applied).

These properties can, for instance, be satisfied by cast aluminum or magnesium structures, with variable thickness and adequate ribs (Fig. 4.14) or, within a limited range, by reinforced plastic composites. However, most bodies are still made using thin steel plates (from 0.6 to 1.5 mm, depending on the task of the

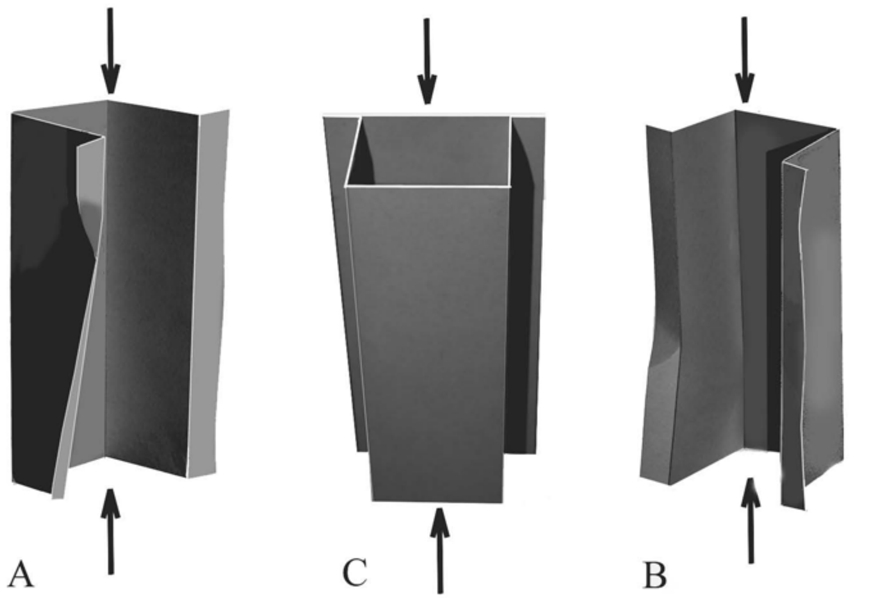


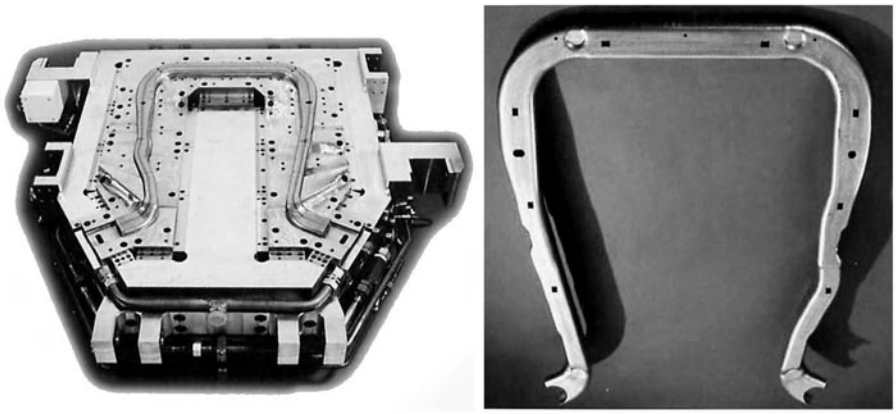
Fig. 4.15. Example of buckling in open sections (A,B), stabilized by mean of a boxing closure (C).

component): such a gauge can even support concentrated loads using, for instance, plate embossing, but cannot avoid warping and collapse of free flanges, stressed by axial compression and bending, due to local *buckling* (Fig. 4.15).

This is the reason why body frames are preferably made of boxed sections, for instance using two braces, one *omega*-shaped and the other one as closure, so that the lip flanges of both elements, used to join them by spot welding, bonding or other process, can provide stability to all frame walls.

Instead of boxed frames, if cost and investment are convenient, tubular *hydroformed parts* can be shaped through a process using high pressure water, in which the complex configuration required is achieved, starting from a bent tubular element, even with holes and slots punched in the die (Fig. 4.16).

Regarding the static stresses caused by the road contact (for instance, due to a wheel standing on a platform), the whole body is involved, as it is substantially a hyperstatic structure, therefore stressed in a way which depends on the stiffness of nodes and beams. Referring to the same example, the body side frame should be designed to maintain deformations at a level low enough to guarantee the normal opening and closing of doors. By analogy, if windsheld and back glass are fixed to the body through rubber gaskets instead of being bonded, under the same stress condition the windshield and back openings should be sufficiently undeformed so as to preserve glass integrity, i.e. referring to this type of static stress, the body should exhibit adequate *torsional stiffness*.



A B

Fig. 4.16. A cradle (B) manufactured from die hydroforming of a steel tube (A).

Regarding the dynamic stresses, caused by loads carried on-board, distinction should be made between people and goods. The load caused by the vehicle occupants are applied to seats and therefore transmitted to the body frame through a number of defined clamping points, while goods are generally distributed on wider floor surfaces. In the case of distributed loads, for instance in the luggage compartment, in order to avoid fatigue cracks it may be sufficient to use steel sheet of 0.7÷0.8 mm, embossed with ridges and supported by frames (rails and cross-members), already existing for other structural purposes.

In positions where strong dynamic loads are concentrated, for instance safety belt anchorages or shock absorbers towers, it is usual to combine the main stamped element with a welded reinforcement of higher thickness (normally, from 1.2 to 1.8 mm), commonly made of high strength steel. In the last decade, in heavy duty components, some local reinforcements have been substituted by *tailored blanks* (Fig. 4.59), made up of patches of different gauge and/or different properties, previously welded in order to press in the die one tailored blank.

In design development process, the appropriate choice of thickness and steel grades, i.e. the correct design of sections and local reinforcements is made through the application of *Computer Aided Engineering (C.A.E.)* analysis, the solutions being then verified by bench fatigue testing, as explained in Volume II.

The dynamic stress in the shock absorbers attachment points should not cause an additional displacement of shock absorber clamping point, which would affect the suspension damping effectiveness; for similar reasons, deformation of the spring, suspension and anti roll bar housing should be avoided. For this purpose, local body attachment stiffness as well as overall body stiffness between the two axles should be improved. Overall stiffness in this case is the body *dynamic torsional stiffness*, a property influenced by the static body torsional stiffness, body mass distribution and therefore the body vibration modes. Despite being a very complex parameter to control in the design process, some reference target for individual parameters as mass, static torsional stiffness, local impedance and resonance body frequencies can be useful tools. Mass should be as lower as possible, in relation to body size, while static stiffness should be as high as possible, in relation to wheelbase and body mass. Local and global resonances should be avoided for frequencies below 40 Hz, in order to avoid interaction with suspension resonances (commonly occurring in the 15÷20 Hz range).

Referring to the main parameters affecting stiffness to mass ratio, overall body structural efficiency could be evaluated in a first approach as the efficiency of a square tube of uniform thickness s and side dimension b, stressed by torsion at both ends, of length corresponding to the wheelbase l of the vehicle being considered.

In this case, the theory of elasticity yields the following relationship:

$$\frac{K_{TORS}}{m} = \frac{Gb^2}{4\varrho l^2} \tag{4.1}$$

where:

K_{TORS}	tube torsional stiffness
m	tube mass
G	shear elastic modulus
ϱ	material density

This rule means that, in condition of similitude, *torsional efficiency* (defined as the ratio between torsional stiffness and mass) of a uniform structure decreases with the square of wheelbase value l, for the same cross section and material.

As a consequence, in order to maintain the same efficiency for different wheelbase length and the same cross section, the real stiffness should be increased in a linear proportion to the increase in mass and quadratic proportion to the increase in wheelbase.

Considerating a sample of body of different size, made by different car manufacturers and plotting the torsional stiffness against wheelbase and mass (Fig. 4.17), it can be observed that this criterion is generally exhibited on average, although single cases do deviate from the trend.

Other types of mechanical stresses which affect bodies also arise, for instance those due to local contact with solid parts (for example, hail or stones) or to manual actions (e.g. due to pushing a vehicle or to the opening/closing of movable parts).

In both situations, the type of strength required is the so called *dent resistance*. Parts mostly affected by this problem are body panels, included the outer panel of movable parts, due both to their geometric shape (large radii, large surfaces without supporting frames) and the material used (usually a deep or extra deep drawing steel, with low carbon content, commonly needed for a better part forming).

This is another case in which structural analysis and verification testing are used to tune sheets gauge and to evaluate need of stiffening ridges or fitting of special impregnated carpets with stiffening properties.

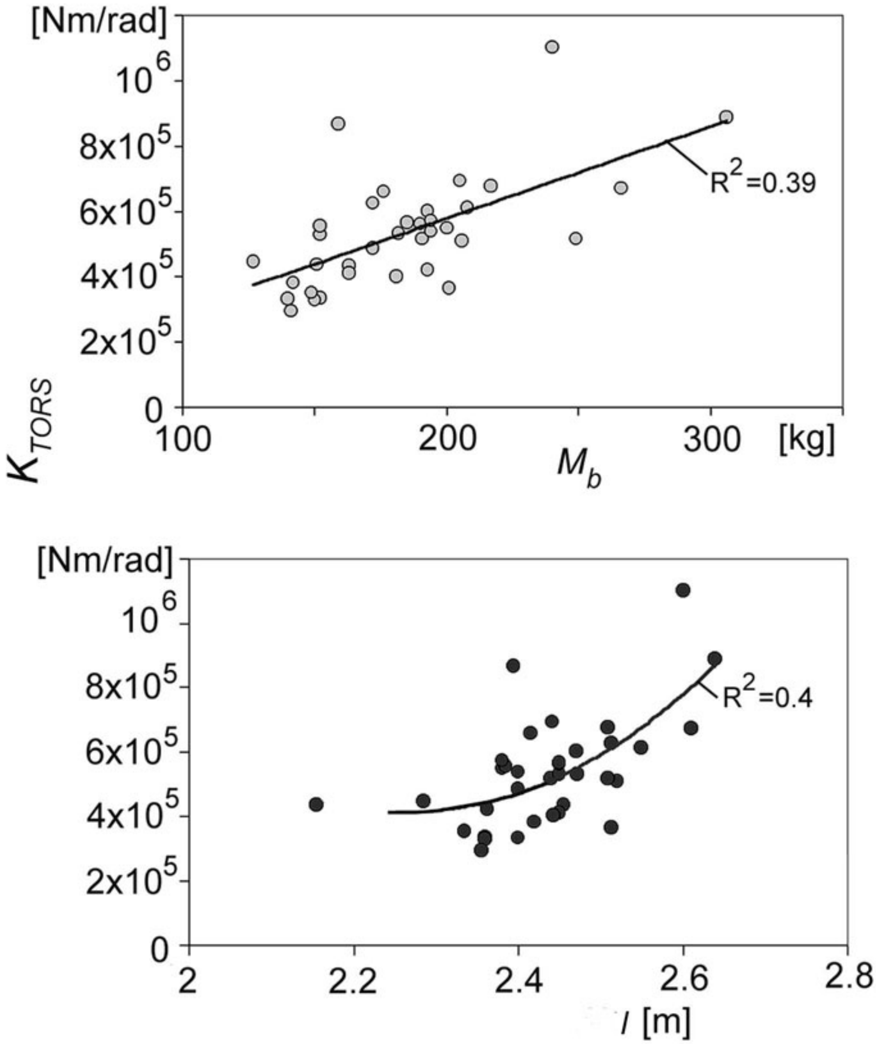


Fig. 4.17. Torsional stiffness K_{TORS} for different body sizes, referred to wheelbase l and mass of body without movable parts, M_b. The plot is completed by regression analysis curve fitting and correlation index R.

Dynamic denting can be explained as follows: firstly striking deforms elastically, therefore reversibly, the body reference panel, which is a plate clamped around its perimeter. According to classic theory of elasticity, the maximum stress of a deformed plate grows with deformation up to a level that corresponds to yield strength σ_y of the panel material. If, during this step, kinetic energy of the impacting bullet has not been completely transformed into deformation work, further panel deformation ocurs during a second step, in which the areas, where the yield stress is reached, become permanently deformed.

During the first step, if the considered panel is, for example, circle shaped with radius R, the maximum stress in the panel is proportional, through a coefficient c_1 (defined by the shown formula), to the deflection f, to Young's modulus E of the panel material, to panel thickness s and inversely proportional to the square of radius R, according to the following expression:

$$\sigma = c_1 \frac{4.188}{(3+\nu)(1-\nu)} \frac{Esf}{R^2} \tag{4.2}$$

where c_1 is given by:

$$c_1 = 0.477(1+\nu)(\ln \frac{R}{r} - \frac{1-\nu}{1+\upsilon} \frac{r^2}{4R^2} + \frac{1}{1+\nu}) \tag{4.3}$$

being ν: Poisson's material coefficient,

r: radius of hitting bullet surface[1].

Elastic deflection limit is given by expression:

$$f_y = \frac{R^2}{sEc_1} c_2 \sigma_y \tag{4.4}$$

where:

$$c_2 = 0.238(3+\nu)(1-\nu) \tag{4.5}$$

Therefore, in mathematical terms, the maximum amount of energy that can be absorbed in the elastic phase, given by the integration of the applied load P multiplied by the infinitesimal panel deflection df, $\int Pdf$, over the integration range $0 - f_y$, after some calculation becomes:

$$\int \frac{1}{R^2} f s^3 \frac{E}{c_2}\, df \tag{4.6}$$

By neglecting changes of c_2 coefficient while f increases, the absorbed elastic energy becomes:

$$E_{el} = \frac{Es^3}{2c_2 R^2} f_y^2 = \frac{c_2}{2c_1^2 E} s R^2 \sigma_y^2 \tag{4.7}$$

[1] Note: this formula is valid for r bigger or equal to thickness s only.

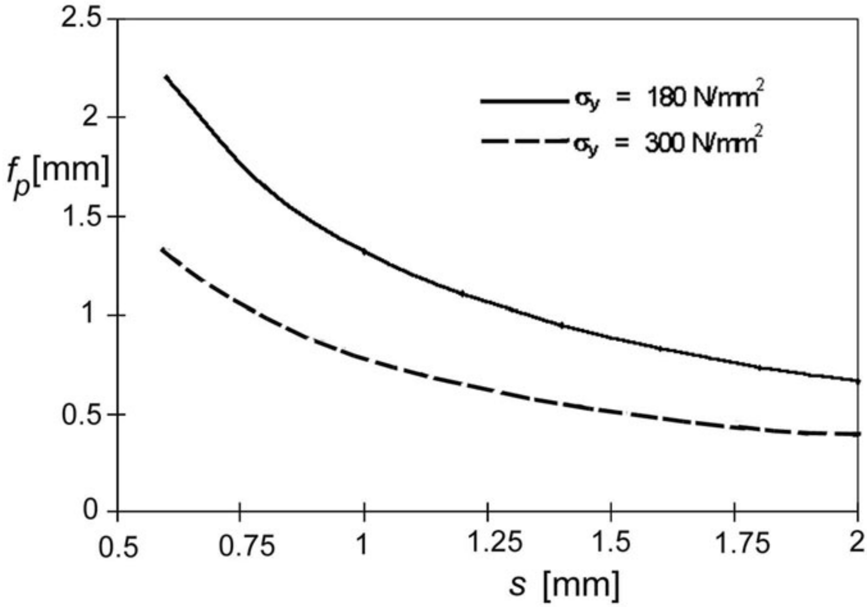


Fig. 4.18. Depth of permanent dent f_p is inversely proportional to the product of thickness s and the yield strength of material σ_y.

This expression means that the amount of energy absorbed in elastic, therefore reversible, deflection, increases with thickness s and yield limit σ_y and is inversely proportional to Young's modulus E.

If we compare, for example, a sheet of steel ($E \cong 210$ GPa) with aluminum ($E \cong 70$ GPa), the above expression indicates that aluminum can absorb more energy, if the product of its thickness multiplied by the square of its yield strength is at least one third of the corresponding steel value. Such a condition can be commonly achieved with same thickness and is one of the reasons why steel is replaced by aluminum for hood and fenders which, together with door panels, are the most dent prone.

In the second step, the impacting bullet succeeds in causing plastic deformation of the panel material, leaving a permanent mark. For this stress condition, theoretical as well as experimental analyses have been made, the conclusion being that the permanent mark is in practice the same, even considering different materials, if the plates used have the same value of thickness times yield strength (Fig. 4.18).

This result can be obtained by replacing extra deep drawing steel sheets (commonly used by car manufacturers) with aluminum sheets even of same gauge, hardened after forming by heat treatment and artificial aging. In the case of steel sheet using a high strength alloy, replacement with aluminum could require an increase in gauge.

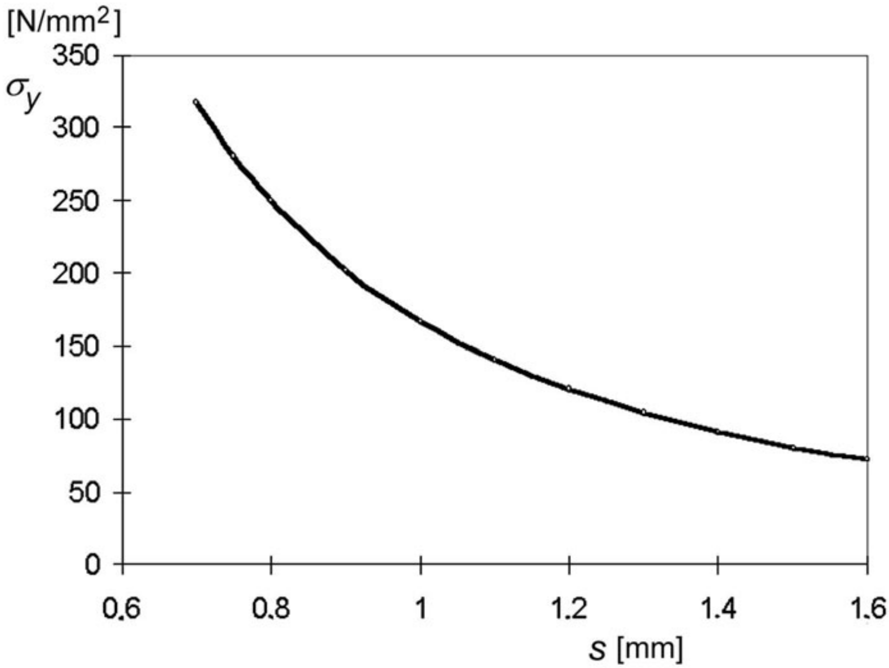


Fig. 4.19. Empirical equivalence in dent resistance for sheets with different thickness s and yield strength σ_y.

According to other empirical evaluations, equivalence in dent resistance among different alloys and gauges can be obtained by keeping constant the following product (Fig. 4.19):

$$\sigma_y \ s^{1.8} \tag{4.8}$$

As a general conclusion, referring both to elastic energy absorption without permanent deflection and to permanent dent resistance, it may prove beneficial to choose an aluminum sheet instead of a steel, for body outer panels.

These phenomena can be computed and displayed by a rendering software, as illustrated in Fig. 4.20, which shows a magnified image of a door panel deflection after loading phase and following subsequent unloading.

By computer analysis the deflection curve in both stages (load and unload) can be plotted, as shown in Fig 4.21.

Using such tool, the potential advantage of replacing a deep draw steel sheet by a thinner sheet of higher yield strength can be evaluated (Fig. 4.22).

Another common reason for permanent body damage is fatigue, caused by dynamic loads transferred mainly through the suspension systems.

Fatigue is revealed by local plate breaking, usually in trimmed flanges or overstressed areas, caused by notches or sharp section changes (Fig. 4.23) or

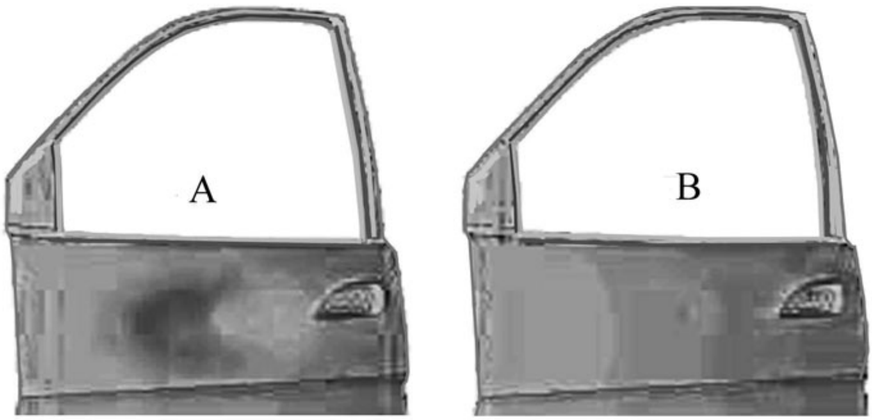


Fig. 4.20. Computer rendering of door panel static denting; A: after loading phase; B: at end of unloading (residual denting). Deflection under concentrated load is displayed with a 5x magnification factor.

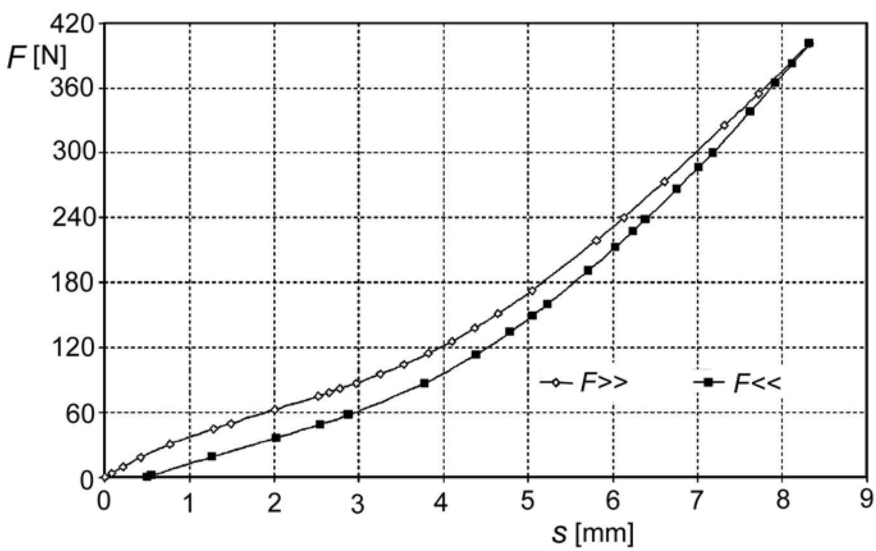


Fig. 4.21. Chart load F - deformation s puts in evidence the residual deflection. $F>>$ means loading path; $F<<$ means unloading path.

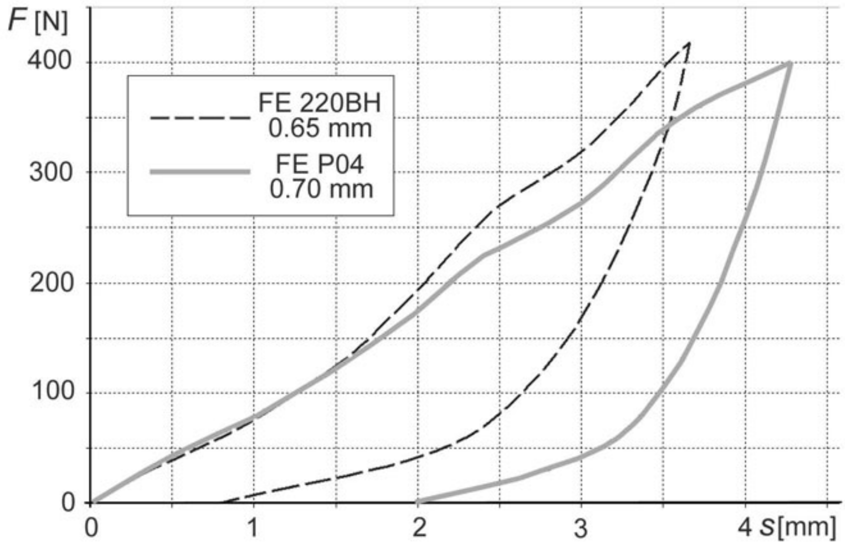


Fig. 4.22. Dent comparison between two hood outer panels, made by steel plates of different yield strength and different gauge. F: applied load; s: displacement of starting load application point.

spot weld pull-offs, often related to local thickness reduction and hardening due to thermal welding stresses (Fig. 4.24).

Some specific body areas are mainly affected in this way, in particular body side openings, in small radius zones close to nodes and near shock absorbers tower reinforcements (Fig. 4.64).

Today tools are available to analyze such high risk situations (see Volume II) and, in any case, consistent bench test methods exist. Test are made on body in white as well as on the complete car, using dynamic loading machines that can apply stresses caused by both road unevenness and driving actions.

Safety

Referring to the safety function, body parts can be divided into three families:

1) *Outer panels*, usually deep drawn, whose resistance to deformation and therefore absorption capacity are very low.

2) *Underbody frame*, with prevailing horizontal layout, designed to face strong axial loads and absorb a relevant amount of energy while crushing.

3) *Passenger cabin frame*, designed to face relevant bending loads.

In practice, thin body outer panels have no influence at all on passengers safety, but are very important with respect to external vulnerable road users (mainly pedestrians and cyclists).

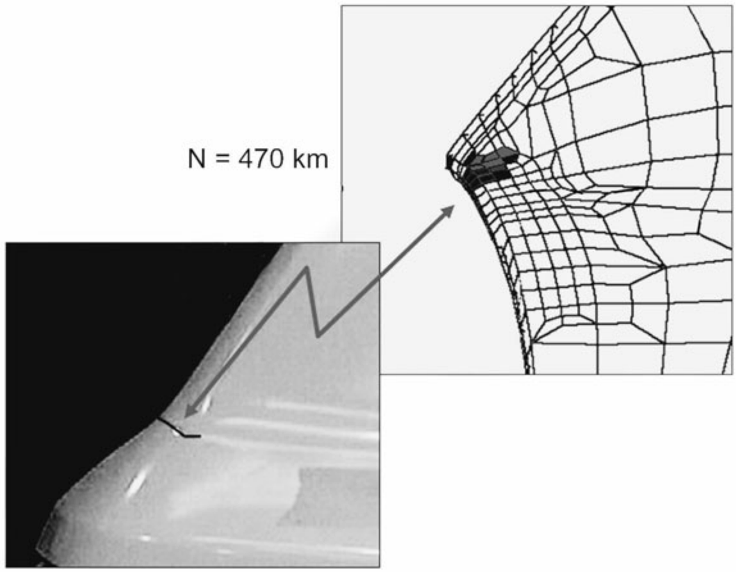


Fig. 4.23. Example of fatigue breaking, due to section properties and stress map of the break source from computer analysis.

In fact, the flexibility of these panels can help absorb, with acceptable loads and large deflections, impact energy of pedestrians and cyclists (of course, at speeds which do not exceed the limits allowed in urban areas). This is true only for panels without rigid frames and/or solid obstructions which are less than 100 mm from the surface (for instance, powertrain parts or upper suspension tower), as they would act as a barrier to panel deformation and prove highly damaging due to fatal acceleration in the event of impact.

Front end and hood are typically involved in event of this kind, up to 30 km/h impact speed. At higher speed, pedestrian or cyclist are likely to be thrown towards further body surfaces, such as the windshield and front pillars; since for these components the stiffness required is determined by passenger compartment integrity, currently they are not the subject of proposals for modifying regulations in terms of providing incresed flexibility.

The frames of the cage that surrounds the passenger cabin are, in fact, fundamental to reducing passengers injury in the case of front, side, rear impact and rollover. Their main task is: a) to keep the compartment as undeformed as possible during crash, i.e. preserve the so called *survival room*, in order to help restraint devices to perform appropriately; b) to absorb, through the structure protruding from compartment, the crash energy imposed on the vehicle depending on specific impact conditions (mass ratio, vehicle collision speed and energy absorbing properties of impacting vehicles).

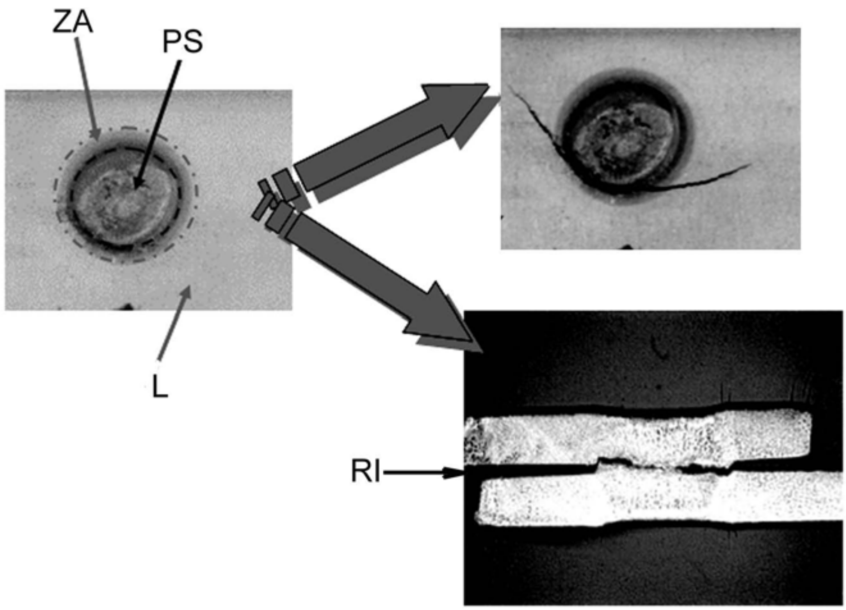


Fig. 4.24. Fatigue breaking of plate L close to a weld nut PS, started by thermal alteration caused by welding. ZA: thermally altered perimeter; RI: interfacial breaking mode.

As a consequence, morphology, materials and assembling technologies of the passenger compartment frame are completely different from those used for the absorption designed structure. The priority for the compartment frame is to enable highest peak resistance to plastic breaking, while for the absorbing frame the main priority is to perform the possible highest amount of energy destruction, before the end of collapse. In other words, since the passenger compartment is a cage made of a number of surrounding curved beams, the design must aim to maximize the break resistance in bending of those arches. Absorbing frames, on the other hand, should be designed to maximize specific absorption, as for example tubular beams designed for axial *folding* (when there is a main load direction) or *honeycomb* elements (when load direction is undefined). In reality, the body frame performs multiple tasks and therefore each individual part must be optimized, according to the multiplicity of its structural task.

For example, front rails must support suspensions and, in the same time, absorb the frontal crash energy, caused by loads with the main component in X direction. For this combination of tasks, a tubular longitudinal beam is considered to be the most appropriate member, with thickness in the range $1.2 \div 1.5$ mm and high yield strength material, enabling axially failure by folding in a stable and highly effective way (Fig. 4.25).

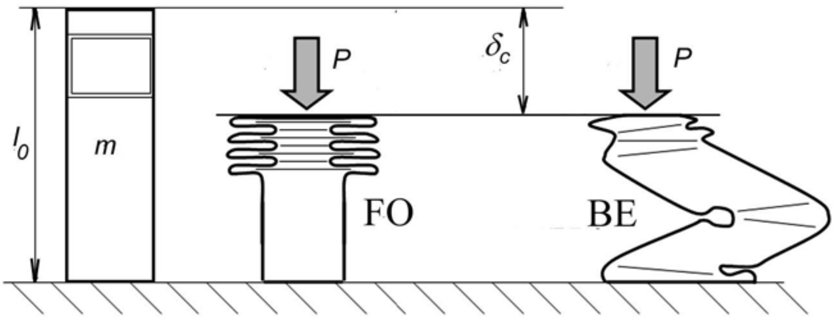


Fig. 4.25. A tubular beam axially loaded can break in two ways: *folding* (FO), through relevant energy absorption during all collapse path; *bending* (BE), with load and absorption peak only in bending phase.

A beam of this type, made by *Dual Phase* steel or a steel that after forming and heat treatment has a significant increase of yield strength, can absorb from 15 to 30 kJ per unit mass (kg) and therefore 10 kg in theory should absorb all the kinetic energy of a vehicle of mass m=1,500 kg, impacting a rigid wall at a speed V=50 km/h.

In fact, the kinetic energy E to be absorbed in these conditions should be:

$$E = \frac{mV^2}{2} = \frac{1,500}{2}\left(\frac{50}{3.6}\right)^2 = 144,676 \text{ J} \tag{4.9}$$

and therefore the collapsing mass m_A, needed to absorb all vehicle energy E, is given by:

$$m_A = \frac{E}{E_s} = \frac{144,676}{15,000} = 9.64 \text{ kg} \tag{4.10}$$

where E_s is the specific absorption energy (or energy absorbing capacity per mass unit).

This expression does not take into account the compatibility of the vehicle with heavier and/or stiffer counterparts, but is useful to evaluate the energy to mass requirement in rigid barrier impact.

On the other hand, it must not be forgotten that not only compartment integrity, but also acceleration limiting is an essential factor in safety. Deceleration depends not only on vehicles speeds and masses, but also on bodies deformation, with higher deformation causing lower acceleration.

Therefore, the frame of a passenger compartment must be very stiff, whereas surrounding deformable structures with relevant absorption capability must be integrated, as previously explained. In current vehicle configurations, adequate room for this function is provided for in front and rear regions of body, but less so in the side body and roof.

The consequence is that the protection capacity of a body in frontal and rear crashes can potentially be much higher than in side crash and roll over, i.e.

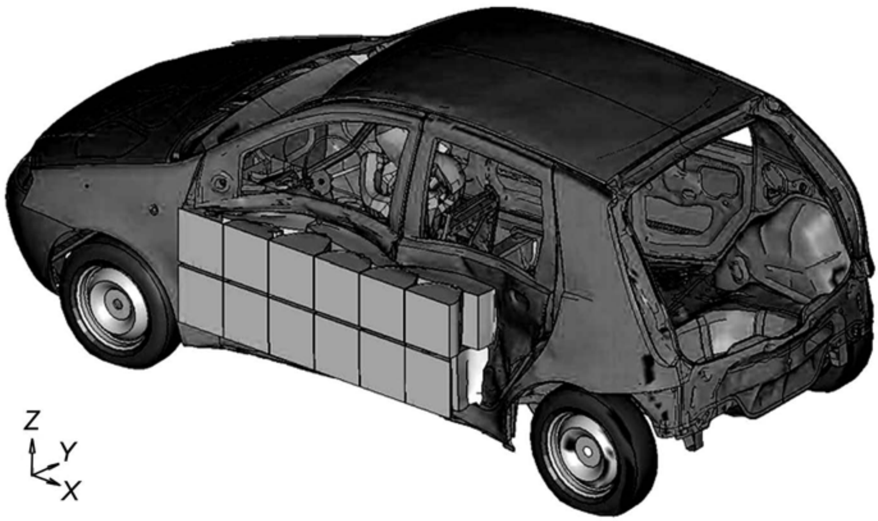


Fig. 4.26. In side impact with deformable barrier, body pillars should not break, while doors, even reinforced by anti intrusion bars, undergo large deformations.

the body can face much higher frontal than side impact speeds, with a similar amount of compartment deformation (Fig. 4.26). In the Chapter on body side, an explanation is provided regarding how to counterbalance lower side deformation space, through effective design of central pillar.

The selection of materials and structural configurations for safety is achieved by intensive use of computer crash analysis and through experimental tests, both with body subframes (i.e. *drop tower* tests, Fig. 4.82) and with complete cars. The final evaluation is performed using standard and rating tests, as explained in Volume II.

Aerodynamics

A moving body, together with underbody and wheels, is subjected to a distribution of aerodynamic pressure, resulting in forces and moments (Fig. 4.27), influencing the required power (and therefore fuel consumption) as well as attitude, driving stability, road contact, engine cooling and effectiveness of interior air conditioning system.

Moreover, air flow affects the noise perceived inside the passenger compartment: in Fig. 4.28, an example of measurements taken inside the compartment, in a wind tunnel for aerodynamic testing is shown.

The properties of the body influencing these results are:

- Body cross section, together with protruding cross sections of front wheels, outside mirrors and underbody parts, named *projected frontal area* of the vehicle.

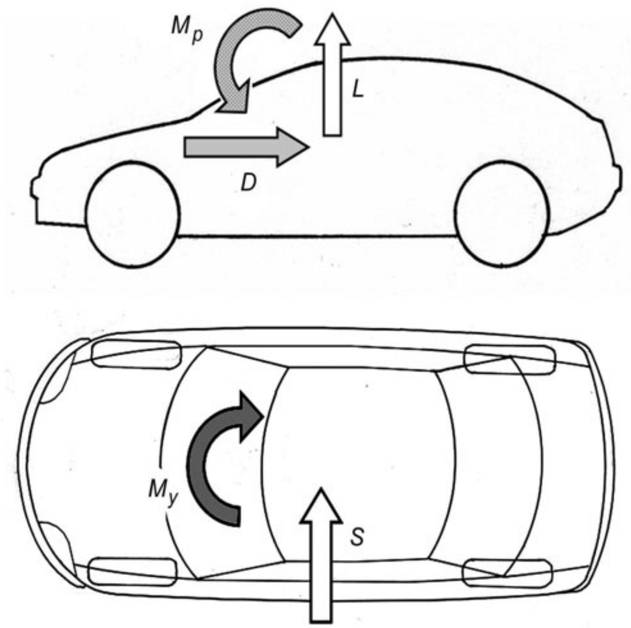


Fig. 4.27. Aerodynamic actions on the body: drag D, lift L, pitching moment M_p, side force S, yawing moment M_y.

- Outer body surface (front end, hood, wings, decklid, roof, doors, glasses, external mirrors), the shape of which influences skin friction and air flow around the vehicle and therefore air speed, pressure, boundary layer thickness and wake vortex.
- Unevenness, e.g. gap or steps among body elements and body fitted accessories protruding from body surface (i.e. gap among metal sheets, windshield wiper, aerodynamic add-ons, moldings, handles, gaskets).

The forces and moments acting when a vehicle is running along a straight road and without side wind, are (Fig. 4.27):

- Drag D
- Lift L
- Pitching moment M_p

In the presence of a side wind or when vehicle is turning, additional actions are:

- Side force S
- Rolling moment M_R (usually with low effect)
- Yawing moment M_y

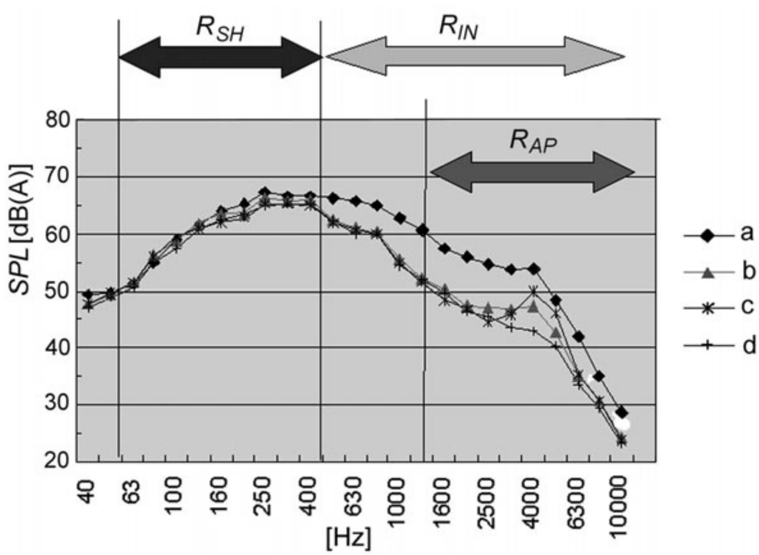


Fig. 4.28. Sample of noise spectra measured at the driver's position in car inside a wind tunnel, indicating different contributions. R_{SH}: shape influence; R_{IN}: permeability influence; R_{AP}: add-ons influence. a: standard car; b: tape sealed; c: without windshield wipers; d: without LH mirror.

During the modeling of a new body (at drawing-board stage), required are C.A.E. analyses of the aerodynamic effects and full scale model investigation in the wind tunnel since, following model approval, any significant change in shape would cause a delay in time to market and considerable costs in term of re-design and re-tooling.

Therefore, as soon as a *styrofoam model* is available, it must be tested in wind tunnel to verify all specified aerodynamic properties and tuned until all the aerodynamic targets are achieved. This model is usually built with the real underframe, in order to perform real underbody air flow and is pierced with a calibrated hole in order to simulate the air intake through the radiator grill and airflow within the engine compartment.

In order to test side wind conditions, the vehicle is clamped in the wind tunnel in a yaw-angled position, with reference to the flow direction, in order to simulate the true ratio between vehicle and wind speed.

At this stage an interesting question arises: what is the main contribution of the different body parts to the aerodynamics of the vehicle?

As with every aerodynamic body, a vehicle causes an overall air flow disturbance that cannot be split into individual contributions, nevertheless individual influences can be understood with a degree of approximation. For instance, the union radius between front end and bonnet is the main cause of air flow variation

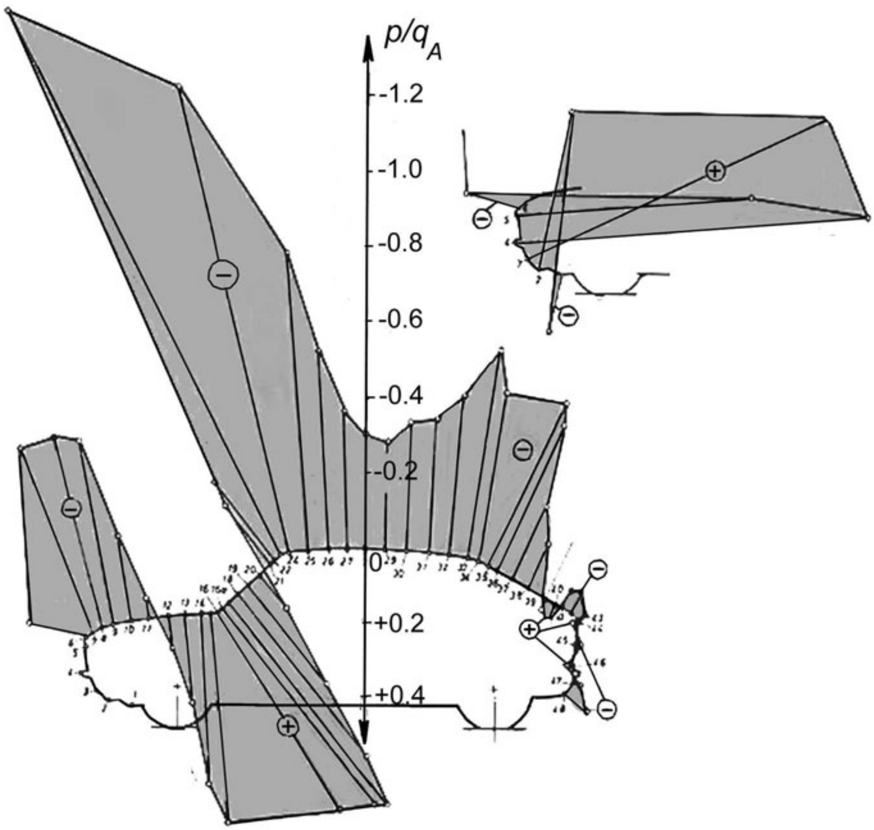


Fig. 4.29. Aerodynamic pressure p in centerline section, referred to the dynamic head q_A.

and therefore air pressure distribution (Fig. 4.29). This pressure field affects not only drag and front lift, but also strongly influences the air flow through the radiator grill.

In side wind conditions it is important to determine the action point of the side force resulting from the pressure field, or *pressure center*.

Usually, the distance a between pressure center and midpoint between axles is measured (Fig. 4.30).

When the pressure center is located in front of the gravity center, both the resulting side force and yawing moment have a tendency to increase the yawing angle, causing instability.

When, on the other hand, the pressure center is beyond the gravity center, the yawing moment causes a vehicle draw up with turning induced by the side force; therefore compensation occurs and any side wind gust is perceived less by the driver.

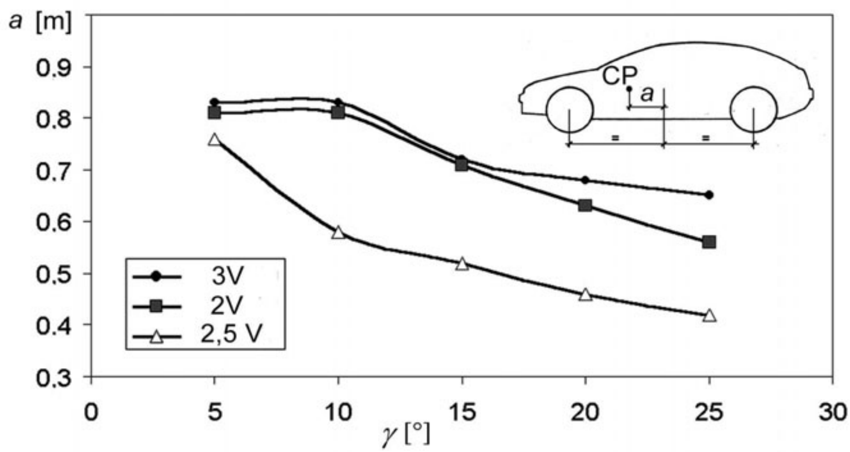


Fig. 4.30. Position of side pressure center *CP* for a 3 Box car (3V), a 2 Box car (2V) and a short decklid 3 Box (2,5V), measured in the wind tunnel, as a function of yaw angle γ.

The location of the pressure center is strongly influenced not only by wind to vehicle angle, but also by vehicle shape. For instance, the large side surface of SUV's and SW's rear body part pushes the pressure center backward, for all yawing angles. In Fig. 4.31, the relationship between distance a of the pressure center from midpoint between the axles and wheelbase, for a three box car (3V) is compared with the same relationship for a station wagon (SW), obtained by transformation of the same basic body. It can be observed that, for yawing angles lower than 30°, both cars are unstable, but the a/p ratio for SW is much closer to the a_B/p ratio (a_B being the distance between center of gravity and midpoint between axles) than for the 3V car. Moreover, the SW becomes stable for a lower side wind angle, i.e. at lower side wind speeds.

Another relevant aerodynamic influence is related to the fitting of external mirrors, due to the disturbance caused to air flow around car sides, with consequential increase in drag, rustle and noisy turbulence.

From this perspective, the most common current location for mirrors, over the belt line and near the lower region of the windshield pillar, is often not optimal because air flow tends to enlarge the wake and generate vortex, whereas a more rearward position on the door outer panel, below the belt line, would be preferable, corresponding to a more regular flow region (Fig. 4.32).

Front bumpers and back body configuration (back glass, decklid, liftgate and sometimes rear spoiler) are important factors with regard to the body lift characteristics (Fig. 4.33). Front and side body configuration, but mostly quarter panels tapered to the rear in a plan view are instead relevant factors in terms of drag resistance.

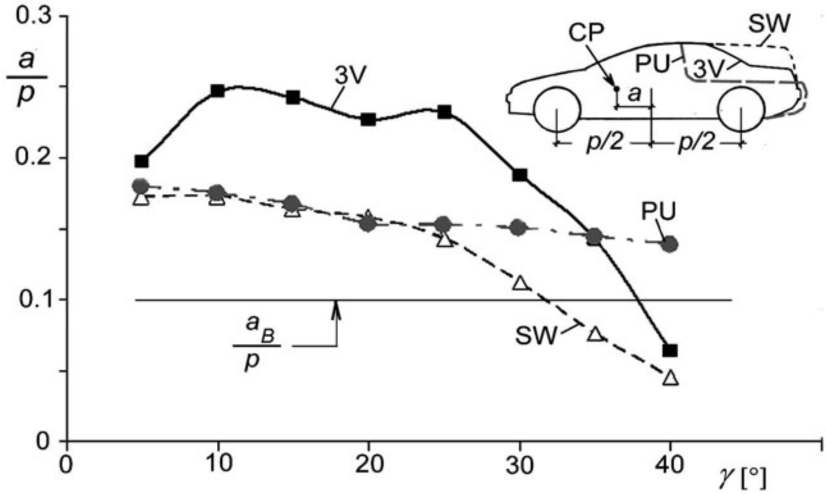


Fig. 4.31. Positions of the pressure center referred to the yaw angle γ, for a 3 Box car (3V) and after transformation into a station wagon (SW). a_B is the distance between center of gravity and midpoint between the axles for the car under consideration (a front engine front wheel drive car).

Drag is influenced by lift, according to *induced drag* theory: in practice, a force component perpendicular to air-vehicle relative speed, causes additional drag. Correspondingly, the suppression of lift is a goal for vehicle designers. Studies and research on this subject in the seventies[2] led to the specification of a nominally ideal shape, so that mid section body line is capable in theory of suppressing overall lift; after several years, a similar result was reached with production cars (Fig. 4.34).

This subject will be considered again in the chapter which focuses on bumpers and spoilers, where some methods to reduce overall lift and consequent drag will be shown.

According to the previous explanation, it can be understood that each body part contributes to aerodynamic vehicle performance, furthermore there is no doubt that only working simultaneously on the whole body can such characteristics be combined in the best way so as to be compatible with other primary functions, like aesthetics and ergonomy. For that reason, the first stage of body development is conducted using virtual analysis, concurrent with model styling: the engineer's task is not single component aerodynamic optimization, but rather to determine an optimal overall balance, defining a technical compromise for individual parts in order to optimize the whole body.

[2] A. Morelli, L. Fioravanti and A. Cogotti, *The Body Shape of Minimum Drag*, S.A.E. Paper no. 760186.

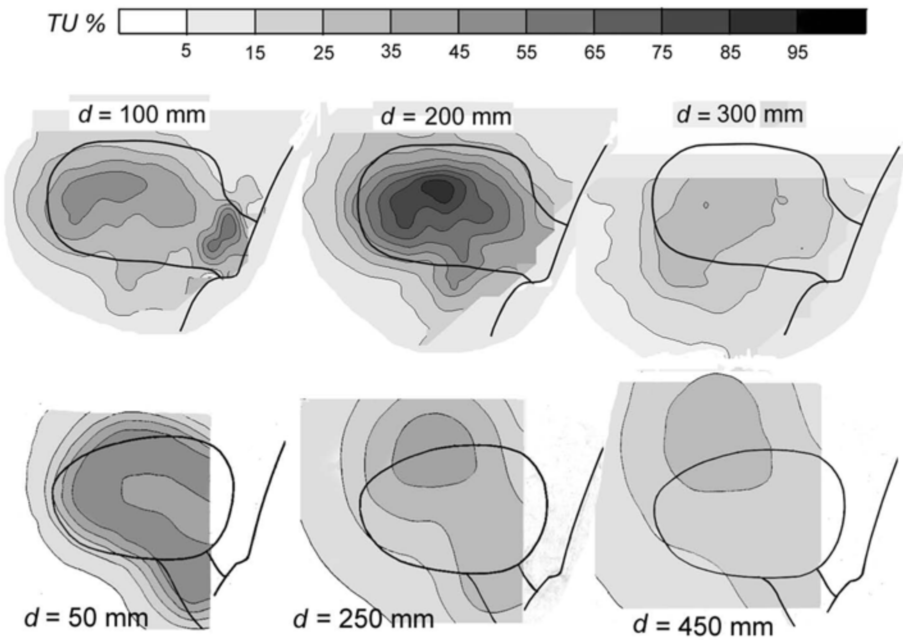


Fig. 4.32. Recordings of turbulence intensity *TU* in a number of wake sections at distance *d* from the mirror for two different mirror installations: above (upper figures) and below (lower figures) belt line. *Turbulence intensity* is defined as ratio between air speed standard deviation and average speed in the measurement position.

Insulation

The body comprises a number of solid surfaces, usually reinforced by frames, interconnected in a permanent way or by using devices that allow relative motion, with gaps or with a degree of play in between. These gaps are provided with permanent *seals*against *permeability* (when gap is in the millimeter range) or with flexible sealing devices, called *weather strips* or *gaskets*, when the gap is in the centimeter range (see the chapter on weather strips). Insulation from environment should therefore be granted by body components materials, by seals and by weather strips.

The physical factors involved in this case are: permeability, or *diffusion* through air channels; *transmission*, *reflection*, *absorption* and *radiation* by walls and surfaces.

The main noise sources are: powertrain, intake and exhaust system, wheel-road contact, suspension, windshield wiper, window regulator, trimming and weather strips squeaks and rattles (sometimes perceived as failure of body sheets junctions), vibration of the compartment frame and walls, and aerodynamic noise.

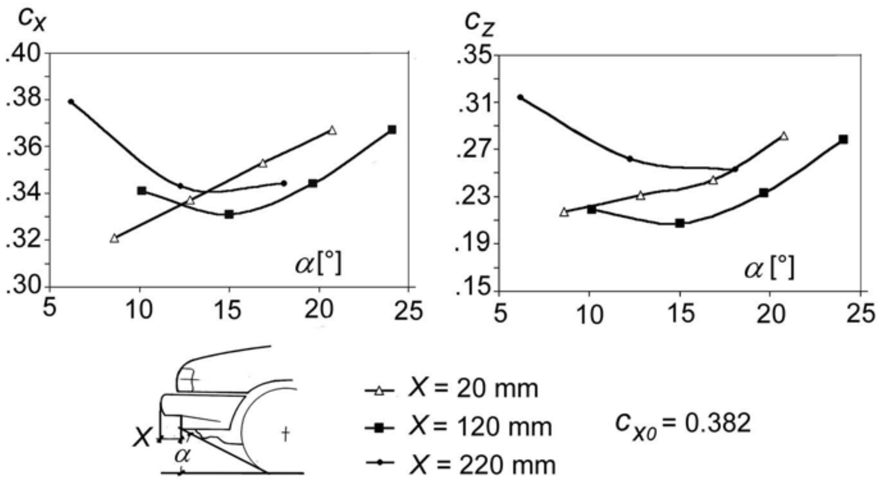


Fig. 4.33. Example of the influence on c_x and c_z of position and heigth of the front bumper spoiler. c_{x0} is the result without spoiler.

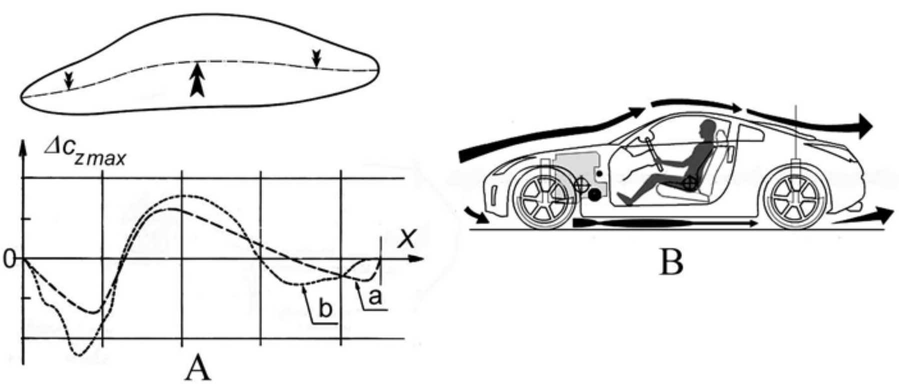


Fig. 4.34. A) Center line section of shape study by Prof. Morelli with Pininfarina, to suppress overall lift. In the lower figure, the distribution of computed (a) and experimental (b) lift along center line are reported. B) Nissan model 350 Z, performing c_x= 0.28 and zero lift.

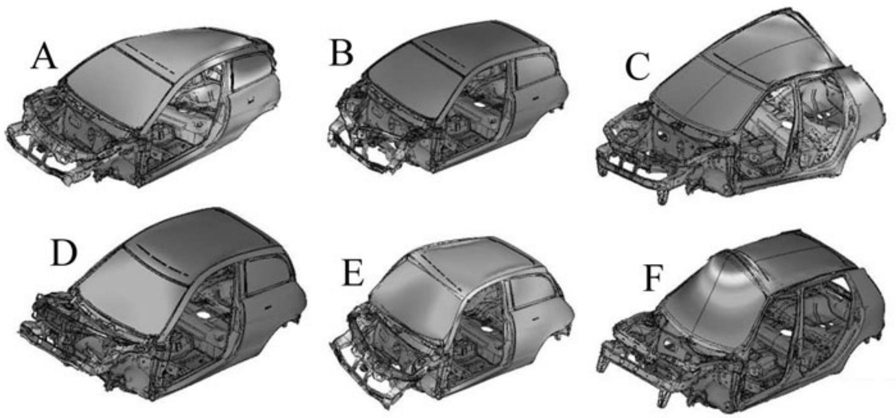


Fig. 4.35. Examples of vibrating mode for a 3 Box and a 5 Box body, for which resonance frequency are lower than 100 Hz. The dynamic deformation scale is magnified, to help interpretation. A and C: global torsion; E: front body torsion; B: side bending; D and F: front bending.

The main heat sources are the environment, mainly for solar radiation, hot powertrain components (heat exchangers and exhaust pipes) and the air conditioning system.

Noise and heat transmission are similar effects and are dynamic phenomena, therefore the previously listed factors should be considered as dynamic events: noise transmission through solids, for instance, is manifest as vibration, the maximum amplitude occurring at the resonance frequency of whole body or detailed body area (Fig. 4.35). In a similar way, noise transmitted by air has the highest amplification factor in accordance with the *cavity resonance* frequencies, that in our case are the cavity frequencies of passenger compartment (Fig. 4.36). In Volume II, the acoustic comfort chapter, those phenomena will be explained in more detail.

With reference to the body, it is important to bear in mind that the outer body sheets represent an effective barrier against environment noise transmission, but produce a high level of heat and noise reflection or diffusion, without any absorption.

It must be kept in mind that, according to *mass law*, noise attenuation through a steel wall is increased 1 dB by every gauge increase of 0.1 mm and that, for the same sheet thickness, attenuation of aluminum is approximately 9 dB less than for steel.

Moreover, in order to reduce disturbance through these sheets, when possible insulating sheets of low density materials (polyurethane foams, ultralight fibers as *thinsulate*®, textile fibers), are associated, being very effective in reducting high frequency noise and thermal fluctuations. The same materials are also

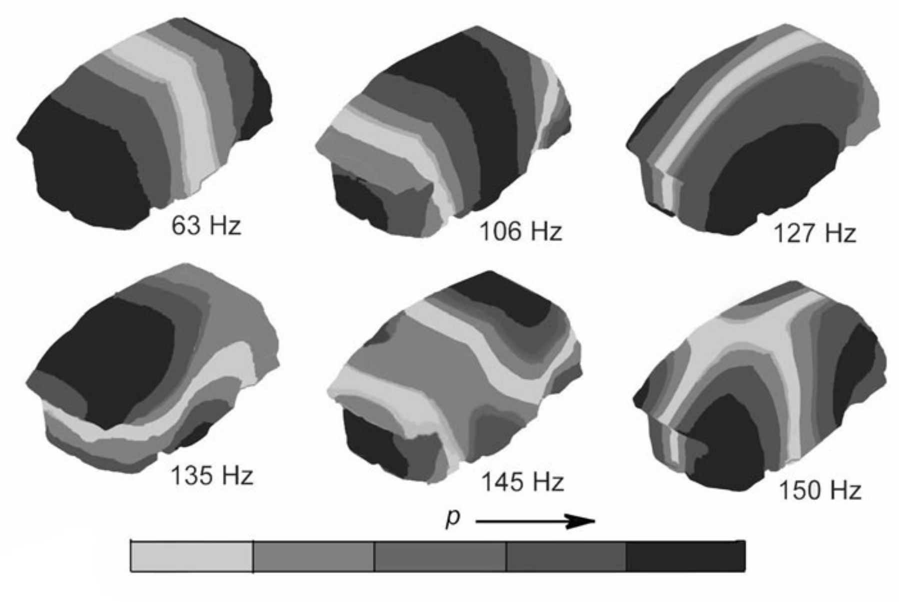


Fig. 4.36. Computed cavity modes for a small 2 Box sedan: the dark regions correspond to higher sound pressure levels.

effective in reducting metal sheet radiation, although cannot be used to attenuate glass radiation for obvious reasons.

In some cases, for maximum insulation, sandwich solutions are used, comprising sheet metal on one side, a heavy bitumen or rubber layer on the other, and a light insulating fiber layer in the middle. These sandwiches are called *septum* and take advantage of a typical dynamic effect of two masses connected by a spring (where the light fiber acts as spring). The system results in two resonance frequencies, the frequency range in between being characterized by a lower vibration response, resulting in attenuation of the exciting noise.

Regarding glass, in the relevant chapter some products developed with the purpose of reducing thermal energy transmission are presented, together with other solutions developed to improve insulation, while the difficult problem is to avoid radiation. Instead, insulation with weather strips is presented in the chapter on sealing.

Visibility

First and foremost, driving visibility is a safety factor. For that reason, the visual angles enabled by the windshield and pillars, and the area cleaned by the windshield wiper must comply with the international regulation (as explained in Volume II). Regarding windshield pillar design, obstruction is determined by its configuration, principally in Y direction. Therefore the pillar section is usually a

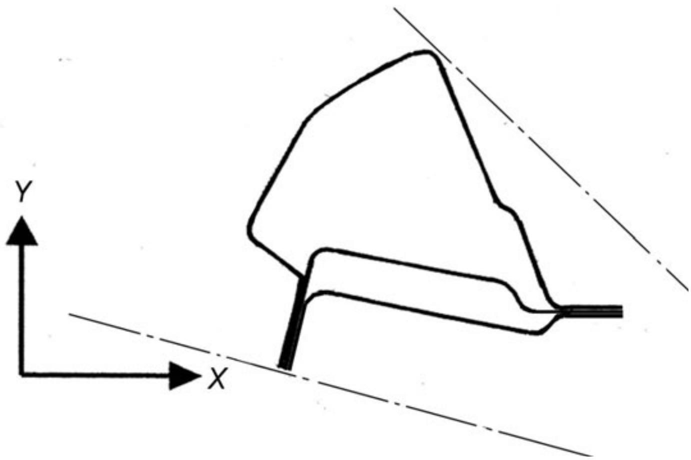


Fig. 4.37. With the purpose of minimizing front pillar obstruction, the section is usually shaped as an extended triangle, of which the top corner is directed towards the passengers compartment.

triangular one, with the top corner toward passenger compartment, the opposite base as narrow as possible and height in X direction (Fig. 4.37).

To respect regulations, pillar sections are therefore a compromise between structural requirements (mainly front impact and consequently higher strength in the X direction) and visibility rules.

On some recent cars, mainly one box or cab forward, a solution with twin pillar and bonded glass in between has been adopted, resulting in a stronger base (Fig. 4.38), the result being an example of synergy between style trends and safety regulation.

Another typical problem is that of side glass vision. On commercial vehicles, to increase downward visibility, a common design of front fixed window is shown in Fig. 4.39. On *MPV* and *SUV* vehicles, higher floor and seating positions enable an increase in downward vision, if a low belt line is preserved. However this solution causes some problems:

- Reduced side glass opening, due to smaller side door panel height;
- Higher extension of door frame and therefore higher flexibility, increasing the risk of vibration and lack of sealing.
- Excessive amount of glass in comparison with metal door panel (passengers shop-window effect).

The geometrical condition to lower the side glass down to the belt line is expressed by a simple relation among dimensional body side parameters, shown in Fig. 4.40:

$$L = C \tag{4.11}$$

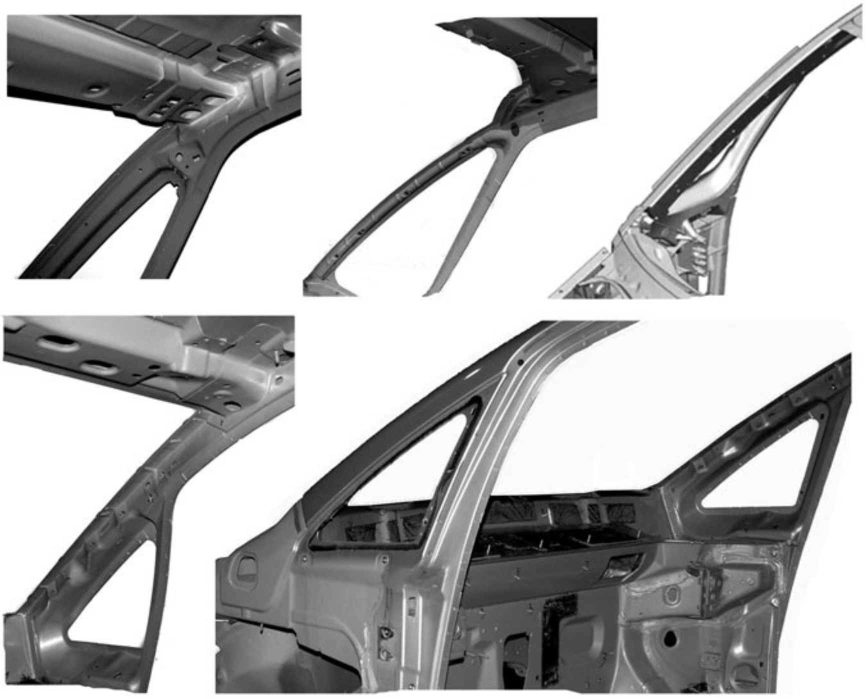


Fig. 4.38. Examples of twin pillar on some recent sedans: the triangular opening in between is stiffened with a bonded glass.

and therefore:

$$L = 0,5(H - R - S). \tag{4.12}$$

It is interesting to note that the mass per unit area of a 4 millimeter thick glass is 10 kg/m^2, 3.5 mm thick glass is 8.75 kg/m^2, a steel sheet of 0.8 mm gauge is 6.24 kg/m^2, two steel sheets one of which 0.8 mm thick and the other 0.7 are together 11.7 kg/m^2; correspondingly, the door mass can be lowered by maximizing the glass surface and reducing the area of the double (inner and outer) steel panels. Instead, the opposite would be true, if aluminum or plastic door panels were adopted.

In a similar way, in quarter panel area, a glass window between two small steel pillars could be lighter than one single steel pillar with the same surface area, made by inner frame and outer panel. In terms of visibility also, particularly in the case of parking manoeuvres, a wide steel quarter panel has a visual disadvantage in comparison to two small pillars with glass in between. However, from a cost and stiffness perspective, the opposite is true.

Regarding the overall body torsional stiffness, in principle body side with two side windows and rear quarter with wide steel pillar is the best solution, followed

Fig. 4.39. Some commercial vehicles with downward extended front window.

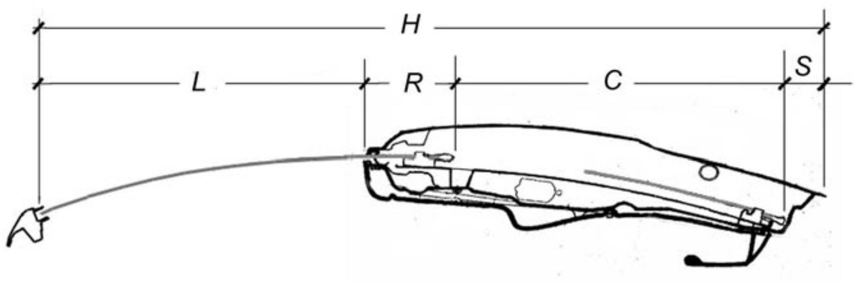


Fig. 4.40. Schematic drawing to analyze complete opening of side window down to the belt line.

by the alternative of three side windows with two small quarter panel pillars; the solution with two side windows and one small quarter panel pillar offers the best all around visibility but is less rigid.

Rear vision is often reduced by quarter panels tapered to the rear, with the purpose of drag improvement, by height of back glass lower side and by back glass slope to horizon, which can amplify glass defects for angles less than 30°.

The other body components that can influence visibility are: mirrors, windshield wiper and lighting devices, the properties of which will be explained in their respective chapters.

Reliability

In the paragraph on *Structural function* some indications have already been given regarding fatigue breaking and fatigue location. In the paragraph on *Insulation*, squeaks and rattles, usually resulting from contact among different components, have been specified. Another issue acting to worsen body reliability is oxidation and sheet corrosion.

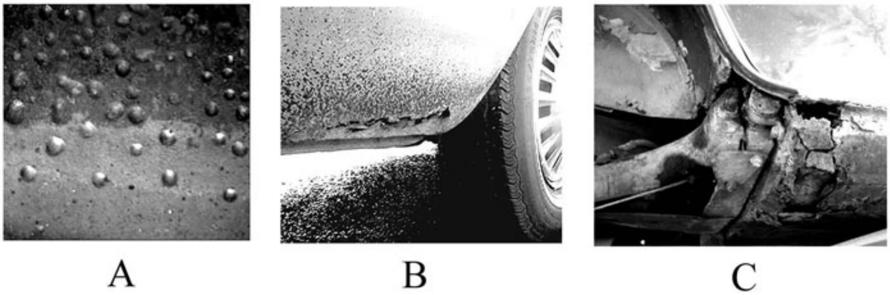


Fig. 4.41. Corrosion levels: A) blistering; B) perforation; C) structural.

Body driving environment presents various extreme physical and chemical conditions, depending on the geographic location and ambiental conditions. These situations include humidity, acids, deicing salt, hydrocarbons and so on.

Resistance of materials to environmental attack is highly specific: body steel sheets, for example, could not be used for the body without special treatment. An untreated steel plate, when exposed to air, is completely covered by rust after just a few days.

Corrosion can be classified into three different steps (Fig. 4.41):

- *cosmetic corrosion*, the consequences of which only really affect appearance, being referred to as paint abrasion, cutting or blistering;
- *corrosion perforation*, when holes in sheets not involved in safety tasks, as fenders or doors, are manifest;
- *structural corrosion*, when holes and cracks appear which affect the body frames involved in safety tasks, as rails, crossmembers or reinforcements where suspensions are fitted.

For many years, this considerable problem was a major concern, which had to be addressed using a complex treatment of preliminary detergent cleaning, phosphating, electrophoretic coating, application of primer, curing of primer and top coating with multiple layers, cured in bake oven and able to supply corrosion prevention for a limited number of years, under specified conditions.

Using traditional protection processes, after one year some cosmetic stain could be expected to appear on the coating, but without damage to the steel sheet. After 2-3 years, blisters began to arise in some places due to rain, dirt and moisture entrapment. This was caused by humidity and electrochemical reaction with steel. When this starts, blisters break and cause corrosion perforation, often appearing first in the wheel house, door panels and underbody boxed frame without ventilation. Even repeated treatment of the box frame with injected wax to cover the unprotected steel (in some areas not reached even by dipping electrophoresis) was unable to provide sufficient prevention.

The only effective solution, which is commonly used today, was to adopt zinc coated or galvanized steel sheets, where a thin layer of zinc (less than 10 μm) is integrated onto the steel through a *hot dipping* process or *galvanic process*. In this way, zinc has been proven to provide an effective barrier against humidity and chemicals, protecting steel through sacrificial corrosion producing zinc salt; as a consequence, corrosion resistance has now a duration which nominally corresponds to the designed vehicle life, even in countries where a significant amount of salt is used in winter for road de-icing.

The advantage of such protection is even greater in the case of cuts or scratches caused by small impacts, for which metal corrosion progression is much lower than in traditional bodies due to the *zinc sacrificial effect*, that allows straightforward repair and repainting.

Of course, changing to zinc coated steel sheets has not been entirely problem-free, partly due to the increased cost of the sheets (even with coating integrated into the steel lamination process) and for welding restrictions. In particular, a greater consumption of welding electrodes has required servicing intervals to be doubled and has caused a reduction in spot weld reliability (which for uncoated steel was already less than 100%). Such problems, which were deemed unacceptable for the robotized welding process, have been overcome progressively through a specific electronic control of the welding parameters, special assembly fixtures, and new electrodes alloys and dimensions.

Today the target for corrosion resistance depends on the climatic conditions, geographical location and mostly on competitors policy. In Europe and where specific regulations do not exist, there is general consensus to consider acceptable a minimum target of 3 years without cosmetic corrosion, 8 years without corrosion perforation and car life without structural corrosion.

In order to reach these targets, apart from using zinc coated steel sheets and an adequate painting process, some special design features in body critical regions must be adopted, particularly in boxed frames:

- Provide adequate holes in box frames at distances defined by process tests, so that electrocoating reaches all frame regions.
- Seal all uncoated edges, since trimming sheets leaves part of the trimmed section lacking zinc protection (Fig. 4.42). For this purpose, an appropriate solution for steel sheets matching consists in combining one flat sheet with a stepped one so that after welding a channel remains in between, ready to be filled with extruded seal. This could be chosen among four main different families: a) seal for outer parts to be hot cured; b) seal for hidden inner parts hot cured; c) aesthetic seal; d) sealing adhesive to apply between sheets that cannot be reached by the seal nozzle.
- Never fit to steel sheets any material that could result in galvanic corrosion and therefore in zinc destruction , due to electric potential difference between zinc and the fitted materials (for instance, never fit stainless steel to steel or zinc coated steel, without the interposition of a plastic spacer).

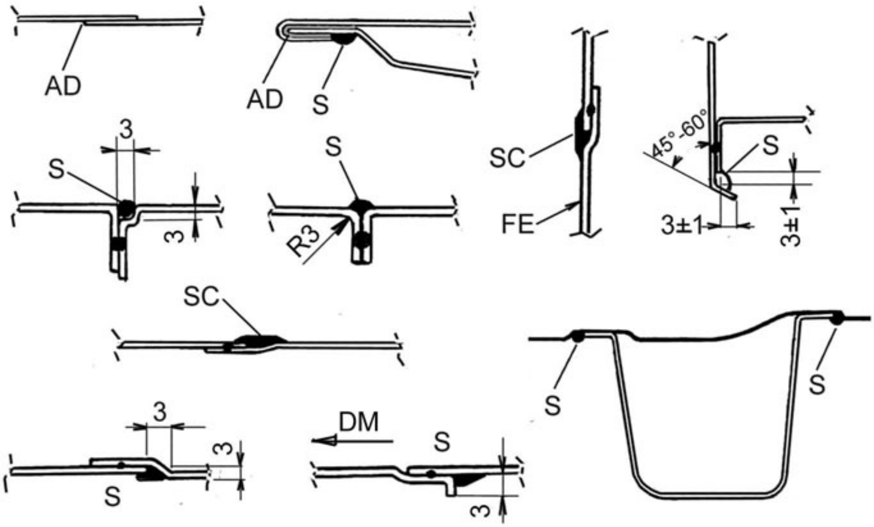


Fig. 4.42. Typical sealing solutions, suggested for different kind of joints. AD: adhesive; S: sealant; SC: extruded seal; FE: body side outer; DM: vehicle direction.

- Avoid weld seams or fusion welding of steel regions prone to humidity, because fusion welding destroys the zinc coating.
- Protect by plastic or rubber shields any body parts that may suffer abrasion from stones, for example such as the wheel houses (see chapter on *fenders*).
- Avoid direct contact between body parts while operating, for instance movable parts due to extreme opening or local deformation, that could give rise to abrasion on painted parts.

4.1.3 Materials and Technology

The most common processes and materials adopted for the bodywork belong to the following families:

- Steel sheet stamped in traditional press line and then assembled by spot welding, with additional seams of arc welding, brazing and possibly laser welding or fastened using self piercing rivets or by clinching. These assembling process, which can be either manual or partially/totally automated, are the most diffused and therefore have been widely tested, continuously improved and tuned and are also the most cost effective. The different steels used have also been subject to an evolutionary process over the last two decades in terms of the alloys, the lamination process and surface treatment techniques.

- Assembly of tubular or simple metal stamped elements (*space frame*), with bonded panels made from stratified fiberglass or *resin transfer molding* process (RTM) with injected resin or by *sheet molding compound* (SMC) of glass or carbon fiber prepreg, cured and hardened under pressure and heating. This process is mainly manual and used for low production rate and very high structural performance, particularly in terms of weight to stiffness ratio. Although investment levels may be limited, the cost of materials and labour are high.

- Assembly of macro elements injected in thermoplastic resin, locally reinforced with metal insert or reinforced thermosetting moldings, connected by rivets or screws and/or adhesives. Being a partially automated process, it is adopted by few models of low production rate, mainly with the purpose of demonstrating a new technology. The most critical aspect is achieving the required structural stiffness, due to low Young's modulus of thermoplastic components and to the medium modulus of reinforced thermoset components.

- Assembly of stamped aluminum sheets and/or *die cast* and/or *extruded* aluminum pieces, welded and glued or riveted with additional die cast nodes. This process offers an average or high level of automation, developed as an improvement or evolution of traditional sheet stamping and assembling inherited from processing steel. The main difference from the steel process is part integration by the specific property of aluminum manufacturing process. For instance, a *die cast* aluminum piece can integrate ribs and punched bosses and have variable thickness, that in a steel part would require additional brackets and reinforcements. Despite innovation effort and many applications, costs of bodies produced in this way still remain higher than traditional steel bodies, while total weight is much lower (up to 40% less than steel) and stiffness sometimes higher (Fig. 4.43).

- Assembly of *hydroformed* sheets and/or tubes by welding or riveting. This process can be quite automated; it has been tested on some model of low or medium production, in order to reduce investments in dies (sheet hydroforming) and assembling fixtures (tubular hydroforming). Performance and weight are similar to traditional steel bodies, but sometimes sheet deep drawing in a hydroforming press (that uses only a matrix or a punch – Fig. 4.44) can assist forming very difficult parts, even with undercuts.

Assembly process

The assembling process includes welding (resistance spot welding, arc welding, braze welding, brazing, laser welding), permanent cold fastening (riveting, clinching), chemical linking (bonding).

Spot welding creates a melted nugget common to both sheets due to the heat obtained from resistance to electric current flow through sheets held together under pressure by electrodes.

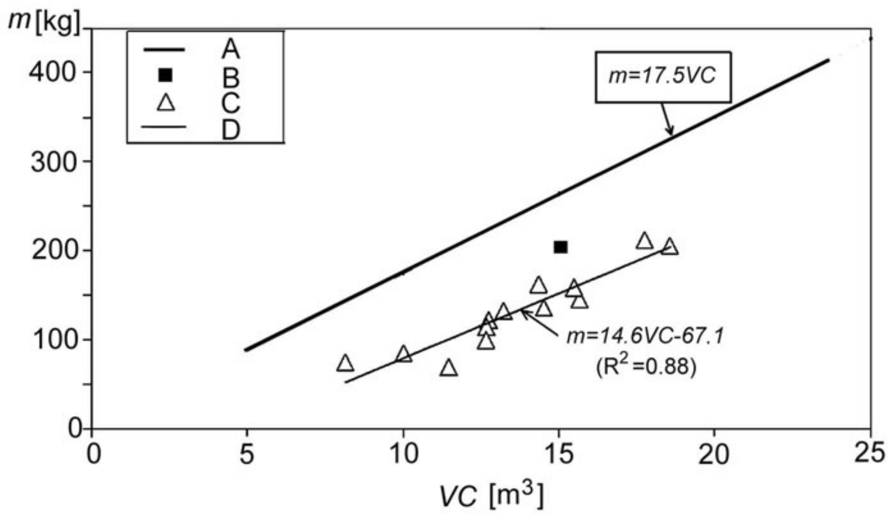


Fig. 4.43. Parametric comparison of body mass m in aluminum and steel, referred to body dimension VC (product of length times width square). Line A: interpolation of steel body masses; B: ULSAB prototype; C: aluminum bodies; line D: interpolation of aluminum bodies.

The spot can be *direct*, when generated by two opposite electrodes, operated by welding guns of various sizes, configurations and clamping modes (Fig. 4.45).

Instead, an *indirect* spot can be generated by an electrode pushed against only one side of sheet assembly, while a copper plate supports the opposite side, with the purpose of keeping the surface smooth, avoiding marks and puncture wounds, that could be present on the electrode nose side.

Roll welding is operated with two rollers or rotating electrodes, rotating as the seam welding is in progress, while the current flow frequency is controlled.

Arc welding uses an electric arc between one wire electrode and the surfaces to be welded, instead of current flow between electrodes, in order to melt a consumable wire in the joint; in the case of thin sheets, this process must be used in blind areas and only when no other joining process is possible, because this kind of welding is uneven and thermal impact can bring metal stresses. This kind of welding requires inert gas (helium or argon) envelope to be shielded from atmosphere, particularly in the case of aluminum.

Braze welding use as filler material a wire of non ferrous alloy with a melting point which is lower than plates to be joined; the result is a groove or fillet or plug weld.

Laser welding makes use of a *laser beam*, concentrated by a lens directly on the plates to be joined or on a braze wire, in order to generate the melting energy.

Cold assembling processes are increasingly sought after due to potential energy savings, investment reductions, reduced frequency of servicing and, specifically,

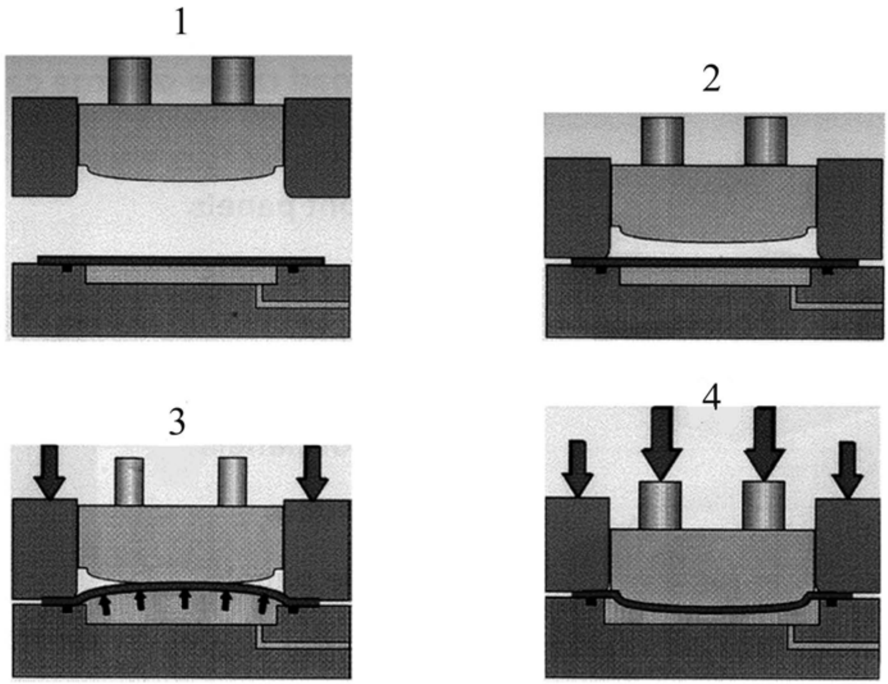


Fig. 4.44. Sheet hydroforming: blank positioning (1); blank holder closing (2); fluid pressurization (3); punch stroke (4).

the possibility of join non weldable materials with relative ease, for instance heterogeneous materials. Among the cold processes, *clinching* is the most efficient in terms of the materials required, since it does not require additional pieces needed, for instance, by *blind riveting* (Fig. 4.46).

Both riveting and clinching cannot be used on aesthetic surfaces; moreover, they should normally be operated by standing fixtures and only therefore on subassemblies.

Bonding is generally used as a complementary function to welding, for some sheet assembling, mainly in aluminum and in hem operations (as will be explained in the specific components chapters). Bonding is compulsory in structural plastic assembly (as composites) and in heterogeneous fittings that cannot be riveted, as with the windshield and the fitting of the back glass to the body.

Adhesives are usually in the form of semi-liquid paste or semi-solid tapes; they are extruded and their most common chemical families are *polyurethane* or *epoxy* resins. Adhesive curing requires time and accelerating factors such as humidity or temperature. When assembled parts must be moved and therefore there is a risk of relative sliding before paint baking, local heating and baking of joint is needed, for instance by *induction heating.* When designing glued parts,

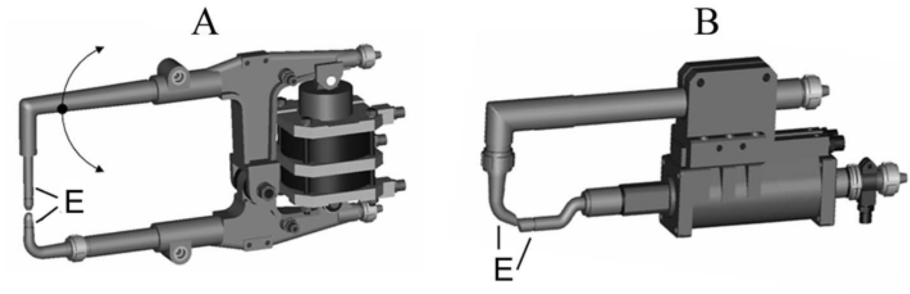


Fig. 4.45. A: X type spot welding gun; B: C type; E: electrodes.

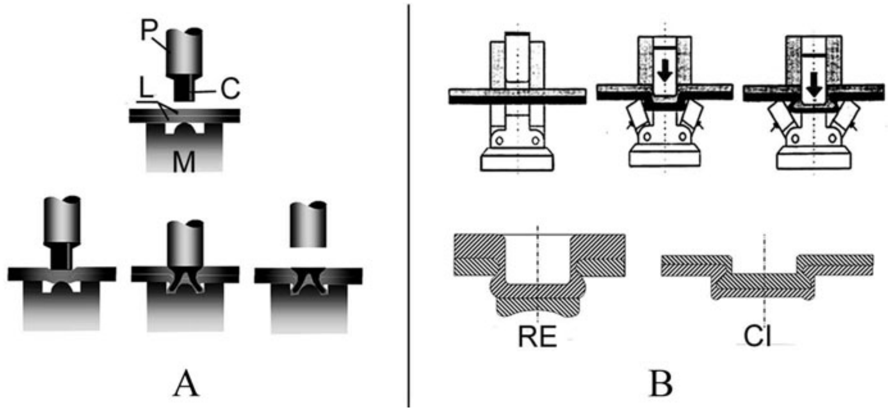


Fig. 4.46. A) Blind rivets fastening; P: punch; M: crank; C: rivet; L: sheets. B) Clinching with punch penetration and permanent deformation of sheets; CI: cylindrical; RE: rectangular.

it must be taken into account that the most critical stress condition is *peeling* or progressive separation of layers, starting from the free extremity. For this reason, it is always recommended to use a mechanical fastener (i.e. rivet or screw) at the edge of the bonded parts.

Painting

According to the selection of body materials, different automated painting process are available, including top coat (base+clear coating) curing in bake oven at 120 °C, or by adopting a two components coating baked at 90 °C (this choice being compulsory in case of combined thermoplastic and thermosetting materials). In the case of steel, before base coating and top clear coating, always required is cleaning and phosphating bath, followed by a cayaphoretic coating at 150 °C for 30 minutes, a primer coating and body sealing.

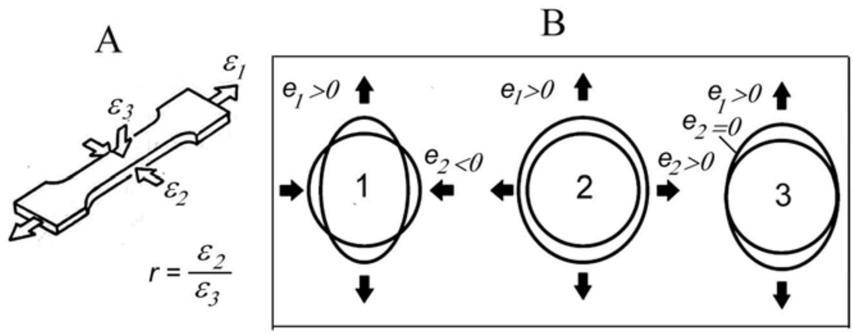


Fig. 4.47. A) typical strains in a specimen traction test and definition of r index. B) sheet forming strain modes: drawing (1); stretching (2); elongation only (3).

In the case of aluminum, cleaning and chrome coating are needed, whilst cataphoresis is not.

In the case of plastics, after cleaning it is possible to pass directly to an electroconductive primer spray and to top coating stages, when the same electrostatic spray gun as for steel is used. Plastic painting together with steel presents a degree of risk, not only due to bake temperature, since thermal expansion of plastic parts in curing process is ten times greater than steel; therefore sliding devices should be provided when fitting plastic to steel.

Hybrid solutions therefore require an accurate analysis of assembling process, to manage each material in the appropriate way.

Materials

Steel or aluminum sheets can be damaged even during manufacturing operations (stamping, assembling), depending on their mechanical and chemical properties. During the forming process, failure is a consequence of the sheet deforming technique: *stretching*, an isotropic elongation of sheet fibers and *drawing*, in which outer or inner fibers elongate in one direction and shrink in the opposite (Fig. 4.47).

For this reason, *formability* of sheets is assessed in relation to certain indicators, computed from a traction test and a set of drawing tests, in which loads, elongation and shrink are measured up to the specimen breaking. Indicators are: *anisotropy index* r, related to drawability (Fig. 4.47 – A) and *hardening coefficient* n, related to anelastic (plastic) deformation during the traction test. In detail, breaking risk while forming a piece is rated by comparison of stamping strain e_1 and e_2 in principal directions (e_1 and e_2 being elongation divided by original dimension in the respective directions) with corresponding strains measured on the specimens of same material and thickness, represented in a curve referred to as the *forming limit curve* FLC (Fig. 4.48 – A).

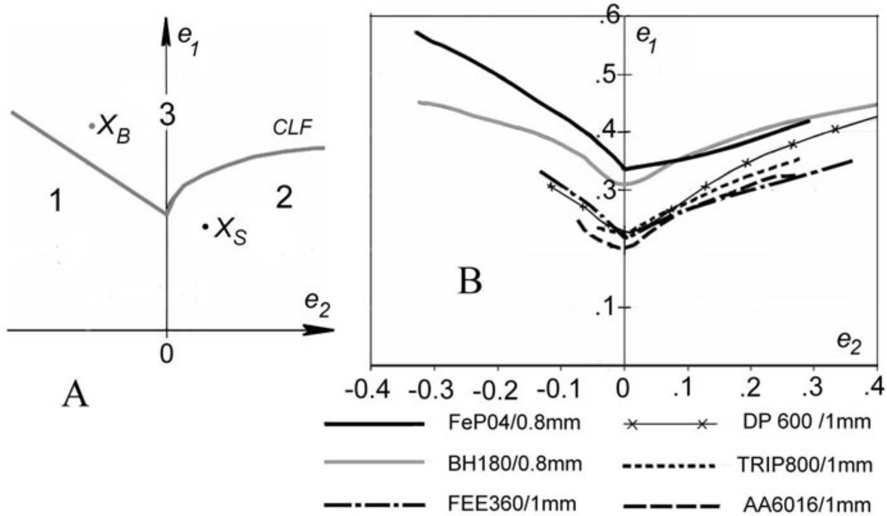


Fig. 4.48. A) example of forming limit curve; B) comparison among experimental FLC of steel and aluminum grades and thicknesses.

In this figure, the regions below CLF are risk free (for example, point x_S), respectively in drawing region (quadrant 1) and stretching region (quadrant 2). Instead, regions above CLF are risky (quadrant 3) as in the case of point x_B.

In Fig 4.48, table B compares examples of limit forming curves obtained by testing different materials.

Another property that makes a difference among draw sheets is *spring back*, which relates to the capacity of fibers not yet collapsed in drawing to return to their original shape following release of the forming load. This effect is more relevant as material yield strength increases, but can be tackled, within limits, by increasing fiber stretching through blank holder loading in a *double crank press* (a press in which punch and blank holder are both movable). The test that enables to rate the spring back property of a material consists of forming a number of the same Ω profiles with increasing blank holder loads, measuring the final configuration of profile wings or permanent deflection of wing edges after forming (Fig. 4.49).

At this stage it is appropriate to review the most commonly used materials.

Steel sheets

Traditional iron sheet alloy has an extremely low carbon content (from 0.02 to 0.08 %), very low controlled quantity of phosphorus, sulphur and manganese and potentially up to 0.3% of titanium, defining the deep drawing capacity, elongation at break above 40% and limited thinning (r index $\geqq 1.8$).

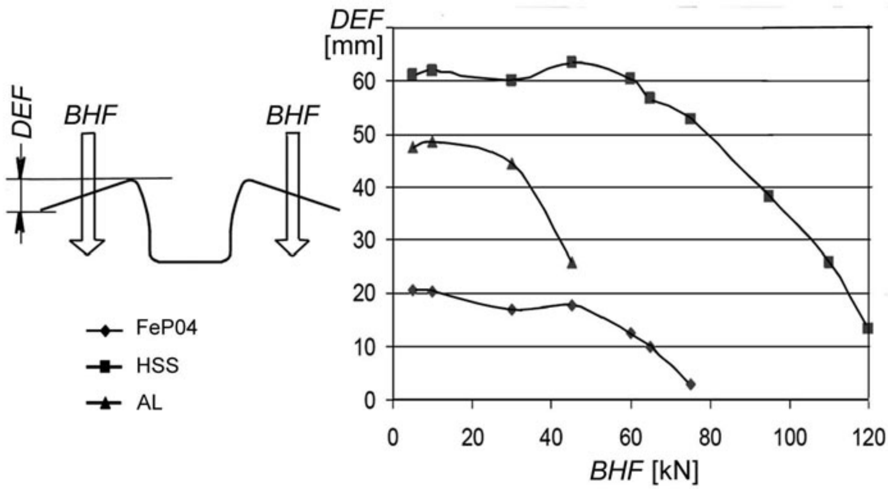


Fig. 4.49. Influence of blank holder force *BHF* on spring back *DEF* of specimen made with two steel grades and one aluminum, U shaped by drawing. On left side, a section explaining how the specimen appears out of the die.

No other material exhibits similar deep drawing properties. After forming, parts appear perfectly smooth and do not require manual finishing. Bending at 180 degrees and welding, both spot- and wire-welding, can be applied without major problems. Gauges used in body start from 0.60 mm and rise up to 2.0 mm and more, for structural non visible parts.

The main drawback is weight (mass is 7.8 kg per square meter of sheet gauge 1.0 mm) and, secondly, dent strength when the thickness is less than 0.80 mm.

Furthermore, the problem of easy corrosion can be considered to have been overcome, as steel automotive sheets are generally zinc coated or galvanized on both sides during the rolling mill process. Over recent years, body designers have been forced to face two additional problems, influencing steel makers research and innovation toward new steel grades. The first was safety strength, that could be resolved with traditional steel only by increasing sheet thickness and therefore weight. The second is fuel consumption and hence air pollution, directly influenced by the weight.

No steel sheet gauge can be thinner in practice than 0.6÷0.7 mm, for reasons of both thinning and breaking during forming and as concerns elastic instability and dent weakness (referring to outer panels). Therefore, body weight could be reduced only by selecting the thinnest sheet possible, consistent with dent and safety strength. In practice, designers needed to be provided with a choice of increased yield steel, without losing traditional drawing capacity. In this context, considerable innovation by steel makers over recent years must be acknowledged, as a wide choice of steel grades with a large range of yield strength and break

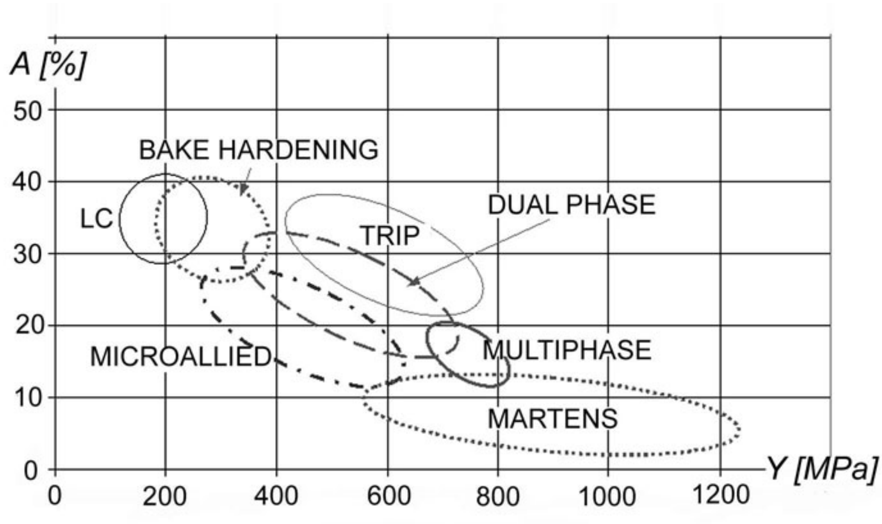


Fig. 4.50. Properties of major steel grade families used for bodies over recent years. Y: yield strength; A: elongation at break.

elongation has been made available, which are capable of satisfy a range of different requirements (Fig. 4.50).

Some of these steel grades (*Dual Phase* and *Multiphase*) have the property of changing their ductility as a consequence of plasticity during the forming stage and following hot curing in the painting oven, meaning they are sufficiently drawable in the stamping stage but then increase hardness and yield strength when the body is painted.

In order to illustrate the application of different steel grades available so as to save body weight, an international consortium of steel makers has promoted a study and the application of new technologies, resulting in a series of prototypes, named *ULSAB* (Fig. 4.51).

Table 4.1 summarizes the mechanical and forming properties of some steel grades used on ULSAB-AVC prototypes.

Aluminum sheets

The main advantage of aluminum over zinc coated steel is the lower specific mass to reduce parts weight, since the yield strength of aluminum alloys is not so much lower than most steel grade today in use.

Traditionally, the performance equivalence between steel sheets and aluminum sheets was rated in terms of the bending stiffness of a plate and therefore was established by elastic modulus ratio, in favour of steel with a factor of approx. 3. Since the plate bending stiffness is related to the third power of gauge, in order to obtain a stiffness equivalence, the required increase of aluminum thickness should be cubic root of 3 or approximately 1.43. Usually in practice, to replace

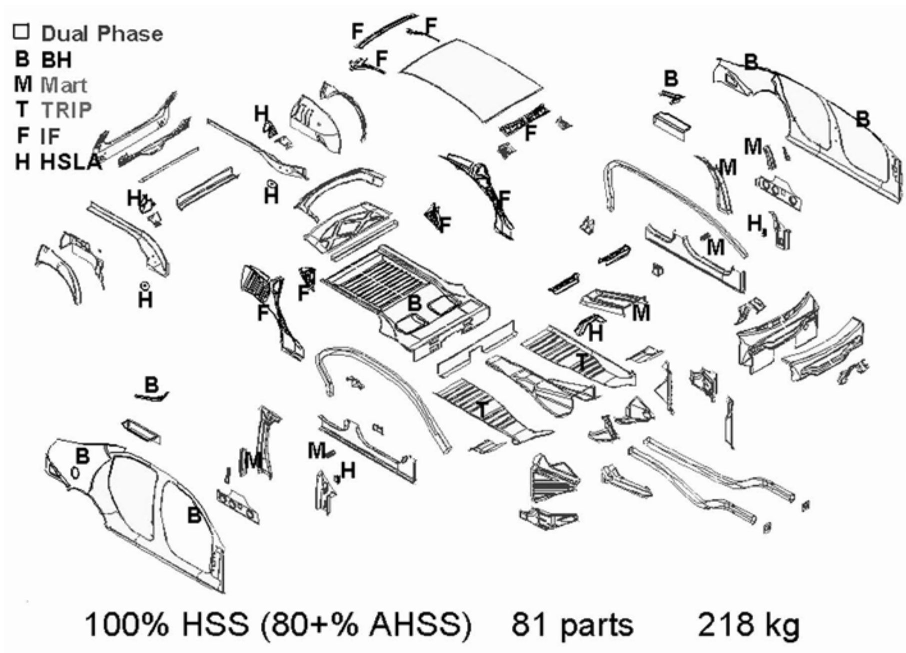


Fig. 4.51. In the ULSAB prototype body parts, the steel families shown in the picture have been used.

a sheet steel 0.8 mm thick, a 1.2 aluminum sheet has been used, offering the additional advantage of an easier manual grinding operation, if required both after stamping or following the assembling process. With such a substitution, the theoretical weight saving should be approximately 45%. If, on the other hand, the stiffness in the elastic range can be considered to be less problematic than, for instance, the dent or yield strength, the consequence is that a steel sheet can be replaced by an aluminum one that has the same product thickness times yield strength, as already explained in paragraph on *structural body function.* In some models, advantage has been made of this property by substituting movable steel parts with aluminum ones (Fig. 4.52).

Regarding formability, aluminum sheets are usually less drawable than steel providing the same yield strength; moreover, lower surface hardness makes aluminum more susceptable to swarf damage. This is another concern regarding hybrid manufacturing (aluminum & steel) in the same body plant, which has been overcome by protecting aluminum sheets with a plastic film, even during stamping. Aluminum welding also is more critical, since it requires an inert gas environment to avoid oxidization. Where possible, riveting with self punching blind rivets or clinching or bonding combined with riveting are to be preferred.

Some aluminum grades, especially of 2000 and 6000 series, exhibit aging characteristics, becoming harder after annealing and stamping, particularly when

Table 4.1. Properties of steel sheets used in prototypes ULSAB-AVC.

Steel Grade	σ_y(MPa)	σ_r(MPa)	A(%)	n	r	Code
BH 210/340	210	340	34-39	0,23	1,8	B
BH 260/370	260	370	29-34	0,18	1,6	B
IF 260/410	260	410	34-38	0,13	1,7	C
DP 280/600	280	600	30-34	0,20	1,0	B
IF 300/420	300	420	29-36	0,21	1,6	B
HSLA350/450	350	450	23-27	0,16	1,0	A,B
DP 400/700	400	700	19-25	0,14	1,0	A,B
TRIP 450/800	450	800	26-32	0,14	0,9	A,B
CP 700/800	700	800	10-15	0,08	1,0	B
DP 700/1000	700	1000	12-17	0,13	0,9	B
Mart 950/1200	950	1200	5-7	0,09	0,9	A,B
Code: A) ancillary parts; B) body structure; C) closures						
Note: Flat sheet, as shipped ; σ_y and σ_r are minimum values						

heated and stabilized simply by paint oven baking (process known as *artificial aging*), therefore increasing their yield strength. As concerns cost, melting of minerals needed for an aluminum alloy requires approximately twice the energy needed by unit mass and, despite the weight saving, the overall economic balance is still in favour of steel.

Aluminum die casting

These components are only used in some aluminum bodies, for those subassemblies (i.e. A pillar) that benefit significantly from replacing a number of sheet pieces by a single die cast piece. In fact, die cast aluminum can be designed with local thickness variation and therefore without brackets or reinforcements. Assembling of die cast pieces with other aluminum parts can be made using bonding or welding.

The lowest die cast thickness can be close to 2.5 mm and therefore parts are still lighter than steel.

In some cases, these pieces have been obtained by magnesium alloy die casting: the specific mass of magnesium is lower than aluminum (1.8 and 2.8 respectively) and the thickness could be reduced to 1.5 mm.

Aluminum extrusion

Extrusion can be used for linear or curved constant section profiles, usually boxed and particularly effective to face bending with defined and constant load direction. In fact, sections can be designed with thickness variation point by point and material can be added in areas that give the higher contribution to inertial properties.

A wide range of alloys is available, proving the opportunity to select strength grades appropriately. The main advantage of these parts is the saving on

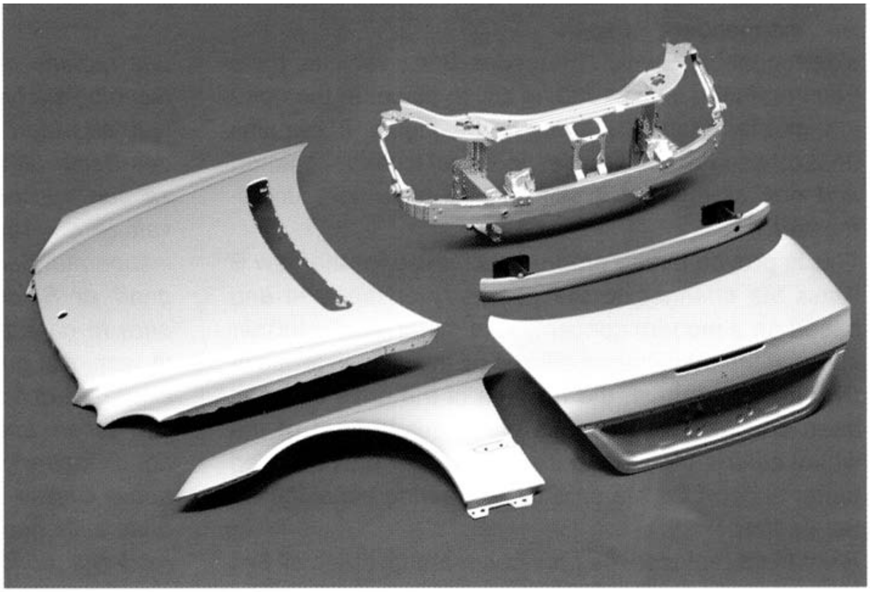


Fig. 4.52. Examples of Mercedes E aluminum panels and frames.

investments, because the only specific tool needed for each section is the extrusion matrix.

Structural plastics

Only composites suitable to replace steel or aluminum parts for structural goals (stiffness, strength, crash absorption) can be considered *structural plastics*. These composites should therefore have Young's modulus and ultimate strength not lower than aluminum. In practice today only carbon fiber composites can reach the required values and in this case they can be used for panels as well as for frames.

The average mass density of these components is between 1.4 and 1.8 kg/dm^3, meaning the potential for weight saving is very high when compared to steel and still of interest when compared to aluminum, even though the minimum thickness recommended for this kind of application is 1.2 mm. The Young's modulus can rise to 150 GPa, falling in between steel and aluminum.

Assembling of composite parts, after steam curing, is usually made by bonding with structural adhesives such as epoxy resins. The cost of such components is still only acceptable for niche, extreme performance vehicles.

A family of composites adopted for mean production vehicles is that of *SMC* (*Sheet Molding Compound*), mostly for outer panels or movable parts (hood, door, fender, decklid, liftgate). Such composites incorporate impregnated patches in vinylester or polyester, reinforced by random glass fiber of small/medium length and sometimes by long continuous glass fiber, cut and laid down in the open die, then stamped under pressure and temperature close to 120 °C (the curing time in the die about 30 seconds per millimeter thickness). Minimum thickness is 2.0 mm for non visible parts, while usually it is difficult to accept less than 4.0 mm for outer panels. The average density is between 1.5 and 2.0 kg/dm3. The Young's modulus, depending on glass fiber percentage, is between 10 and 20 GPa.

Usually, a SMC part weighs at least 90% of the corresponding steel part, although sometimes it can replace more than a single steel piece, integrating their functions.

The main problem is that of surface appearance quality, which is the primary aim for all outer panels, since these composites, if reheated after stamping at a temperature higher than that used during curing, tend to eject gases through very small holes, that remain open and visible after painting. In order to minimize scraps, it is first necessary to coat the piece in the die with an *in-mold-coating* and ensure that the bake temperature during all painting stages is maintained lower than the die curing temperature. The cost of a SMC component can be kept at the level of steel only for very low production volumes, thanks to the die investment advantage, because material and manufacturing process are generally more expensive than for steel.

Another composite family for small production is obtained by the *RTM* (*Resin Transfer Molding*) process, which uses a preformed light fiber cloth, inserted in the die as a core and then injected at medium pressure with thermosetting resin (for instance, glass reinforced polyester) while the die is closed (Fig. 4.53).

The resulting piece is light and stiff, thanks to its sandwich structure and can be used for outer panels of movable parts. As regards painting, the same problems as with SMC arise, while the overall costs are comparable.

As regards reinforced thermoplastics, their Young's modulus is much lower than 10 GPa and therefore they can be recommended for deformable components, such as bumpers and wings, but not for structural body parts.

Some technological constraints affecting aesthetics

During style modeling and pre-engineering, body is divided conceptually into macro elements, each being not only paired with the preferred material but also designed with regard to boundary configurations, mainly angles and curved connection fillets: at this stage, technological constraints and manufacturing opportunities are sometimes in conflict with the styling targets.

Some general rules, relating to the manufacturing process constraints are listed here.

- All outer panels, stamped by sheets, should have a main curvature radius not larger than 2,000 mm, in order to avoid sheet pumping and visible surface waves. The risk of flat regions and pumping increases with the yield strength of the sheet.

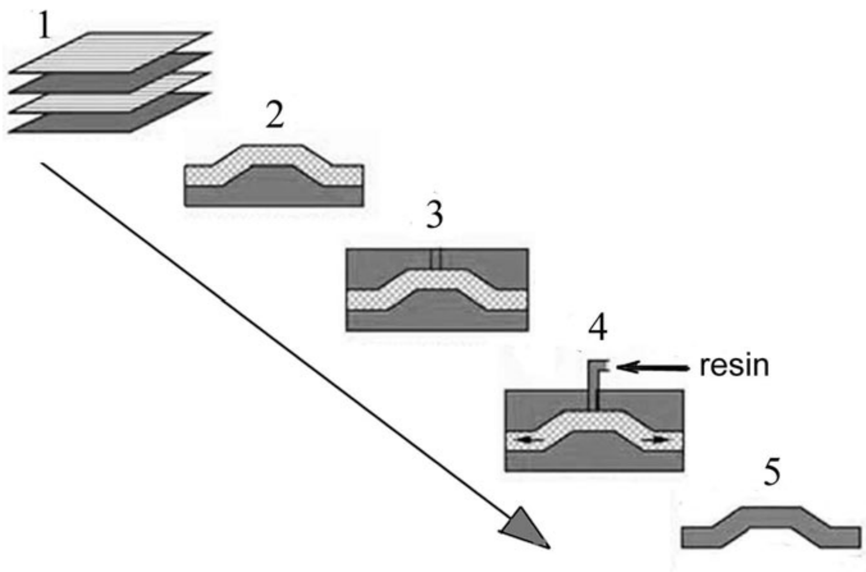


Fig. 4.53. Resin Transfer Molding: 1) insert layers feeding; 2) insert preforming; 3) die closing; 4) low pressure injection and reaction process; 5) stamped piece.

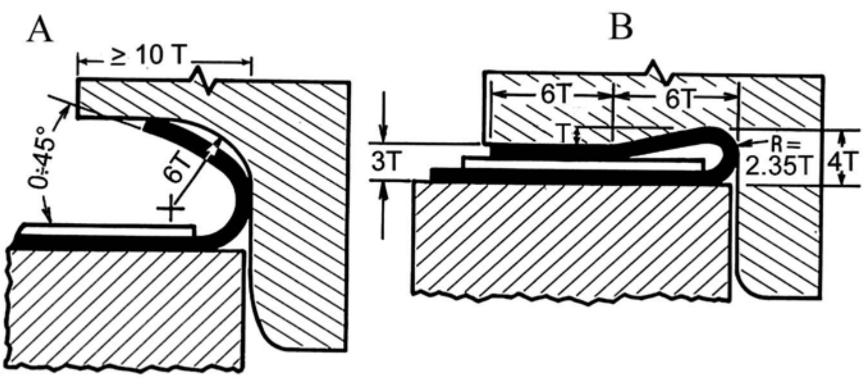


Fig. 4.54. Dimensional rules for aluminum 2000 and 6000 hem tool design, to avoid cracks while hemming: preform hem operation (A); final hem operation (B).

- The edges of sheet stamped parts should not have angles less than 60° between concurrent sides, in order to leave *hemming* or at least a downflange of a 3 mm lip.
- The same angles should have a radius of at least 7 mm, to leave hemming of a minimum 6 mm flange.
- Out of the connection area, hem flange should be at least 8 mm wide.
- Hemming of aluminum sheets should have a toric outside radius of at least 2.35 times sheet thickness (Fig. 4.54), to avoid cracks during the flanging operation, while steel sheets can be bent with outside radius of 1.5 times thickness.
- Flange needed for spot welding of 5 to 6 mm core, should normally be at least 12 mm wide; if L [mm] is the flange width and s [mm] the gauge of thinner sheet, the following should hold true:

$$L \geqslant 5s + 3 \tag{4.13}$$

- Moreover, the edge of a welded lap should always be further than L_0 [mm] from the spot center, where:

$$L_0 \geqslant 2s + 2 \tag{4.14}$$

- Windshield and back glass should be always designed to be recessed at least 3 mm from the panels surface, in order to avoid that in some position, due to tolerance superposition, there is glass overhang.
- All play and gaps between movable parts or between movable parts and fixed inner parts should be designed with a sheet step in order to hide underlying parts (*masked gap* – Fig. 4.69).
- Spot welds should have a minimum spacing $d_0 \geqq 13s{+}4$ [mm], where s is the gauge of thinner sheet.

4.1.4 Specifications and Delivery Tests

Assembly drawings include specifications regarding gaps among panels and related dimensional tolerances, reference holes for assembling fixtures and quality control data. Performance targets are listed in the delivery specifications, while regulations constraints are listed in homologation specifications.

International regulations are summarized in Volume II and include both geometrical and performance targets. Among dimensional body legal constraints, it must be remembered that the radius of outer panels should be at least 2.5 mm, the allowed visibility obstruction front and rear is stated in terms of wiped area, mirrors visibility area, lighting and licence plate position setting.

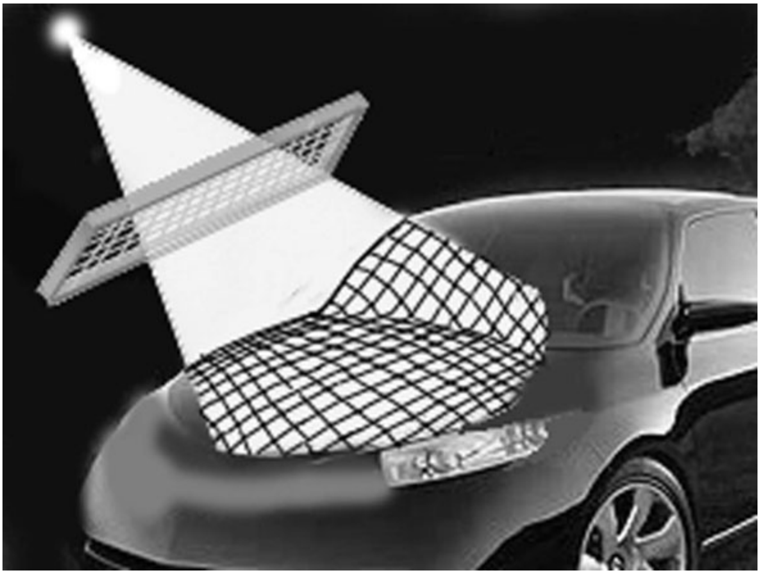


Fig. 4.55. By projecting conic or parallel light rays onto a body through a grid of straight wires, surface unevenness can be detected.

Among the performance targets required by law, the crash test behaviour and the strength of roof, doors, locks, seats and safety belts anchorages are strongly related to body design. Apart from the regulations some performance target exist which are defined in terms of consumer rating and therefore effectively mandatory for commercial reasons: pedestrian impact, insurance impact, movable part resistance to effraction.

Moreover, every car manufacturer has their own list of delivery tests, generally performed according to standard delivery test specifications, as for example:

- Body panels surface quality: the presence of waves and unevenness can be detected simply by projecting a light through a grid of straight wires (Fig. 4.55).
- Static stiffness in torsion and bending, movable parts openings stiffness, inertance of powertrain and suspension attachment, door vertical and horizontal yelding.
- Dynamic stiffness: first torsion and first bending resonance modes.
- Aerodynamic properties: drag, lift, pitching moment and yaw moment coefficients; noise spectra in the passenger compartment at 80 and 120 km/h.
- Fatigue strength: body endurance on paved simulated road and underbody durability rig.
- Accelerated reliability test in climatic chamber with paved road input.

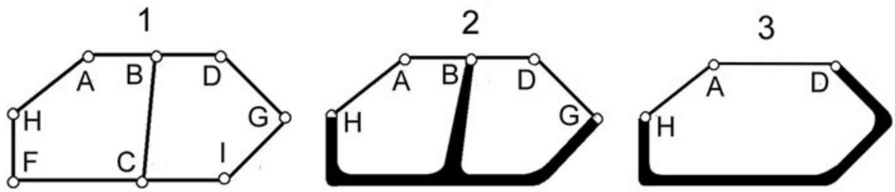


Fig. 4.56. The body side of a 5 door car can be analyzed as a structure with 8 hinges connected by 9 beams (1); some hinges can be replaced by extremely stiff nodes and only 5 hinges (2); or only 3 hinges in case of pillarless body (3).

- Door opening and closing loads, locks noise.
- Corrosion resistance in humidostatic chamber and special tracks.
- Aging and environmental resistance of plastic and rubber components.
- Hail and stone denting resistance of outer panels.
- Roof crushing under distributed load (snow) and local load (roof rack).

4.2 Body Side

The body passenger compartment can usually be conceived to be a box surrounded by six main walls with frame in wall intersections and more precisely a floor, a roof, two side walls, named body sides, a firewall or dash panel, a rear bulkhead. The latter is always missing in SW and SUV, and is occasionally lacking or limited in sedan cars.

The body side is a lean ring frame, empty in the middle and therefore subject to shear stresses in the wall plane, as a consequence of roof to floor or firewall to bulkhead sliding.

The body side is loaded by static and dynamic loads concentrated on doors hinges and latches, by distributed dynamic inertia forces while driving and by pulse loads on certain areas in the event of impact. Body side perimeter elements, as individual components of a unitized structure, should therefore be sized in bending and torsion, especially close to nodes.

In a typical side frame, eight main nodes can be identified (Fig. 4.56). The most relevant stresses on side frame assembly arise from body torsion (Fig. 4.57 – A) and from crashes, mainly frontal (Fig. 4.57 – B) and side crash. At least four of the eight nodes include roof and floor crossmembers connections between body sides: the stiffness of these nodes is a priority in order to achieve adequate torsional stiffness and impact protection (Fig. 4.57 – C). Moreover, at latches and hinges fitting positions, adequate reinforcing brackets are welded.

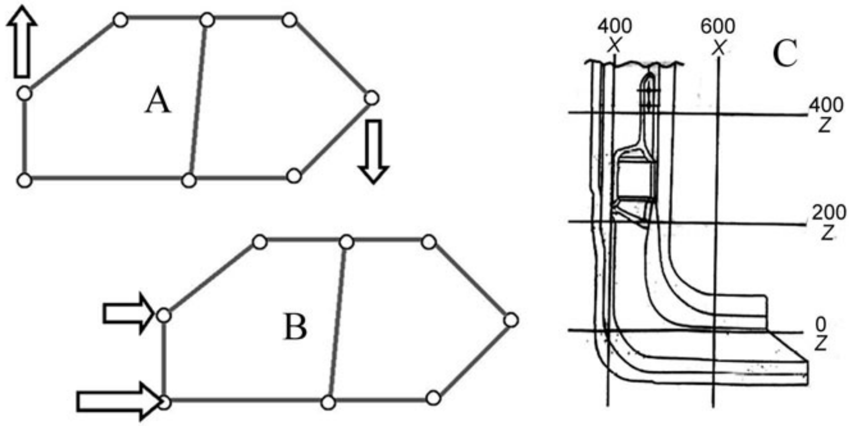


Fig. 4.57. A) Main loads on body side in body torsion; B) loads applied to body side by front crash; C) example of side frame reinforcement for D node.

Access to the passenger compartment is consistent with a size increase of nodes F-C-I (Fig. 4.56) and related beams only. As a consequence, the weaker part of body side is the upper one, particularly between nodes H and D. These members are usually reinforced by an inner diaphragm of adequate thickness and high strength plate. A similar weakness condition is present in the pillarless body side (Fig. 4.56 – 3), a countermeasure being to stiffen as much as possible the whole rear pillar or quarter to the D node.

As concerns material selection, since they have to be strong and stiff as well, the main candidates are steel plates with adequate properties or aluminum assemblies (made by different alloys and processes such as stamping, extrusion, rolling or die casting) or in few cases carbon fiber reinforced moldings.

4.2.1 Body Side Setting

In order to understand how design relates to the above listed problems, we can start by considering a typical saloon body side setting. The main parts included in most body side assembly, with reference to Fig. 4.58, are:

1. body side outer (from 0.7 to 0.9 mm thick – steel grade FEP04 – FEP05),
2. front pillar reinforcement (from 1.0 mm FEE220BH to 1.6 FEP04),
3. central pillar reinforcement (from 1.2 mm FE600DP to 2.0 FEP04),
4. central pillar boxing (from 0.7 to 1.5 mm FEE220BH),
5. quarter panel assy (from 0.75 to 0.9 mm FEP04),

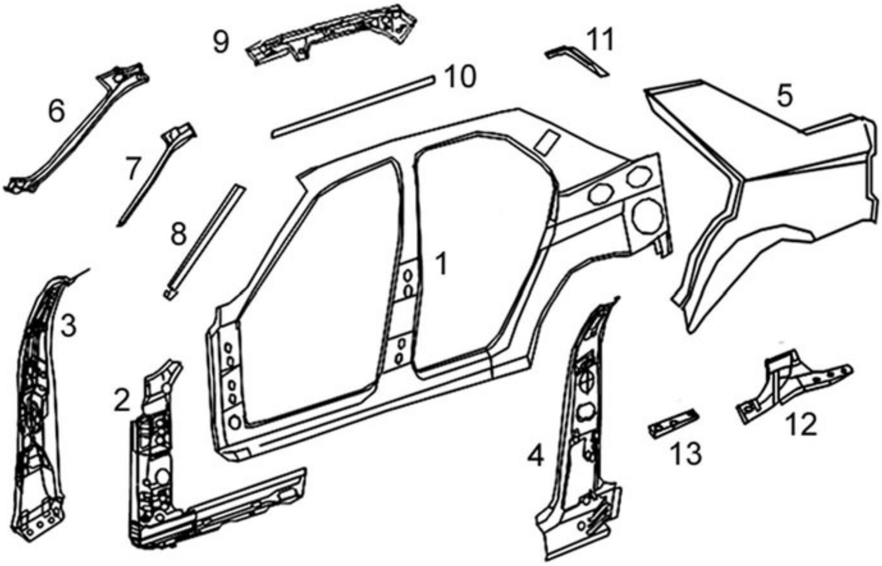


Fig. 4.58. Split view of main body side elements.

6. windshield pillar box (from 1 mm FEE220BH to 2.0 FEP04),
7. windshield pillar reinforcement (from 0.8 mm FEP04 to 1.2 mm FEE355),
8. front pillar rail (from 0.8 to 1.2 mm FEP04),
9. roof rail box (from 0.8 to 1.5 mm FEP04 or 1.0 mm FE600DP),
10. roof rail (from 0.8 to 1.2 mm FEP04),
11. rear pillar rail (from 0.8 to1.2 mm FEP04),
12. rear side brace (from 0.8 to 1.5 mm FEP04),
13. reinforcement plate (from 1.5 mm FEE355 to 2.5 mm FEP02).

(Where: FEP are low carbon deep drawing steel parts, FEE high yield strength steel, BH means bake hardening, DP dual phase).

Sometimes a quarter boxing frame is present, the inner wheel house (when not included in underbody assembly) and some local reinforcements for safety belt anchorages, hinges and latches attachment.

In summary, the body side assembly is made of an outer panel (better visible with the doors open) defined by body side styling and door shapes; an inner panel (box or rail) completely covered by internal trim, defined mainly by structural analysis and designed to static and dynamic stress, complete with holes, slots, insert, brackets; intermediate members (diaphragm or reinforcement), coupled with the box in higher stress area. The quarter panel is a complementary panel, with main aesthetic function, conditioned by dent risk and completed with pre-assembled parts such as the liftgate weather strip channel, fuel filler housing and rear lights housing.

The body side outer, sometimes also including quarter panel, can be stamped from one blank or divided into 5 members (front, center and rear pillar, side sill, roof rail) assembled in a single assembly jig, where also reinforcements, boxes and brackets can be welded.

If we compare both body side design solutions, i.e. the unitized with the split, the latter has the following advantages:

- individual die cost,
- sheet use efficiency (less scrap),
- stamping quality of individual members before assembling,
- availability of members for different bodies (standardization),
- materials and thickness selection related to need .

Instead the following aspects favour the unitized body side:

- lower number of dies,
- lower number of parts to manage and assemble,
- lower overall investments for stamping and assembling,
- lower manufacturing cost, principally when there is no braze welding and following finishing of quarter panel to body side assembly,
- weather strips seats (usually metal flanges) continuity, absence of steps and therefore better insulation,
- uniform thickness in outer & inner panels joint,
- lower influence of assembling tolerances,
- no visible junction.

In any case, for unitized body side as well as for body split side frame, significant innovation has been required to overcome the reduced thickness and sheet grade adaptation to local performance need: this is the *tailored blank* process, consisting in a laser or a mash resistance seam welding to assemble a number of different blanks before die drawing (Fig. tailor1).

The assembled blanks can be of different thicknesses and material grades; the stamped part coming out of the drawing process is apparently one single piece (blank welding overlap is usually positioned where it can be hidden) but its strength is differentiated zone by zone without needing additional reinforcement.

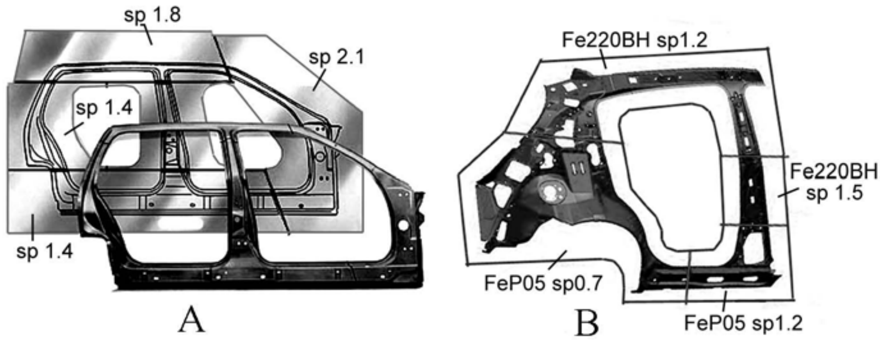


Fig. 4.59. Examples of body side tailored blanks: outer body side (A); inner rear body side (B).

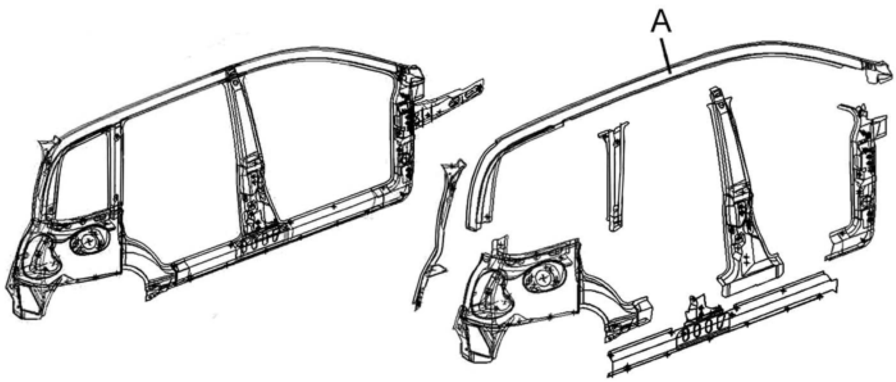


Fig. 4.60. Fiat Multipla body side is assembled from a number of stamped parts and rolled steel profiles (A).

Technology innovations

Moreover, in some multiple member split side frames, technologies offering investment reduction potential have been used, for example extrusion of aluminum profiles or rolling and stretch bending of steel sheet profiles, for a relevant part of the body side ring (see ULSAB body side or FIAT multipla – Fig. 4.60).

Also, new process have been adopted to weld members. In the traditional process, the sheet laps of outer elements and inner frame to be connected were spot welded: spacing among spots can vary point to point, in a range commonly included between 25 (minimum) and 75 mm.

In the new process, spot welding has been replaced by short laser welding seams: the advantage is lower waving, lower flange warping and less puncture wounds because of the lower thermal energy transmitted.

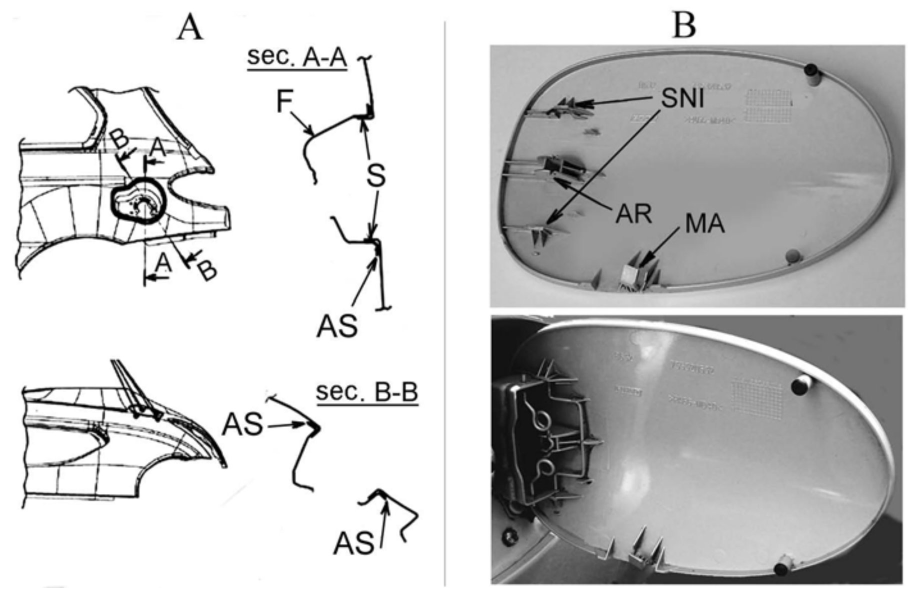


Fig. 4.61. A) Example of metal housing welded and bonded to quarter panel; F: housing bottom; S: spot welds; AS: structural adhesive. B) Example of thermoplastic (polyammide) filler flap, both free and fitted to body; SNI: hinge holes; AR: reaction spring clamp; MA: integral hook.

In some aluminum bodies, a lower number of spaced weld spots has been combined with continuous bonding of flanges with epoxy resins, resulting in a significant increase of joint stiffness.

Nevertheless, in some fitting positions of different parts with structural function, there is no way to spot weld sheet lips due to lack of flanges; therefore arc or laser welding seams or braze welding is needed.

4.2.2 Fuel Filler

The fuel filler housing is usually located in the body side, most commonly in the quarter panel. Due to its depth, the housing is normally drawn and trimmed, with insertion of a metal or composite plastic stamped bottom and covered by a door or flap, made by various materials and process (Fig. 4.61).

If the filler flap and the quarter panel are made of the same metal, they are spot welded in the quarter subassembly and sealed by a structural adhesive, cured seccessively in the painting bake oven. In the case of heterogeneous materials, spot welds are replaced by rivets or adhesives cured by a specific subassembly baking.

The filler door can be stamped out of steel or aluminum sheet, with perimeter downflange and trim or hem, or molded with thermoplastic or thermosetting

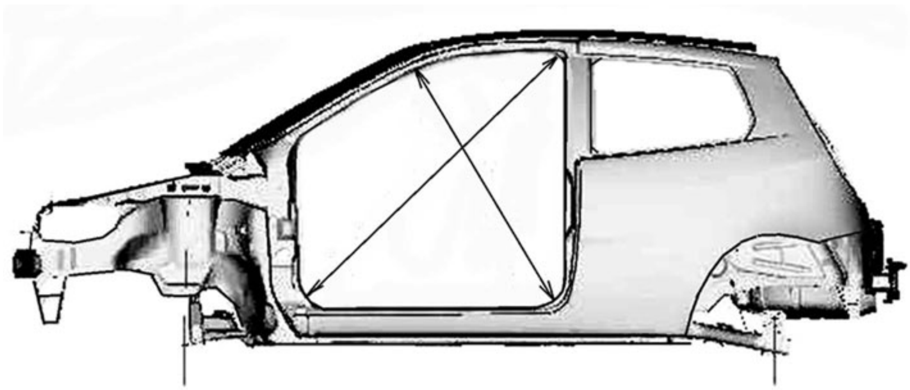


Fig. 4.62. The layout of dimensional measurement of door opening deformation in body torsion test.

resin: in this case, the design of hinges is critical and therefore the selected material should be sufficiently tough.

Thermoplastics do not allow the molding of thick ribs due to risk of sink marks on the door surface. Thermosetting flaps, on the other hand, lack toughness and are therefore relatively easy to break, especially with misuse.

4.2.3 Body Side Specifications

The critical design properties of the body side are:

- dimensional precision of door housing,
- stiffness of nodes and beams,
- resistance to concentrated loads on hinges, latches and belt anchorages,
- fatigue strength,
- impact resistance,
- air and water tightness.

The precision and stiffness of the door housing are major targets in order to ensure effectiveness of the body side weather strips and door operation for any vehicle attitude. A typical dimensional door opening tolerance is ± 1 mm, whilst the allowed diagonal length change in the torsion test is less than 1% (Fig. 4.62).

Node stiffness, obtained by appropriate parts matching and local reinforcements, is a primary objective in the first stage of body analysis: design data are available to preliminary select the archetypes required to achieve the body stiffness target. Among the most critical nodes affecting stiffness is node D (Fig. 4.56) particularly in two box cars with liftgate.

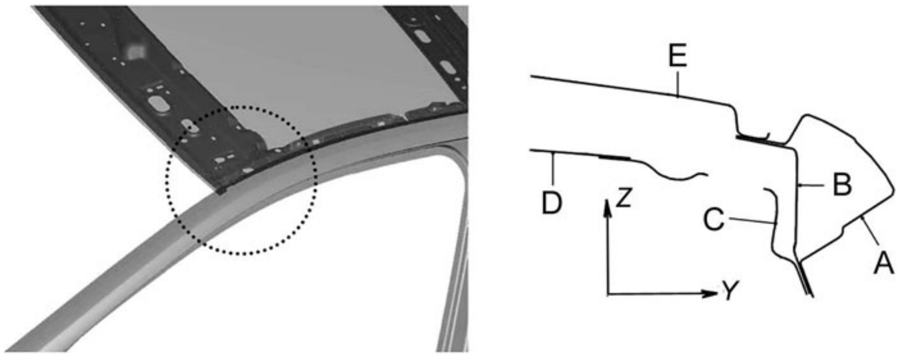


Fig. 4.63. Node A is the most conditioned by body openings and styling. E: roof panel; A: body side outer; B: roof rail; C: pillar boxing; D: front roof crossmember.

The usual way to deal with the concentrated loads of latches, hinges and safety belts is not only provide sheets of adequate thickness and yield strength, but also additional reinforcements welded to box parts with thickness often exceeding 2 mm.

During side impact, nodes B and C are the most stressed, whereas in frontal impact it is nodes F and A. The latter is the node most affected by dimensional constraints and therefore certain advantages can be obtained through contributory connection with the front roof crossmember (Fig. 4.63).

The most critical body side features as concerns fatigue behavior are the flange lips unions between the roof rail and central pillar and the door opening flange at node D. Occasionally fatigue cracks appear on the quarter panel near the belt line, due to the sharp section change from the lower quarter panel to the rear pillar, the small union radius and the high degree of panel stretching in drawing stage (Fig 4.64).

Computer analysis of fatigue stress cycles indicates where the main stresses are most likely and therefore enables the selection of materials, thickness and design to reduce shape overstress. Furthermore production variations influencing local gauge reduction, or increased notches or wrinkles can deviate to some extent from computed results. It is recommended, therefore, that a set of full body endurance test on fatigue bench be performed, using as input is a paved road time history; usually endurance tests are not performed on the free body side, because the test would give limited and less reliable results in the same amount of time.

Regarding the properties of individual body side parts, the primary contribution to the body stiffness is provided by sills, and the basic resistance to side impact by the central pillar. The sill section can be designed with some discretion, principally in Y direction, while central pillar is heavily affected by the

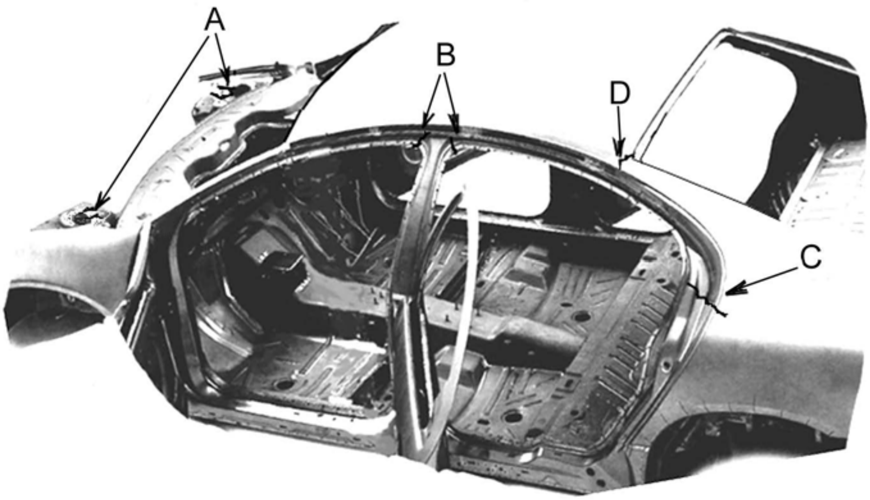


Fig. 4.64. A, B, C, D are the common fatigue crack initiation locations.

door styling, door cuts , ergonomy and the obstruction of the safety belt retractor, usually located in a hole in the lower part of the central pillar. As a consequence, sills width can be increased and sills gauge selected to be as thick as required, while preferably the central pillar is made from ultra high strength materials (for instance, *Dual Phase* steel) with appropriate thickness ($1.2 \div 1.5$ mm).

In Fig. 4.65 are displayed examples of sill section evolution with time for three following models of the the same size class made by a European car manufacturer. Section increase is mainly in Y direction, while thickness variation is limited resulting in a polar moment of inertia increasing 91% from model A (from the 1950s) to model B (1970s) and 45% from model B to C (1990s).

Regarding behavior of the central pillar during side impact, it should be borne in mind that homologation and rating tests use moving barriers with a uniform front crushable surface (aluminum honeycomb) and that the vehicle is impacted below the side belt line. Therefore, the central pillar performs as a bow, loaded in its lower part only, just leaning on or partially embedded at its extremities in crushable body parts. Then the pillar design should provide the lowest possible risk of collapsing at the belt line (despite a sharp section and stiffness change) and, more generally, should deliver outstanding stiffness in all sections, to avoid any crush other than at the crushable controlled extremities. In this case, stiffness does not refer simply to elastic behaviour but rather to permanent collapse; this is the reason why ultra high strength steel is commonly used for box parts and reinforcements.

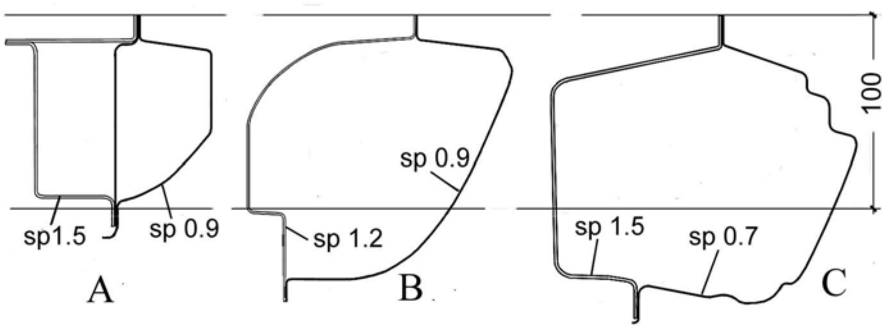


Fig. 4.65. Sill sections of three successive models of the same class and manufacturer.

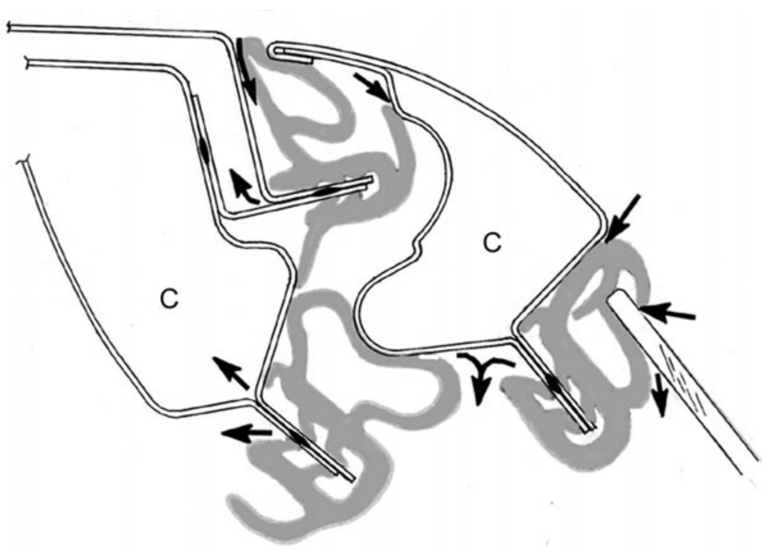


Fig. 4.66. Airborne noise passing through weather strips and roof, door sheets and door glasses and through sheet fastened flanges, can be transferred to the passenger compartment through channels (C) with turbulent flow.

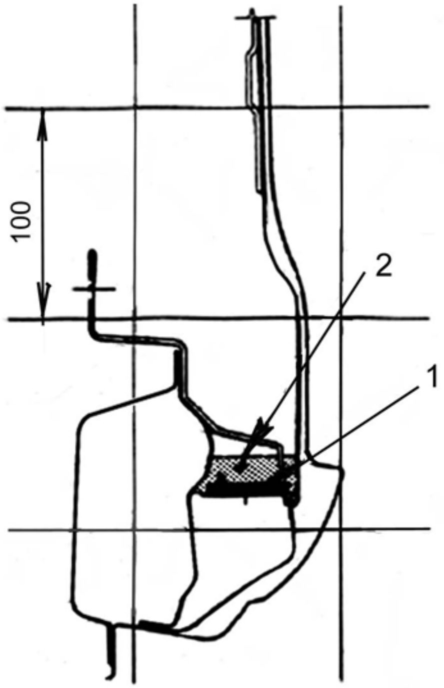


Fig. 4.67. Sealing by a thermo-expandable buffer positioned in node C: 1) start position of expandable diaphragm; 2) volume after expansion.

Regarding air and water ingress, the main area of risk is the roof to body side junction: one specific design solution shall be explained in roof and weather strip chapters (Fig. 4.66). Flange lips, where weather strips are fitted, should be free of waving, making hard weather strip insertion and toe sealing (therefore laser welded or bonded lips are better than spot welded) and without gaps or steps (as in split body side, not in unitized one and moreover between two boxing parts, mostly when the thickness is different). In the case of the split body side, it is therefore recommended to fill with braze and finish by grinding, gaps between contiguous sheets, in order to provide a continuous surface for the weather strips. Moreover, the flange of door openings should always be designed with a radius of 60 mm or more, to avoid wrinkles in weather strip bulbs. If this is not feasible, instead of having a continuous closed section, the weather strip should be molded in angle areas and therefore with an open side.

An often critical region for the transmission of rolling noise is the base of the central pillar, because the sections usually designed to provide embedding of the pillar in the sill and the belt retractor housing result in a hard to seal node. One solution consists of positioning a thermo-expandable buffer in white body side that later expands (while passing in the bake painting oven) to fill the contiguous cavity (Fig. 4.67).

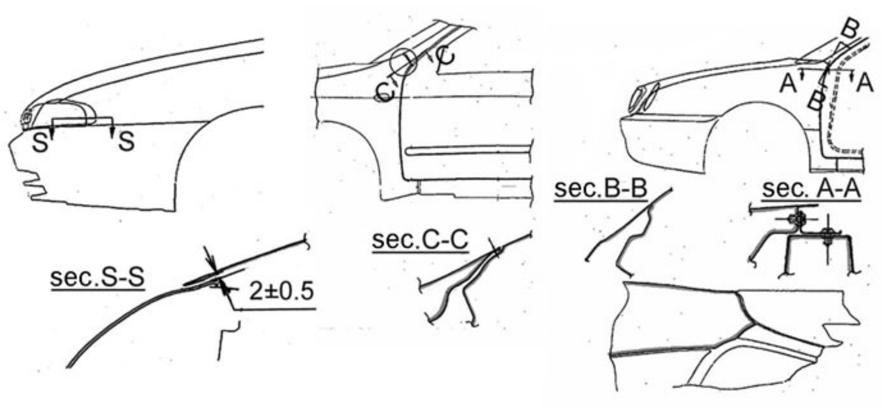


Fig. 4.68. Examples of matching zones between the front fenders and body parts.

4.3 Fenders

Today the main function of the fender is related to aesthetics and aerodynamics, however the first reason for their introduction was to shield wheels and protect passengers compartment from projection of water, mud and stones.

In comparison to the body frame, the structural contribution of fenders is zero with the exception of a few cases (mainly spiders) where the front fenders are welded to the body frame in order to increase the overall torsion stiffness. Usually front fenders are only screwed on, while on the rear (quarter panels) they are welded to the body side.

Metal front fenders commonly comprise few parts: a main drawn panel, a back completion flanged to main panel, the purpose of which is to seal the space between fender panel and lower front pillar, and some brackets to fit the fender to body and hold accessories.

Fig. 4.68 shows some typical fender to body fitting sections. Some fender properties are specified by manufacturers as standard such as: the fastening characteristics, the masked gap section, the fitting of interior *mudguards* (Fig. 4.69). In this figure, the free distance available for fender crushing under pedestrian impact should be, according to standard approximation, at least 80 mm in order to limit pedestrian head acceleration.

The main advantages of detachable front fenders are :

- the fitting process for movable parts can follow a longitudinal path, starting from quarter panel and ending with front fender; in this way, a degree of lack of precision in body side or doors can be recovered;
- fenders, mainly front, are frequently exposed to impact and damages: consequently the cost of repair is lower for fittings which are detachable;
- fenders can be made from a different material than the body.

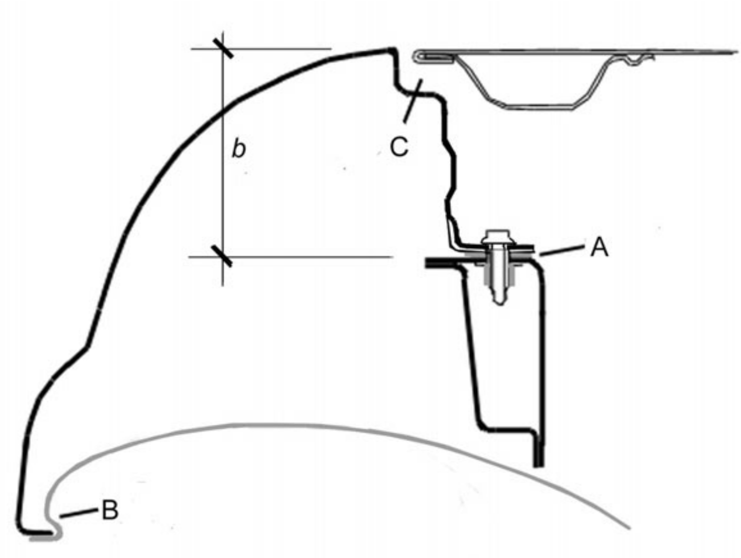


Fig. 4.69. An example of fender and wheel opening section. A: fastening with spacer, screw and riveted nut; B: lokari® fitting; C: masked gap; *b*: amount of deflection designed for pedestrian impact absorption.

As a result of the ease of denting fenders due to normal use conditions and the fact that the absence of structural requirements tends to promote the use of thinner gauges (even less than 0.7 mm in the case of steel sheets), these parts represent the most appropriate candidates for materials which are more flexible than steel, such as aluminum or plastics. Moreover, plastic moldings offer the advantage of integrating in a single shot, brackets and other ancillary parts, which would otherwise need to be welded, and thus compete with steel in terms of cost even for mass production.

In principle, the benefits of thermoplastic molded fenders with respect to steel are as follows:

- lower die cost,
- lower weight,
- higher flexibility, mainly an advantage with respect to pedestrian impact,
- removal of mudguards or at least lower area of wheel housing which needs to be protected against stone, sand, etc.;
- straightforward integration of brackets and completion panels,

Table 4.2. Steel versus plastic fenders.

PROPERTY	STEEL	PLASTIC	WHY
weight	-	+	plastic: - 50%
performance in small impact	-	+	% elastic strain
corrosion resistance	-	+	
stiffness	+	-	Young's modulus
dimensional stability	+	-	plastic creep
thermal expansion	+	-	plastic: + 400%
style freedom	-	+	die constraints
recycling	+	-	plastic degradation

- overall cost benefit for average and large production volumes.

Instead, the main disadvantages with respect to steel, are:

- the need to fit in the paint shop, before top coating,
- the need of a *conductive primer*, because of mounting after electrocoating,
- the need for body fitting devices which are consistent with different thermal deformations,
- the need for higher tolerances and therefore larger gaps,
- the need for dies with an outstanding surface quality, as the part comes out finished from molding,
- higher thermal deformation (approx. five times that of steel),
- higher influence of chemical and thermal agents on mechanical performance.

An overall comparison between material alternatives is presented in Table 4.2, where the plastic material is *Noryl GTX*®.

Fig. 4.70 shows an example of plastic fender, designed to cost to compete with steel.

The number, type and position of fender fasteners to the front frame are specified independently by each car maker: Fig. 4.71 shows one example.

The principal problems faced with fenders are linked to stone, sand and mud projections by wheels causing fender abrasion and annoying noise levels which can be perceived inside the cabin due to the high acoustic transparency of the metal walls over the relevant frequency range.

Before fenders were produced without zinc coating or other effective forms of protection, abrasion usually caused rust and corrosion perforation. Correspondingly, the main innovation that resolved the problem was the introduction of guards, usually called *lokari*® , consisting in a plastic shield located inside

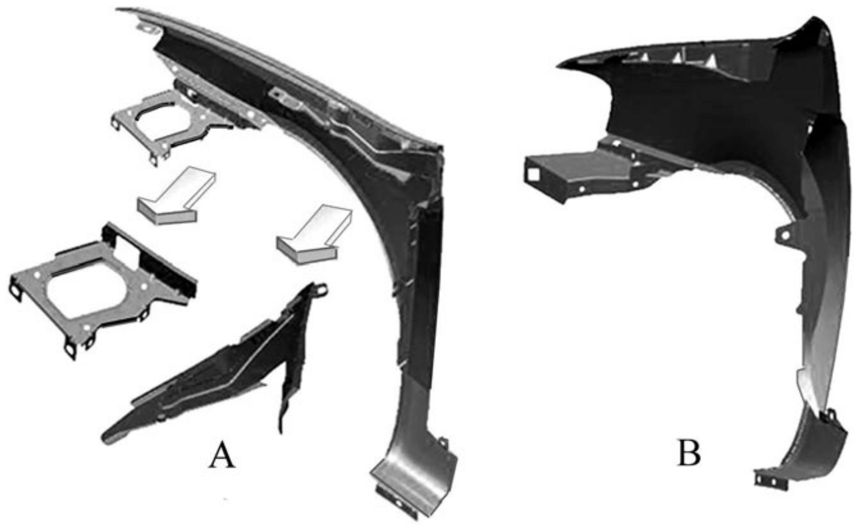


Fig. 4.70. A) steel fender, showing the additional pieces before assembling; B) plastic fender.

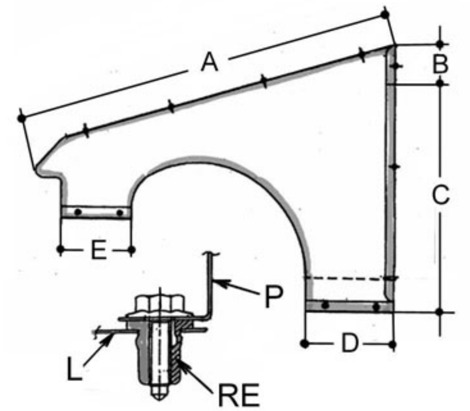
wheel housing, which are part snap-fitted and part riveted or screwed to the body, using plastic inserts.

Regarding noise transmission, the most problematic region is the rear wheel house and, of those tested, it has been found that an effective solution is to cover wheel house with a fiber carpet (*non woven fabrics*) that not only provides protection from abrasion, but offers a much higher absorption of sand, water and stone beating when compared to thermoformed plastic mudguards.

Referring to lokari® manufacturing, the most widely used technologies are:

- High pressure injected polypropylene (thickness not less than 1.8 mm): highly automated process, higher investment, lower manufacturing cost, heavier. This is the preferred solution among European car makers.
- Thermoformed polyethylene, vacuum formed thin sheet (thickness not less than 1 mm): partly automated process, enabling lower investments but higher manufacturing costs due to manual trimming and punching operations, lighter. This is the most common solution amongst Japanese car makers.

Fenders delivery includes dimensional regulation compliance (panel radius $\geqq$2.5 mm), pedestrian impact performance, dent resistance, salt and humidostatic chamber corrosion resistance. For plastic fenders, also paint adherence and environment aging must be verified. Mudguards should comply with chemical and environment resistance in the climatic chamber (typical for plastics) and



POS	N.
A	3 - 5
B	0 - 1
C	0 - 2
D	1 - 3
E	1 - 2

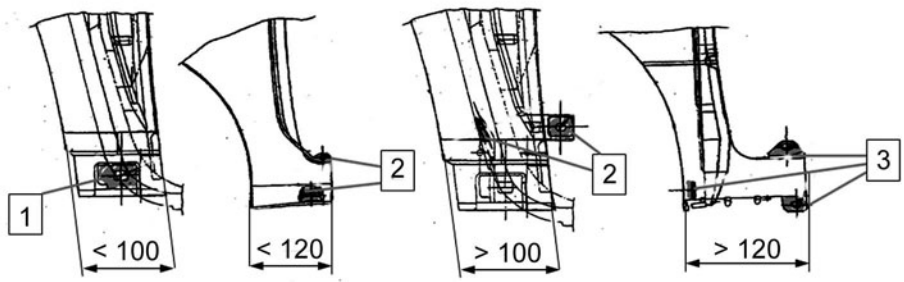


Fig. 4.71. Fiat specifications for position and number of front fenders fittings. P: fender; L: body surface; RE: rivet nut.

moreover should be verified during full body endurance testing, with regard to fenders and underbody protection from abrasion and noise absorption.

4.4 Roof Assembly

The conventional task of the roof panel is that of compartment shielding and connection of body sides, front and rear roof cross members. In the case of roll over, compartment integrity is provided by the compartment frames, whilst the roof target is only to avoid the ejection of passengers, providing protection against hard local contact (Fig. 4.72).

Correspondingly a wide selection of suitable materials is available: steel, aluminum, thermosetting plastic sheet, glass. In the case of steel grade FEP04, the usual thickness is in the range $0.70 \div 0.85$ mm. In all cases, any roof panel material requires braces to prevent panel flexing and vertical waviness, commonly known as *oil canning*: for this purpose light steel bows are introduced, which are welded or riveted or screwed to the body side and bonded to roof panel by

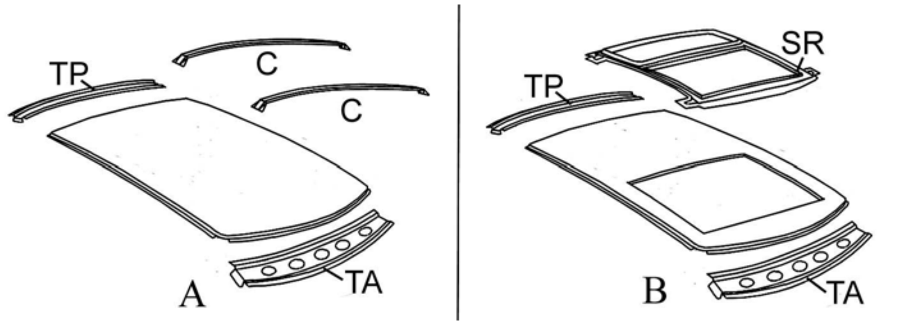


Fig. 4.72. Typical set of roof assembly parts for a metal closed roof (A) and in case of partly sliding top (B). TA: front roof cross member; TP: rear cross member; C: bows; SR: brace for roof top opening.

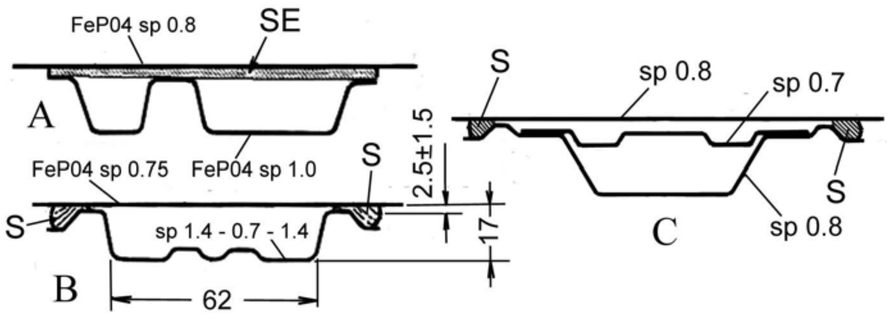


Fig. 4.73. Some examples of roof bows: A) open section, uniform thickness; SE: thermo-expandable sealant strips; B) open section, tailored blank; S: extruded sealant; C) boxed bow; S: extruded sealant.

smooth flexible adhesives such as butyl mastic (in order to avoid sink marks on outer surface), mainly providing a damping effect (Fig. 4.73).

These bows can moreover provide a connection between the two body sides and the roof in a side impact. For that reason, simple bows are made from steel sheet at least 1.0 mm thick or from steel tailored blanks 0.70 mm thick in the central area, 1.4 mm at both sides. Side bow edges, preferably screwed to the body side for tolerance adjustment, must in any case include deep drawn ribs, to avoid local buckling under compression and bending loads.

In the case of higher class vehicles, preferred are boxed bows made from FEP04 steel and thickness $0.7 \div 0.8$ mm for both welded elements. It is always recommended to verify that roof panel and bows assembly do not exhibit any resonance frequency coincident with compartment *cavity frequencies*.

Another task of roof bows is to support the interior roof liner (see *roof liners chapter*) which requires a number of fittings both in the central and boundary

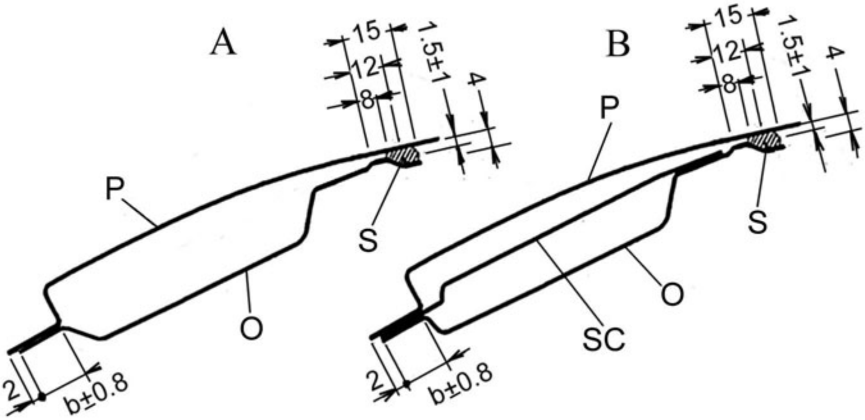


Fig. 4.74. Examples of open (A) and boxed (B) sections of front roof cross member assembly. P: roof panel; O: inner frame; SC: boxing member; S: sealant.

areas to avoid deflections and vibrations. Fittings are usually plastic clips or *velcro®* *strips*. Some roof liners, mostly on less expensive vehicles, are bonded directly to roof panel.

Continuous roof panel connection to the body sides, windshield and back glass, mainly horizontal, help to avoid compartment frame *lozenging* under shear stresses, therefore contributing to torsional body stiffness. In order to achieve this goal, it is not necessary to weld the roof panel to the body side; instead it is sufficient to bond it with a medium stiffness adhesive, as used for the windshield and back glass.

Regarding the front roof crossmember (Fig. 4.74), lighter cars have open sections, thickness 0.7 – 0.8 mm, material steel FEP02, while heavier cars adopt more robust sections, often boxed, with thickness between 0.65 mm in steel FEE355 and 0.80 mm in steel FEP02 or FEE275. Rear roof crossmembers have completely different sections depending on the body type (with or without liftgate – Fig. 4.75).

Three-box cars without tailgate do not require a cross member designed for torsion; a simple open section beam, with thickness in the range 0.70 to 1.2 mm, above the back glass being adequate. In the case of the liftgate, the cross member contribution to the body and opening stiffness is usually relevant; therefore the cross member has wide sections and is boxed, with thickness up to 1.2 mm, both for the cross and boxing members, while a higher yield strength steel is recommended, for instance bake hardening FEE220BH.

The roof contribution to body stiffness reduces if a top is mounted in a large opening (e.g. panorama top). Even the resonance frequencies and body vibration modes can be significantly influenced, in case of a large opening to accomodate a movable top (Fig. 4.76).

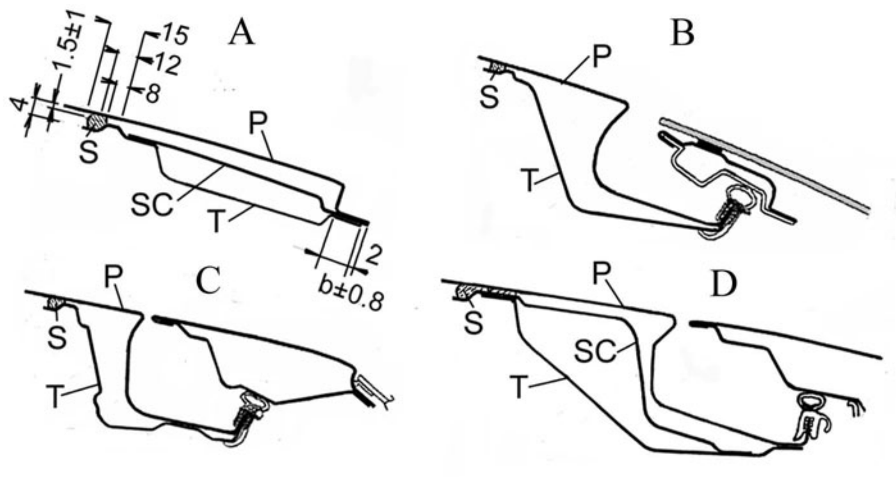


Fig. 4.75. Examples of boxed rear roof cross members for car with back glass (A) and liftgate (D); open section rear roof cross members for frameless tailgate (B) and steel frame tailgate (C). S: sealant; P: roof panel; T: cross member; SC: boxing member.

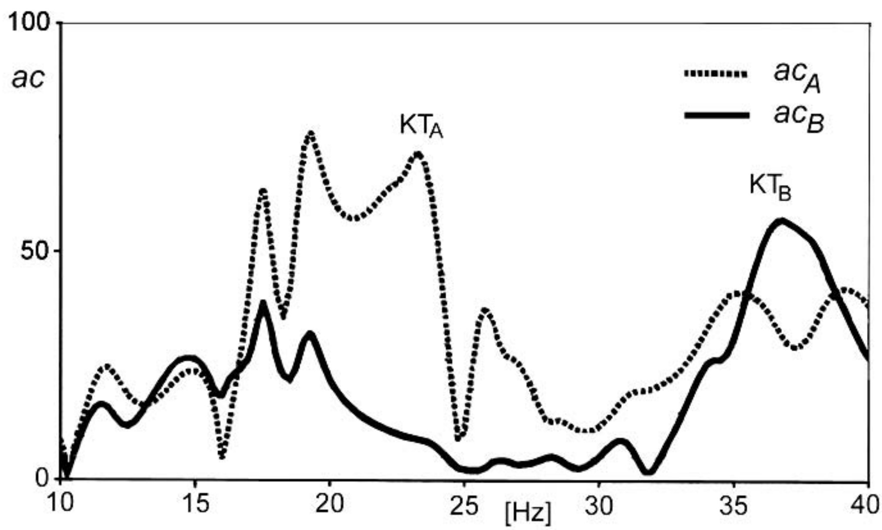


Fig. 4.76. Example of change in body resonance frequencies, due to a large opening for a glass *panorama* roof. ac_A: body acceleration index with panorama roof; ac_B: with standard steel roof; KT: body resonance frequencies.

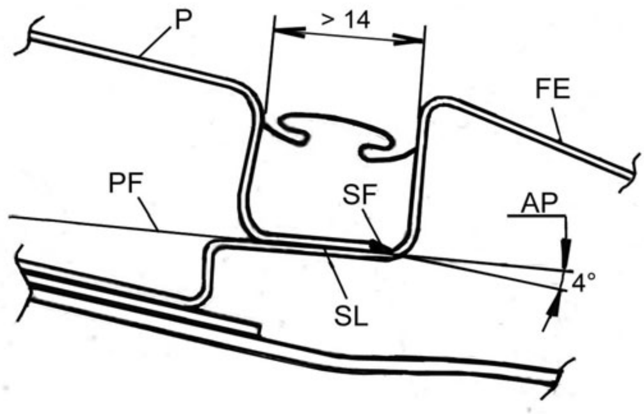


Fig. 4.77. Roof to body side laser welding requires the precise design of contact surface and a continuous sealing seam SF. P: roof panel; FE: body side outer; PF: reference body side plane; SL: laser welding; AP: preload angle of roof panel flange, referred to body reference plane.

In the case of a traditional smaller sliding top, both in glass and steel, the reduction in body stiffness is usually relatively low or none; nevertheless an increase of roof panel thickness to 0.9 mm for a steel FEP04 or FEP05 is recommended, in order to avoid panel deformation as a result of opening trimming and flanging operations.

As regards the assembling of the metal roof to the compartment frame, the conventional approach is spot welding of cross members and spot or roll welding to the body sides. In recent years, resistance welding has increasingly been replaced by laser welding (Fig. 4.77), because of the lower waste of thermal energy and, consequently, the lower risk of waviness and spots burning. On the other hand, laser welding requires a higher precision of parts to be joined (typically waviness should be less than 0.5 mm, and sheets must be pressed together to improve contact). Moreover, since the fastening surface between the roof and body side presents a border between compartment and the outside, the roof flange and body side surface must be adequately sealed with a continuous tape in order to avoid noise, air and water ingress. For this reason, one preferred type of welding is *laser braze welding* (Fig. 4.78), consisting in the laser melting of a continuous non ferrous seam between the roof and body side. Through the appropriate design of the junction and adequate tolerance specifications, laser braze welding can completely achieve both tasks of structural fastening and sealing.

At this point it is appropriate to consider some sections of roof to body fitting and their dimensional and technological aspects (Fig. 4.79).

The solution with the fewest parts has a drip mold on the roof; moreover, this design results in a junction with the highest moment of inertia for dimensional equivalence and therefore is the most efficient solution. Design with folded

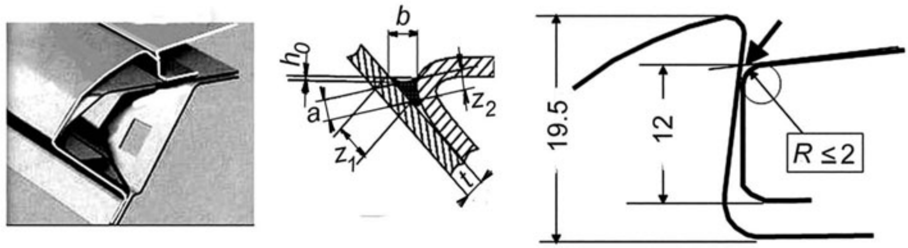


Fig. 4.78. Examples of roof sections designed for laser braze welding.

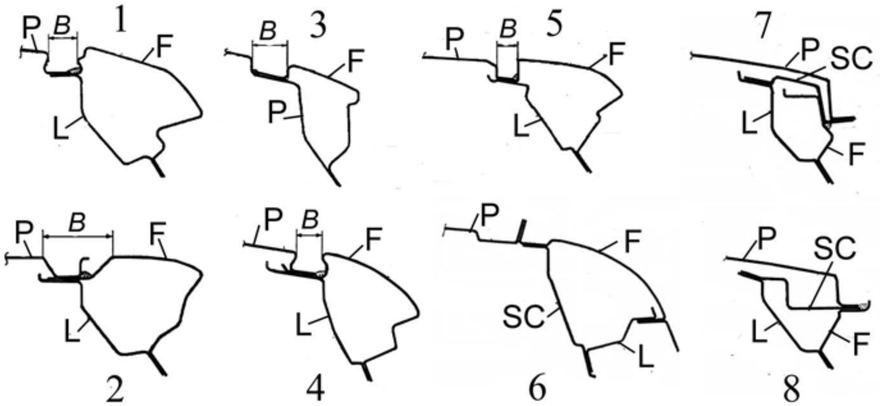


Fig. 4.79. Examples of *Y-Z* sections of roof to body side junction. From 1 to 5: with drip mold housing; 1) B= 16 mm; 2) B= 37 mm; 3) B= 22 mm; 4) B= 17 mm; 5) B= 13 mm; 6: folded and roll welded flanges; 7 and 8: side welded drip and body side boxing.

and rolled flanges presents sealing problems. Side junction design is consistent with doors that have a window frame wrap around body side frame if body side weakening is considered acceptable. For each design, sealing ease must be granted.

4.4.1 Roof Specifications

The delivery tests specified for roof assembly are static, dynamic and impact. The purpose of static testing is to verify that the roof assembly exhibits no permanent deflection due to a distributed load representing snow load: the distributed pressure applied is in the range $10 \div 15$ N/dm^2.

Dynamic bench and paved road tests are intended to verify the absence of roof contribution to compartment noise, due to panel drum-like vibration and the lack of bow damping effect.

As concerns impacts, the roof contribution to both side crash and roll over is mainly related to the roof cross-members and their connection nodes to the body sides. Roof bows, as already mentioned, must have strong edge fittings. Impact testing is performed on the assembled body, in accordance with regulations.

For these properties it is not easy to provide standard design specifications: finite element analysis represent the best approach to reach an appropriate design solution.

4.5 Front Frame

The front frame is the assembly between the firewall and front bumpers. For most cars, this frame surrounds and supports the power train and its auxiliaries, and is therefore relatively complex and specialized. Moreover, fitted to the front frame are the front suspension links, steering box, part of the air conditioning system and front lamps.

Last but not least, the front frame is in responsible for absorbing front crash energy, impact loads together with the compartment frames (body side and floor) and for attenuating potential injury to vulnerable road users as pedestrians in the event of an impact.

If the boundary cabin frame has been conceived to be a strong cage, these functions could be satisfied, for instance, using a cantilever embedded in the cage, with an increasingly strong section from bumpers to firewall, equipped with brackets to support the different various mechanical sub-systems, and sufficiently distant from the critical area to avoid direct contact with vulnerable road users during impact (Fig. 4.80).

However, this simple scheme must comply with other requirements such as volume and obstruction restrictions, and enable operation of the different subsystems, specifically the power train itself (which may be longitudinal, transverse, inclined, horizontal mounted), exhaust and intake systems and the wheel motion envelope. Moreover, such a cantilever should be connected to a resilient

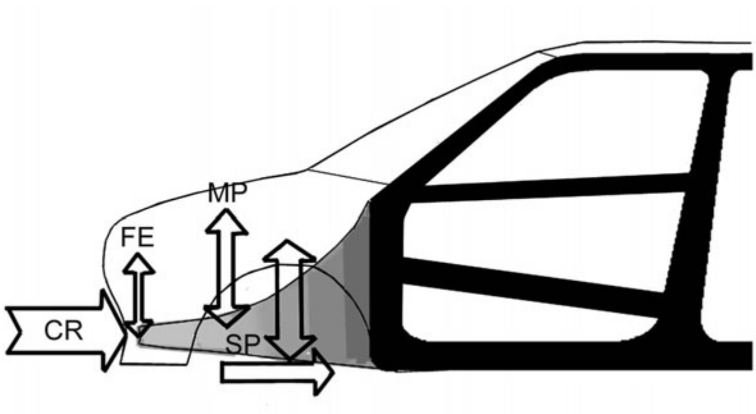


Fig. 4.80. Main load position on front frame and their cause. MP: power train; SP: suspension and steering; FE: front end; CR: crash.

compartment boundary frame (for example, the body side or floor members) and not directly to a wall such as the firewall for example. This is not only due to the extremely high loads (hundreds of thousand N) to be faced during front impact, but also to avoid the fact that a cantilever bending could excite vibrations of the firewall and floor, giving raise to air pumping and noise within the compartment cavity.

Many configurations of front rails embedded in the compartment cage can be found (Fig. 4.81). In practice, all known configurations are a combination of basic members, shown in view (1) of Fig. 4.81, with additional members that could be longitudinal, as in case (3) of same figure, cross members as in case (2), inclined as in case (4) and (5) or parallel to tunnel as in case (6). Front rails P, mainly responsible in front crash handling, are connected to upper shorter rails R, by vertical strut towers D, where the spring and shock absorber housings are located. The assembly of these three members which are always present is the structural block supporting the wheels vertical, longitudinal and side loads.

The front rails P, that in Fig. 4.81 appear to be straight and with constant section, often have a twisted axis and variable section both in the planar and lateral view, caused by the space restrictions due to the mechanical parts and their operation, in particular the suspensions, steering system and transmission links displacement. Therefore respective impact tuning is very difficult and the differente allowable section configurations (circular, squared, rectangular, hexagonal) do not each exhibit the same energy absorption effectiveness.

In order to evaluate the crash performance of front frames, in addition to computational tools, drop tower or pendulum real frame testing (Fig. 4.82) is often used , in which a front car prototype is struck by a stiff mass.

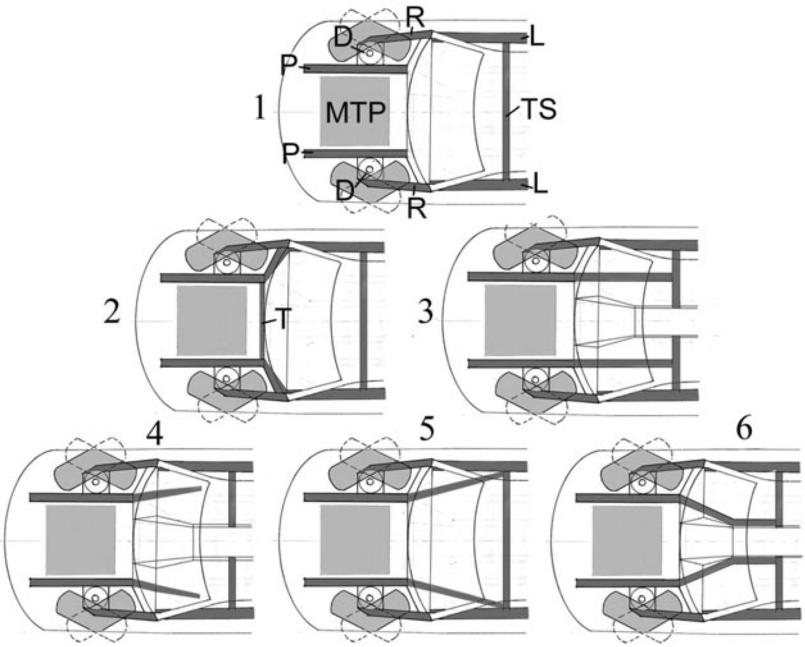


Fig. 4.81. Archetypes of front frame connections with compartment frame: real life frames are combinations of these archetypes. Lower front rails P are always present, between the power train and wheels, as far as upper front rails R, strut towers D that connect both rails, sills L and front seats cross-member TS.

In computer simulation and experimental tests it is possible not only to analyze the crush behavior of frame members (stable – unstable) but also to determine the proportion of energy absorbed by each member (Fig. 4.83).

The following criteria can be adopted to increase front frame energy absorption capacity:

- avoid section throats, that could become plastic hinges;
- increase sections and thickness towards the compartment in order to have a progressive reaction of members;
- avoid curves and joints with respect to the longitudinal axis, because these areas would collapse suddenly, effectively wasting the potential contribution of straight members;
- connect single members assigned to the task of energy absorption in order to provide a consistent reaction against different impact counterpart frames and impact directions;

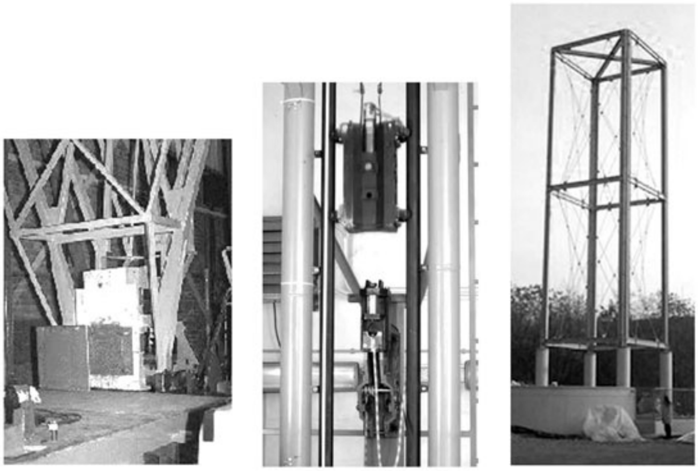


Fig. 4.82. Examples of pendulum or drop towers used to impact a rigid mass against the front underbody frame.

- connect front members to strong cabin frame members instead of single walls, even if they are ribbed or deeply stamped; indeed high impact loads could generate deep crushes of these walls, without providing relevant levels of energy absorption.

As an example of the results which can be attained by the application of these criteria, Fig. 4.84 shows a direct absorption comparison between two front frames with a common base. Loads related to crush and therefore absorbed energy are measured. Frame 2 has been obtained from frame 1, by implementing the following changes: increase of front rail connecting section to firewall and sills, and increase of stiffness of double firewall for a better fitting to sills. The increase in impact energy was about 80%, with only a slight increase in weight.

Another typical solution for today's front frame are *crash boxes*, made up of a small boxed member screwed to the front rail and to bumper cross member. This device has the task of crushing during a front crash between 10 and 15 km/h, absorbing the impact energy without plastic deformation of the front rail. After crash, the crushed member can be removed and changed, providing significant savings in comparison to traditional repair operations which consist in a complete removal of the mechanical sub-systems and restoring of front members.

Fig. 4.85 shows an example of a crash box fitted to a car (A), designed as single element (B) and preassembled with the bumper cross member (C and D). The design target for crash boxes (15 km/h) was a consequence of the *repair cost rating*, which is defined by insurance Companies according to statistical criteria:

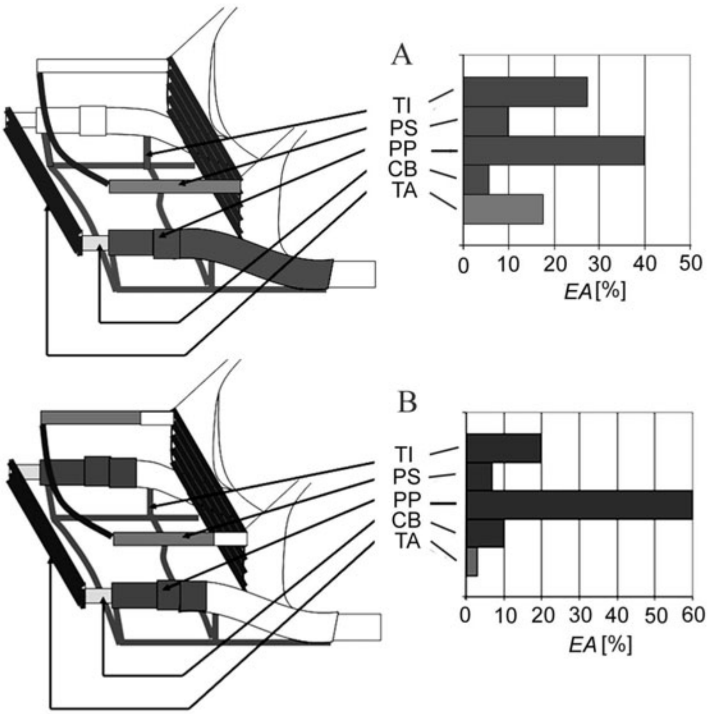


Fig. 4.83. Contributions of front frame single members in terms of front crash energy absorption *EA*. A) impact at 56 km/h against offset rigid barrier - Auto Motor und Sport; B) full front impact at 56 km/h against rigid barrier - U.S.A. NCAP. Contributors: TI) lower frame; PS) upper rail; PP) main front rail; CB) crash box; TA) front cross member.

15 km/h is the impact test speed for all vehicles compared in terms of repair cost rating and consequently car manufacturers' design target.

Overall impact resistance in insurance testing is provided by bumpers, cross member and crash box; therefore the preferred approach is to assign to a single supplier (usually the bumper supplier) the task of meeting with the target through the design of all three parts included in the system. Correspondingly this aspect is discussed further in the chapter on *bumpers*.

As concerns manufacturing the front frame, usually the firewall and each wall dividing the front volume from passengers cabin are included. These walls enable a number of interface functions, through the openings for mechanical control devices (as steering system, gear operation, pedals, hood release cable), multiple connectors for electrical harness and for electronic systems as air bags, housings for components as air conditioning.

Moreover, the firewall (also called lower dash panel) supports the cowl top or top dash panel, fulfilling the important function of front pillars connection and

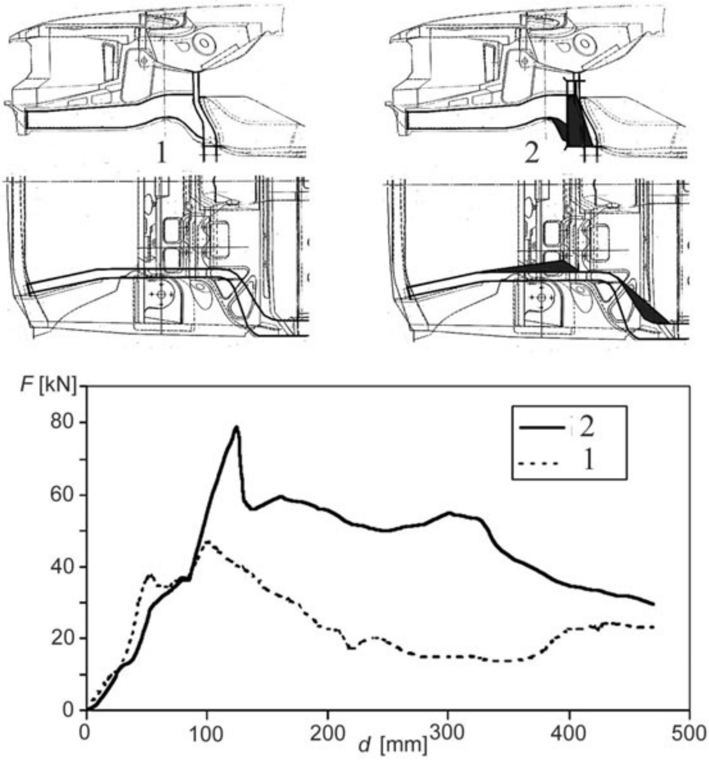


Fig. 4.84. Effect of minor front frame changes on energy absorption: 1) load F – crush d recorded in pendulum test for original frame; 2) after black marked changes in frame figure.

windshield support. To these panels, an instrument panel assembly, supported by a frame, is usually fitted.

The most common arrangement of lower and upper dash panel are shown in Fig. 4.86. In practice, the upper dash panel is used as the housing for the air conditioning and windshield wiping systems. The lower dash panel, where openings for operations and controls are cut, can be designed with a twin or single wall with a reinforcement cross member, or sandwich panels with a plastic damping sheet in between, included to attenuate dash panel vibrations.

4.5.1 Front Frame Specifications

1. Progressive crush load in front impact (X direction), capable of generating a mean body acceleration between 10 G to 30 G.
2. Resistance to maximum vertical shock absorber load.

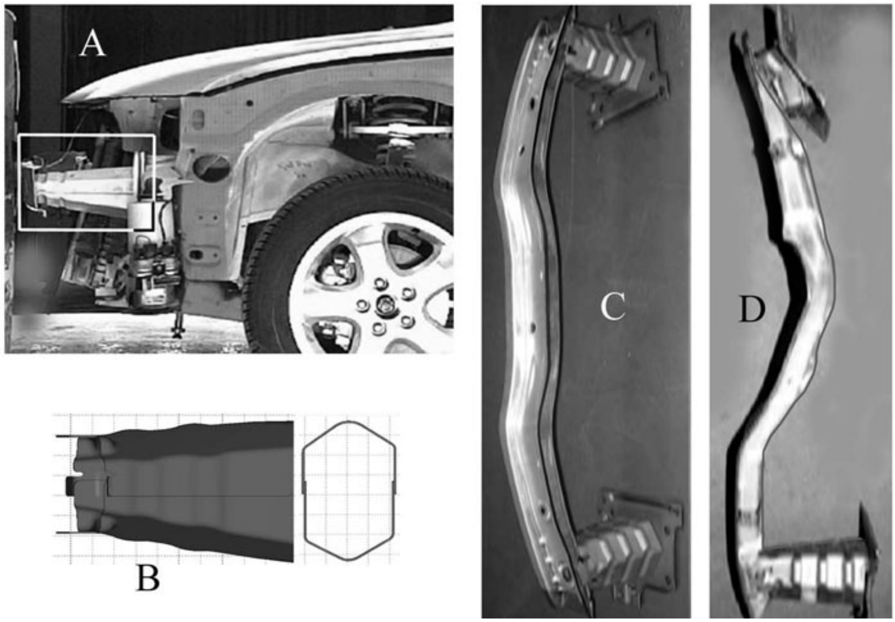


Fig. 4.85. Example of body installed crash box (A), view and section of absorbing device (B), bumper beam and crash box assembled (C) and deformed after offset impact test (D).

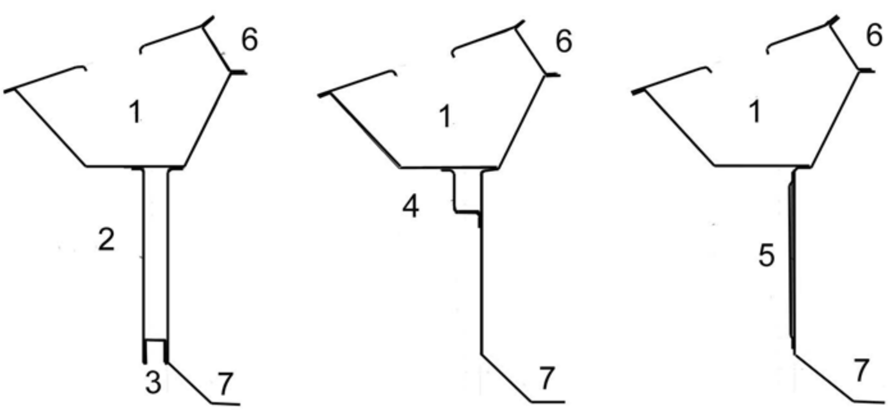


Fig. 4.86. Vertical simplified sections of different dash panel. 1) dash upper; 2) twin fire wall; 3) rear fitting of front suspension arm; 4) reinforce cross member, sometimes used to fit steering housing; 5) sanwich assembly with plastic sheet in between; 6) cowl top; 7) front floor connection to dash lower panel.

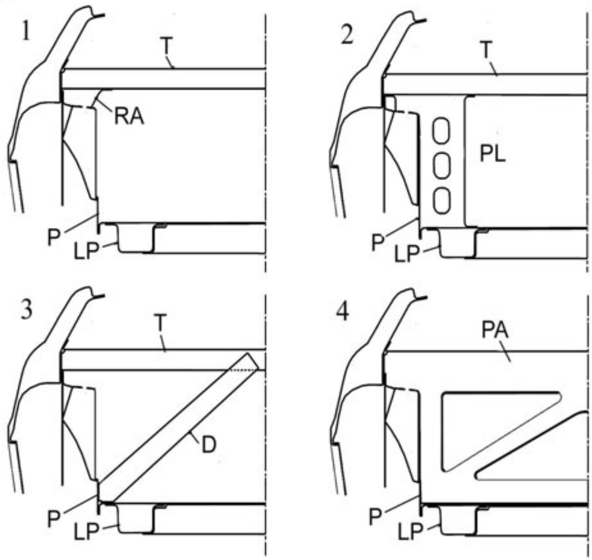


Fig. 4.87. Schematic examples of rear seat pan adopted to stiffen three-box cars with fixed back glass. LP) rear rail; P) inner wheel house; T) pillar bar or crossmember; RA) corner brace; PL) side brace; D) diagonal members; PA) closed rear seat pan.

3. Resistance to maximum wheels transverse load.
4. Torsion and bending stiffness consistent with overall body requirement.
5. First torsional resonance mode higher than 40 Hz.
6. First dash panel resonance mode, in complete car condition, higher than 40 Hz.

4.6 Rear Frame

The rear frame is conceptually divided in two sub-assemblies. The lower, comprises two longitudinal rails, close to rear wheel houses, connected at both ends by cross-members and supporting the rear floor as main task, together with rear crash handling. Instead the upper sub-assembly layout and tasks dipend on the vehicle type: three-box car with fixed back glass and separate decklid or two-box car with liftgate.

Three-box cars have usually a *pillar bar*, connected to body sides and rear strut towers, completed by stamped parts (braces, ridged walls, cross diagonals) to oppose lozenging of the rear opening below back glass which strongly influences torsional body stiffness (Fig. 4.87).

Passing from solution 1 of Fig. 4.87 to solutions 2, 3 and 4, the torsional body stiffness is increasingly influenced. In case 1 there is only one pillar bar or open cross member with a corner brace. In case 2, the cross member, body side frames and rear floor are connected by two side vertical braces. In case 3, between the cross member and rear rails diagonal members are fastened, behaving as struts or ties in torsion. In case 4, an entire wall in embossed sheet is welded to the body side frames and the rear floor, providing two advantages, namely torsion body stiffening and compartment insulation from rear airborne noise (mainly from exhaust pipe).

Clearly the structural benefit of closing the rear seat pan is counterbalanced by the loss of flexibility for goods transportation; for this reason, usually only three-box cars correspond to these solutions, the priority being with driving comfort as opposed to large goods transportation.

On the other hand, the distinguishing characteristics offered by two-box cars with liftgate include luggage volume versatility; therefore such cars must be designed without cross members or other obstructions between the rear seat and luggage compartment. Usually, a closed ring frame around the liftgate is included, which is connected to the body sides and to rear rails, in order to resist torsion stress. The upper portion of this ring comprises the rear roof cross member, shown in *roof chapter*; side portion by body side, mainly quarter frame and lower portion by cross member connecting rear rails.

The main task of the rear frame is not only to contribute to torsion stiffness, but also resist rear crash, avoid central floor crushing and finally provide resistance to liftgate loads. In the case of decklid (three-box cars), around the decklid opening instead of closed frames there is just a U-shaped water draining channel to stiffen the opening. Structural contribution is provided anyway by quarter panels, welded to the floor and body sides.

The back panel, often boxed, connects the rear rails at their rear end and supports the rear bumper absorbing devices, often made from expanded foam, without a bumper cross member.

4.7 Compartment Floor

The compartment floor is an assembly of cross members and almost longitudinal members supporting stamped metal sheets extending from the dash panel to the car rear end. The floor frameor frame can be assembled with floor sheets before the final body assembly or remain split (in the case of body *on frame*) from the body, to which it is fastened in a later stage by screws or elastic bushes, remaining possible in any case to unscrew and divide the chassis from the body.

The following section relates to the floor integrated frame.

The traditional solution uses zinc coated steel sheets although aluminum sheets are used instead in some vehicles. Studies and some prototypes have

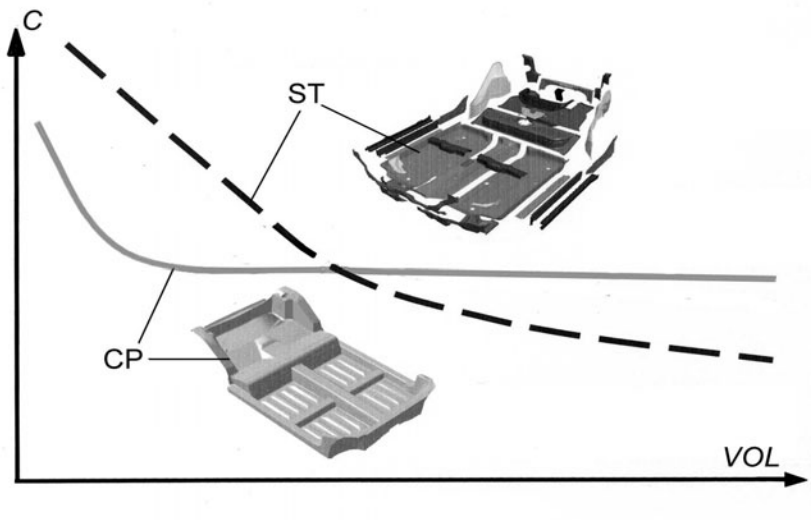


Fig. 4.88. Conceptual cost comparison C between two floor types, referred to production volume VOL. ST) traditional steel floor (20 kg); CP) fiber reinforced plastic floor (1 piece, 10 kg).

also been developed of sandwich composites floors, made of two plastic (usually thermosetting) stamped parts with a closed cell stiffening core.

In theory also thermoplastic floors offer a feasible solution when reinforced by metal braces to meet structural targets (in terms of impact and stiffness) and should result in lower vibration levels.

Fig. 4.88 shows a qualitative cost comparison between two different floor technologies, illustrating the potential advantage of a polymeric floor for low production volumes.

Today typical floor parts are (Fig. 4.89): two longitudinal rails (LA) below front floor and two (LP) below rear floor; two side sills (LL); a front seats cross member (TA) and a rear seats cross member (TS); a cross member between rear wheel houses (T) and a rear cross member (TP); a front floor (PA); a rear floor (PP), sometimes split in two pieces for stamping requirements. Only in a few cases is a single piece floor feasible.

The front floor with central tunnel (needed in rear-wheel and four-wheel drive cars) is more articulated; in this case, if the floor cannot be drawn as a single piece including the tunnel, it is usual to divide the floor into three longitudinal spot-welded parts: the tunnel and two side floors.

Longitudinal front rails are commonly straight, whilst rear rails have variable sections with twisted axis, extending from the side sills toward the inside, then turning around the inner wheel house before straightening towards the rear.

Cross members are usually straight, with the exception of the tunnel wrapping, where they are arched; in this case, a smaller section is designed above

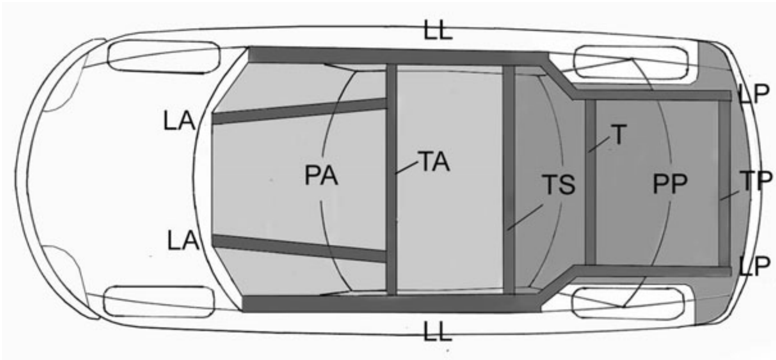


Fig. 4.89. Frame elements and panels of a typical floor for 2 or 3 box car.

tunnel. It is useful to note that cross members can better resist heavier loads (as in belt anchorage testing) if fitted below the floor, because in this case the reaction to cross member loading is distributed across the entire surface of contact between the cross member flanges and the floor, instead of being concentrated at the weld spots.

On the other hand, as concerns corrosion resistance, a floor with inner cross members is preferred since joint surfaces are not exposed to dust and salt projection. However, if the floor sheets are not zinc coated, the risk of humidostatic corrosion could be higher inside boxing inner cross members.

In the case of vehicles with higher ground clearance and higher floor, such as Vans and SUVs, the floor frame may be simplified to be a grid of linear beams, folded or rolled, as in case of Fig. 4.90.

Floor specifications are referred to two main goals: absence of resonances coincident with compartment cavity modes (meaning for most cars no resonances in the range 50 to 70 Hz and 120 to 140 Hz) and resistance to dynamic seat and belt loads.

To face the first problem, floor panel and frames are designed by computer analysis so as to avoid resonances coinciding with the body frame; in any case, the amplitude of panels vibrations should be attenuated using heavy damping patches (made by viscoelastic bituminous or polymeric materials, bonded or melted to the floor, with a mass of at least 3 kg/m^2).

Fig. 4.91–A are shows floor and tunnel regions usually covered by thermofused elastomers; Fig. 4.91–B shows areas and dimensions of damping patches optimized by computer analysis to reduce area covered and hence weight/cost while maintaining effective vibration attenuation. Fig 4.91–C compares the damping performance of the conventional with the computer-optimized solution for dash lower panel and floor panels.

For safety belt and seat fittings resistance tests, related to front crash behavior, it is recommended to bolt all anchorages through local plates to cross members and avoid traction stresses on plate spot welds.

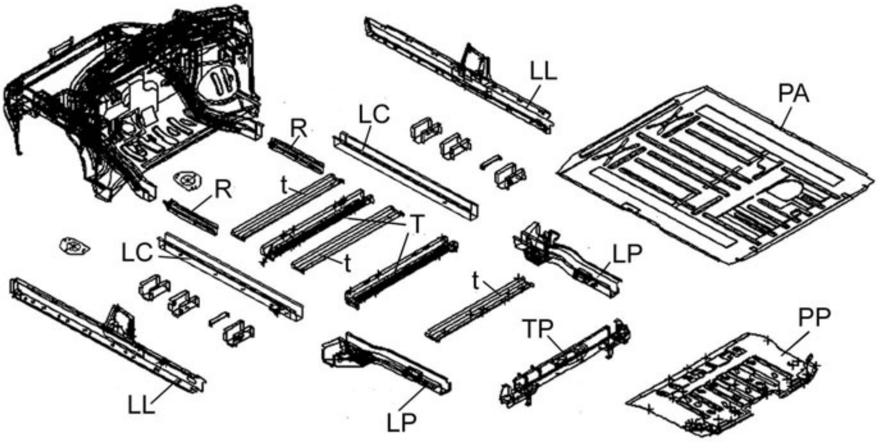


Fig. 4.90. Floor of Fiat Multipla: PA) front floor; PP) rear floor; LL) sills; LC) logitudinal floor rails; LP) rear floor rails; R) floor rails reinforcements; T) main seats cross members; t) ancillary cross members; TP) rear cross member.

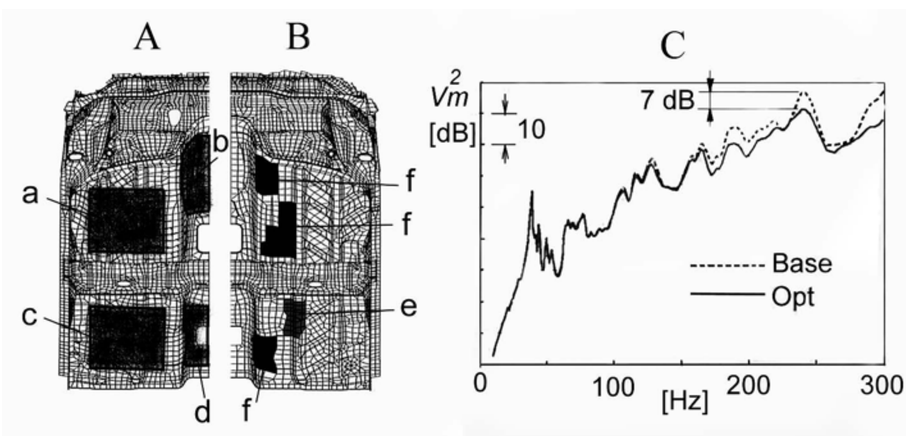


Fig. 4.91. In A, traditional damping patches on floor panels (a,c) and tunnel (b,d) are shown. In B, an example of computer optimized design (patches e,f) resulting in weight and vibration reduction. In C picture, comparison of panels mean square speed V_m^2 in case of traditional (Base) and optimized (Opt) patches on floor and dash panel.

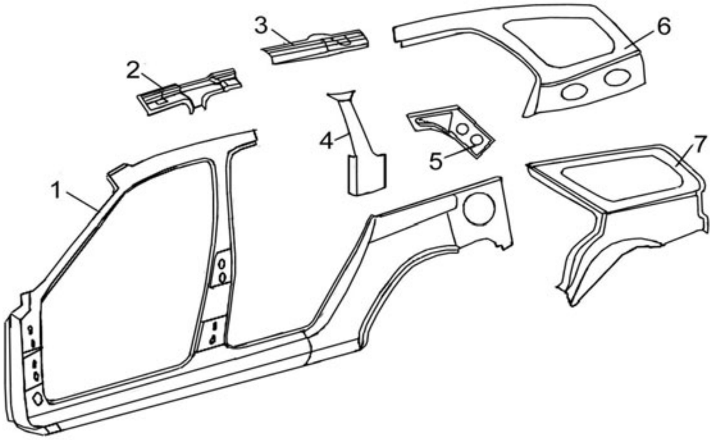


Fig. 4.92. SW specific body side parts or resulting from original sedan reworked elements: 1) sedan cut outer body side; 2) central upper rail; 3) central rail back assembly; 4) rear safety belt loop reinforcement; 5) rear upper rail; 6) SW inner quarter assembly; 7) SW quarter panel assembly.

4.8 Closed Bodies

These car families (Sedan, Station Wagon (SW), SUV and Off-road) are the most common among vehicles and their characteristic design relates to specific target uses. The level of variety continues to increase in response to customer demand and to marketing pressure to search for and create new needs.

The structural properties of closed bodies can be classified through comparison of the different families, using sedan cars as the historical design reference.

The sedan usually has a two-box 3- or 5- door body or three-box 4- or 5- door body. The main task is to transport people and baggage on ordinary roads. The liftgate of the 3- and 5- door sedan allows loading on the rear floor with luggage and goods, even as bulky as domestic appliances, for example.

The structural difference between two- and three- box sedan, with and without the rear seat pan, have been examined in previous sections. Instead here it is appropriate to analyze the difference between the bodies of the SW and sedan.

Despite the different names (Station Wagon, Sport Wagon, Family car), SW bodies are derived from sedan (2 or 3 boxes) by lengthening the roof above the rear luggage compartment, in order to provide a loading space which is two or three times the original volume.

As a consequence, roof lengthening bears a new body side or a body side consisting in front sedan side frame and a number of specific additional parts in the rear (Fig. 4.92).

Specific SW parts in the example shown are designed according to following aspects:

- Central upper rail, central upper rail back, rear upper rail: for geometrical reasons, these parts replace the sedan roof rail and are extended to the rear pillar.
- Reinforcement for rear seat belt loop: to increase the thickness of the rear pillar frame, where the pillar loop and adjuster are fitted.
- Inner rear quarter panel: additional to sedan body side outer panel, trimmed for fitting to SW boundary, in order to complete inner panel of SW body side.
- Quarter panel: outer panel adapted to SW rear shape, including rear light housing, liftgate gas strut housing and fuel filler housing. Moreover, it contributes to provide structural strength and stiffness to the rear pillar and liftgate opening frame.

The SW floor is often the same as the basic sedan; in some cases, floor members reinforcements are added to achieve a higher loading target of the rear floor, and in some cases the rear floor is longer than in the sedan.

Regarding performance, principally in terms of torsional stiffness, the SW requires the maximum available loading and flexibility of use in the area behind the front seats; therefore the rear seat pan is always missing and reference should be the 2 box with liftgate body. But, due to the increased length, SW bodies could be less stiff than the 2 box, unless specific reinforcements are added.

Turning now to the comparison of the SW with SUV and Off-road vehicles, it should be observed initially that the SUV is in principle an intermediate family of vehicles between SW and Off-road, aiming to maintain the levels of comfort and luxury of the SW while offering chassis performance similar to Off-road vehicles. If the comparison is limited to the body, usually Off-road vehicles have a strong chassis with longitudinal members (body on frame), while SUVs have unitized body frame as used in SWs (Fig. 4.93 and Fig. 4.94).

The ground clearance of the SUV floor is higher than the SW and a little lower than Off-road vehicles, while the size impression, due to vehicle height and length being similar for SUV and Off-road, is different for the SW.

Regarding body side setting, SUVs do not use parts of sedan or SW; rather specific parts are used even though manufacturing technologies and materials are often the same.

As reagards loads specifications, the people and goods load target for SUV may be higher than for the SW, while road stresses are intermediate between SW and Off-road; therefore, the fatigue resistance and stiffness targets for SUVs are usually more severe than for SWs.

Regarding the bodies of Off-roads vehicles, the required performance is the highest in terms of the transported load and the type of road tracks encountered: bodies should have static, fatigue and corrosion resistance at highest level among

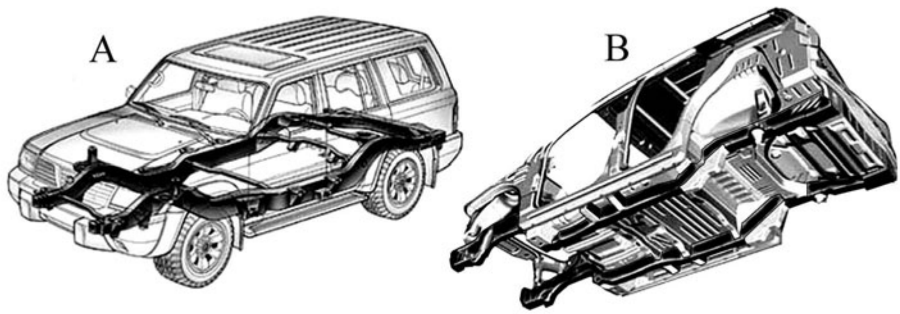


Fig. 4.93. Examples of off-road (A) vehicle with chassis and SUV (B) with integrated underbody frame.

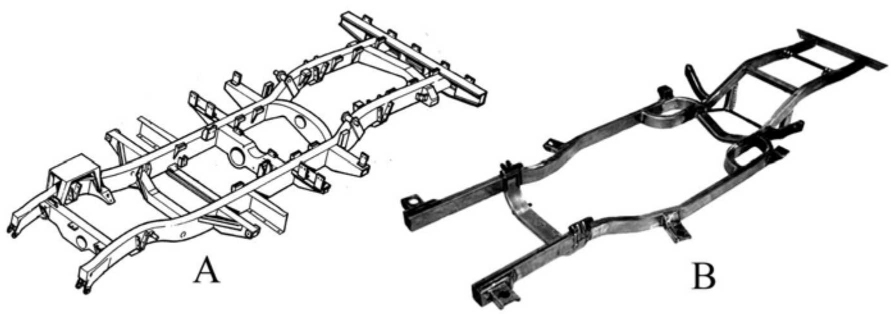


Fig. 4.94. Examples of off-road chassis (A) and SUV underbody frame (B).

cars, with ground clearance enough to tackle small sterams and every kind of track, while using the simplest manufacturing technologies possible in order to maintain production costs low and facilitate repair even without official service. For example, an Off-road vehicle can be manufactured with aluminum riveted sheets, because aluminum can be easily embossed, cut, part replaced and hand riveted without the risk of corrosion.

4.9 Spider, Coupe and Cabrio

The bodies of cars in this class are the most sophisticated in terms of styling while also requiring a characteristic design for the following reasons.

Coupes can be classified as sports car with high speed and road holding targets; therefore their static and dynamic stiffness, principally torsional stiffness, represent the primary goal for body design. Usually this target is easier to achieve than with a 5 door sedan since coupes have only two side doors, a relatively small liftgate and above all a rear seat pan.

Today, a coupe body torsional stiffness is usually higher than 1,000,000 Nm/rad, reaching or even exceeding 1,500,000 Nm/rad. However the static stiffness is often not enough: ideally, the design should result in first global torsion mode of the complete car over 40 or better 45 Hz, in order to avoid coupling with suspension main resonance, which usually falls in the range 15÷20 Hz.

Also, coupe aerodynamics must be accurately tuned, primarily in terms of guaranteeing road holding or road contact and therefore lift properties. In most cases coupes are provided with spoilers or wings, resulting in a zero lift rear axle condition or sometimes down force. The front bumper and underbody are designed to minimize front lift, providing an advantage also in terms of induced drag.

Spiders (2 places) and *Cabrios* (4–5 places) are usually considered to be free-time, more environment friendly products and therefore they do not aim to provide the same levels of high speed performance as coupes. Due to the fact that the upper frame is missing, some typical problems of these cars are:

- lack of torsional stiffness,
- lack of protection in the case of roll-over,
- high structural unevenness and risk of fatigue local weakness,
- lack of sealing against water and air ingress (both with soft and hard top).

The lack of stiffness is a natural consequence of the spider concept, more similar to a platform than to a sedan or coupe. It can be observed that the torsional stiffness of a vehicle underbody, without upper body frame, could reach 200,000 Nm/rad, just 20÷30 % of the stiffness of current production mid sized sedans.

Some conventional measures to increase the platform torsional stiffness are, for instance, to increase the sills section and/or rocker panels and sills thickness, if not detrimental to the ergonomics of passengers access. However in this way it is not possible usually to increase the stiffness by more than 20÷25 %.

In most cases it is possible to connect the sills rear end with a very stiff cross member or a boxed rear seat pan: the aim is to unite five subassemblies (two sills, a rear cross structure, underbody and firewall) to result in a stiffened box missing just one wall.

Further stiffening can be obtained using a large cowl top with small openings connected to the front suspension strut towers and by a tunnel strongly embedded in the firewall and rear seat pan. Finally, boxed frames can be added between the sills and rear suspension strut towers.

All these features or at least most of them, shown in Fig. 4.95, have resulted in levels of torsional stiffness which are close to sedans (400,000 to 600,000 Nm/rad) and a first torsional vibration mode sufficiently far from the suspension main

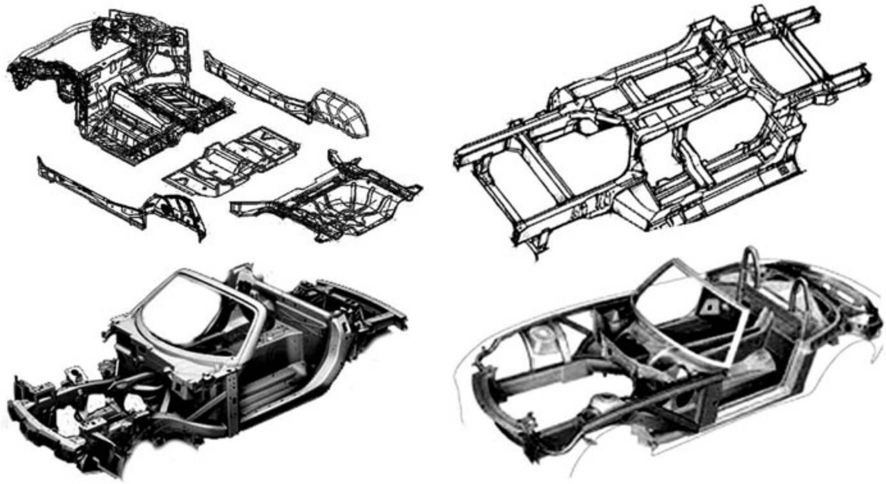


Fig. 4.95. Examples of recent spider frames.

resonance. However such results have not been achieved by all spiders in the market and never yet by cabrios (due to the cabrio wheelbase and side door opening which is much longer than in spiders).

Regarding roll over protection, which is always more difficult to guarantee for cabrios than for spiders, additional features are commonly added in two regions: windshield and seat back. The windshield frame is reinforced by strengthening A pillars, both with a stronger embedding of the lower pillar end in the body side and by inserting a tubular or hydroformed reinforcement of high strength steel between the body side outer and inner (Fig. 4.96–A).

The roll bar (Fig. 4.96–B) is an additional frame, usually fitted to the body frame, in steel, aluminum or carbon fiber, specified according to design invention and engineering analysis.

Regarding structural unevenness, one precaution is to specify all rather than just a limited number of the features suggested in order to enable the higher stiffness to be shared across different nodes to avoid local overstressing, bearing in mind that *F.E.M.* analysis represents the only reliable tool for a valid performance forecast.

Regarding water and air tightness, related issues shall be examined in *weather strip chapter*.

4.9.1 Spider and Cabrio Soft Top

Traditionally spiders and cabrios feature with soft tops which are foldable and stowable behind passengers seats, according to the following two solutions:

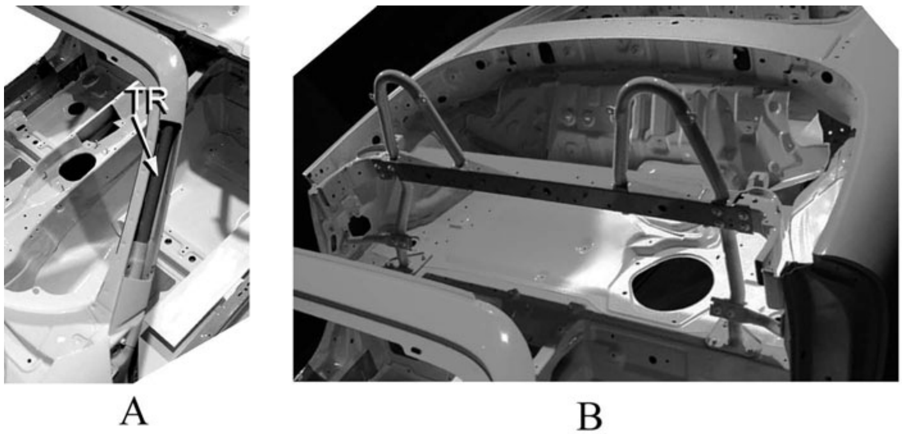


Fig. 4.96. A) example of tubular reinforcement TR inside A pillar of Mazda MX5. B) example of same car roll bar, where connections to body frame are visible.

- soft top stowable beneath a deck, between rear seat pan and baggage compartment;
- soft top foldable above a cross outer panel behind rear seat pan, fitted to this panel and hand wrapped with a fabric cover.

The main soft top parts are (Fig. 4.97):

- a set of tubular or rolled bows in steel or aluminium, to hold the top cloth;
- a set of articulated forged or tubular rods, to lead the bow ends during raising and lowering and to establish them in opened and folded position;
- weather strips, fitted to side rods, front and rear bow (fig. 4.98);
- two rear brackets, to fit rear top frame nodes to body;
- one or more fabric layers, including at least a waterproof outer layer, but more often also an insulating, absorbing core and an inner lining;
- side cloth tensioning wires (Fig. 4.98)
- a plastic or glass transparent panel, sewed to soft roof (Fig. 4.99);
- strikers and pins on front roof cross member, if locks are on windshield header; or pin and strikers manually operated by handles on front roof cross member (Fig. 4.100);
- two rear locks to clamp last rear bow, when soft top is stowed beneath its deck.
- Motor devices, with pistons and run stops, in electromechanical or hydraulic version.

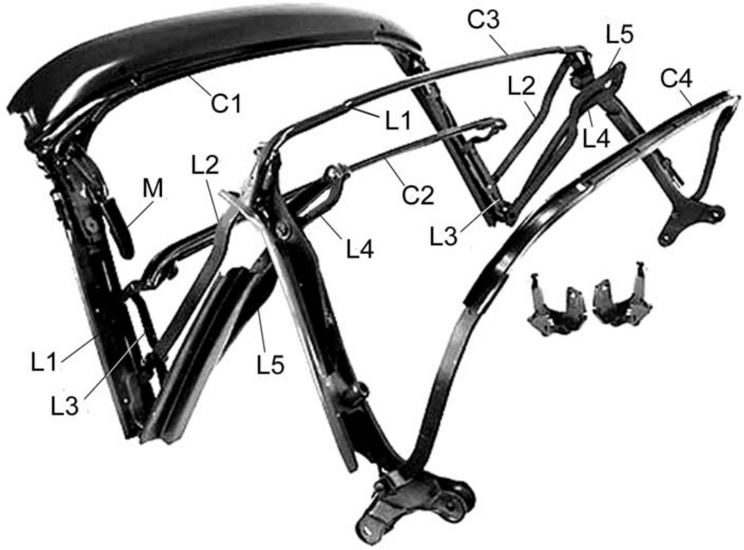


Fig. 4.97. Main components of a soft top frame. C1, C2, C3, C4: bows; L1, L2, L3, L4, L5: kinematic rods; M: operation handles.

Despite being derived from the original horse-driven coach (and obvious revolution in materials and manufacturing process), today the soft top is still used by a large number of spiders and cabrios mainly because of the relatively low cost and stowing volume.

Nevertheless there are a series of disadvantages with the soft top including the lack of acoustical insulation, air and water tightening, cloth deformation with time and following clamp and seal problems, back transparent plastic deterioration, ease tu cut with a knife, vibration at speed, and lack of overall visibility.

The main soft top design problems are related to overall top and body tolerances, to kinematic components obstruction and to gaskets fitting between top frame and side windows.

High top tolerances depend on complex three dimensional top configuration, rods manufacturing and materials (rolled or tubular or forged and worked iron pieces) and nodes play. These tolerances can result in ± 2.5 mm variation of longitudinal top dimension.

High body tolerances are depending not only on body parts where top assembling reference are, as windscreen header and rear seat pan or deck cross member, but also on deformation of assembled body in painting and mounting process. Overall, an average tolerance of ± 2.5 mm between windscreen header top fittings and rear fittings can be considered.

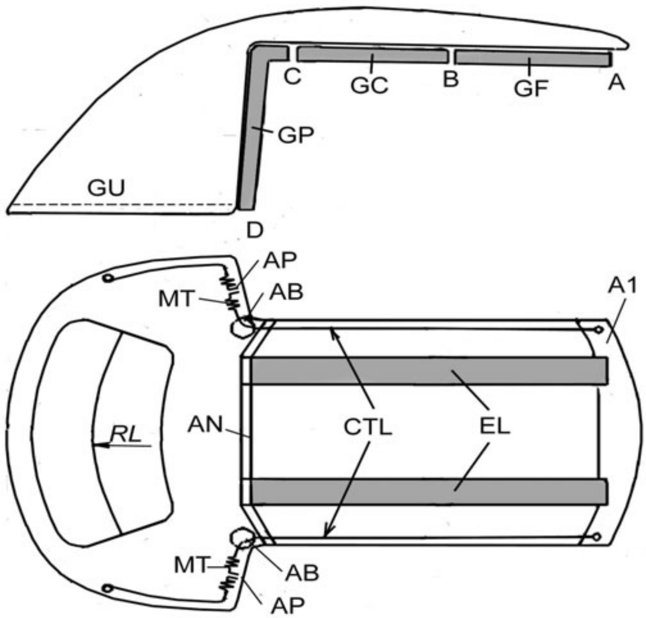


Fig. 4.98. Main soft roof cloth parts. A, B, C, D: nodes; A1) first bow; AN) last but one bow; EL) side elastic strip; CTL) tensioning side wire; MT) pretensioning spring; AP) side rear run fitting; AB) loop ring; RL) back glass radius (> 3500 mm); GF) side front weather strip; GC) side central weather strip; GP) side rear weather strip; GU) last bow gasket.

Through the summation of soft top and body tolerances, it may be possible to find a fitting difference of ± 5 mm at the top mounting station.

Regarding obstructions of kinematic devices, a fewer number of rods is generally preferable.

Gasket installation shall be examined in the specific chapter.

Soft top specifications

With reference to the conventional body tests in open top conditions, additional delivery tests with closed top for spider and convertibles are:

- bench durability test;
- squeak and rattles bench test after thermal cycling;
- noise road test;
- aerodynamic noise and rustle in wind tunnel;

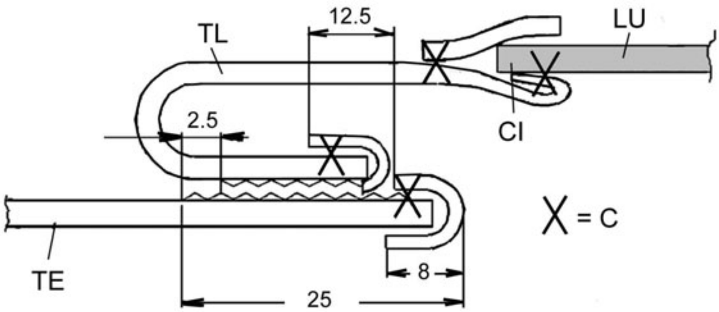


Fig. 4.99. Schematic view of detachable back glass - soft top junction. LU) back glass; TL) top cloth with female *velcro*® strip; TE) outer layer with male *velcro*® strip; CI) sew and bond seam; C) sewing stitch.

- dynamic top cloth deformation in wind tunnel; less than 60 mm is generally acceptable;
- water leakage in high pressure spray water chamber;
- dust or powder ingress;
- door closing and opening durability with side window glass operation;
- system misuse test; unusual or incorrect operation by customers.

Subassembly delivery tests on soft top and its components are:

- salt fog corrosion resistance of coated top frame;
- kinematic system durability through raising and lowering tests for at least 8,000 cycles;
- static traction top cloth test;
- physical and chemical tests on cloth layers and weather strips, to verify resistance to hydrocarbons, chemicals, abrasion, UV radiation and thermal cycling;
- current absorption, in the case of electromechanical top;
- durability test of motoring system, both electromechanical or hydraulic.

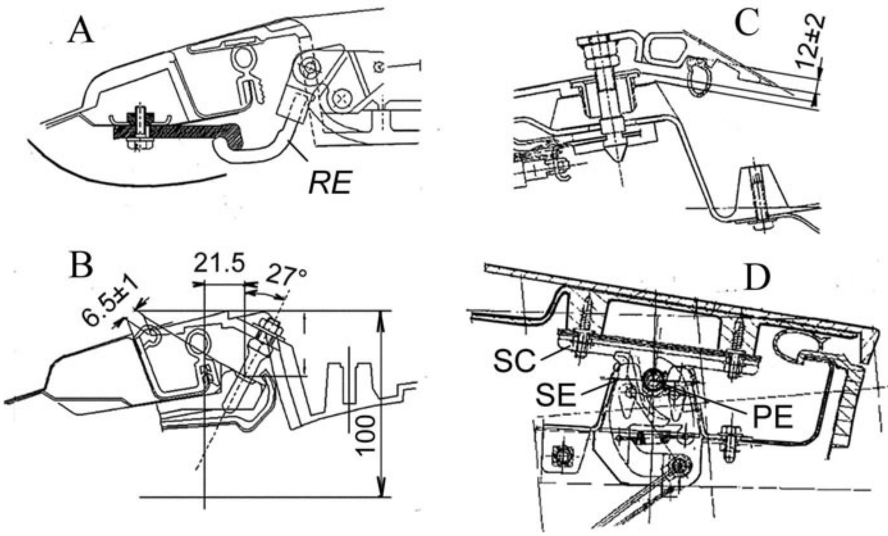


Fig. 4.100. Example of locks for manual operated soft top with rear deck. A) front hook; B) front centering pin; C): rear deck to top latch; D) rear deck to body latch; RE) adjusting stroke: ± 2 mm; SE) latch; SC): striker; PE) overmoulded (e.g by *Hytrel*®)anti-noise pivot.

4.9.2 Convertible Top

For many years winter hard-tops in fiberglass or metal sheet with back glass were provided as optionals to replace the soft top when needed. However, in recent years, many new models have been put in production with a *retractable hard top* (comprising a number of retractable segments) operated by motorized kinematics; in this way, a spider can be effectively changed into a coupe in just a few seconds (Fig. 4.101).

Although these solutions are much more expensive than traditional soft top, when the top is closed, acoustic insulation and water tightening are much more effective; moreover full or partial glass tops are commonly available which enable a panoramic view of the surroundings.

However one issue with these solutions relates to the volume of the folded parts, commonly obstructing 80% of already limited luggage compartment. An interesting solution has been designed for Ferrari Superamerica (2006) (Fig. 4.101–B) which features a glass roof with carbon fiber frame rotating while opening and stopping when laid down above the decklid; in this way, a much lower obstruction of luggage compartment is achieved.

The contribution of hard tops to the body stiffness is relevant and therefore their stress condition is specified. On the other hand, the same car, in spider configuration, should offer ride and road-holding performance not too different from the coupe configuration.

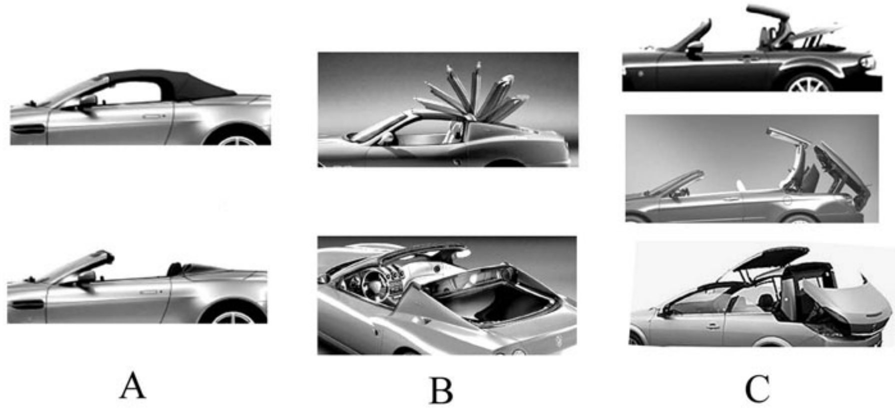


Fig. 4.101. A) traditional spider with fabric soft top; B) spider–coupe with rotating top; C) spider/cabrio with retractable hard top.

The delivery specifications for the hard top are similar to those for the soft top without, of course, top cloth testing.

4.10 Commercial Vehicle and Trucks

Large and small trucks, articulated lorries, vans and pick-ups belong to this family of vehicles. They can carry a rear open or closed cargo area, and the smallest vehicles in the family be derived from car platforms.

4.10.1 Articulated Vehicles

These vehicles comprise a *tractor*, featuring a frame, a *cabin*, a power train, driving wheels and a *turntable hitch* or *fifth wheel*, where a semi-trailer *coupling pin* or *king pin* is linked; the semi-trailer includes a complete chassis with wheels and brakes, carrying containers of various sizes. Articulated lorries can be multi-trailers (Fig. 4.102).

The tractor can have 2,3 or 4 axles, whereas trailers can have from 2 to 3,4 and more.

Regarding the body, the cabin, chassis frame and closed cargo vans are examined below.

Cabin

We will refer to a semitrailer cabin as a unitized construction made of stamped sheets; this clarification is needed because some manufacturers (for instance,

Fig. 4.102. Example of articulated vehicle: A) tractor; B) semi-trailer; C) trailer.

ASTRA) are used to construct the cabin with a tubular steel space frame completed by bonded fiberglass panels.

Moreover, it must be remembered that a cabin is pneumatically suspended and can tilt forward thanks to two front fitted hinges and two rear lifters.

Cabin assembly (Fig. 4.103) includes 5 main sub-assemblies:

A) floor assy;

B) back panel assy;

C) windshield frame;

D) RH and LH side frame.

It can be observed that the cabin assembly does not include the roof panel, because it is usually made in three sizes fiberglass, then bonded to the cabin assembly.

The windshield frame (Fig. 4.104) is related to the front cabin style, by outer windshield pillar RH and LH (1) and cowl top (2); windshield header (3), header boxing (5) and reinforcement (4) are assembled as front roof cross member.

RH body side (Fig. 4.105) can be split in two sub-assemblies: a front door opening frame and a rear frame (rear cabin pillar) that is connected to the floor and back panel assembly; upper outer panel (6) boxes upper side frame and defines side cabin style.

Fig. 4.106 shows the complete set of RH floor rail parts, where the main member is the longitudinal floor rail. The RH side floor provides support for the passengers feet, while the floor reinforcement carries four threaded plates for the seat frame fittings. Some brackets shown in the figure stiffen the floor rail where the front cabin support is connected.

Fig. 4.107 shows the 6 cabin versions designed for the reference truck, with their basic dimensions (width and length); instead the height can be chosen across a range of values. Modularity is achieved in the following way:

- The door opening assembly is standard, therefore body side assembly and doors are the same for all versions (Fig. 4.105).

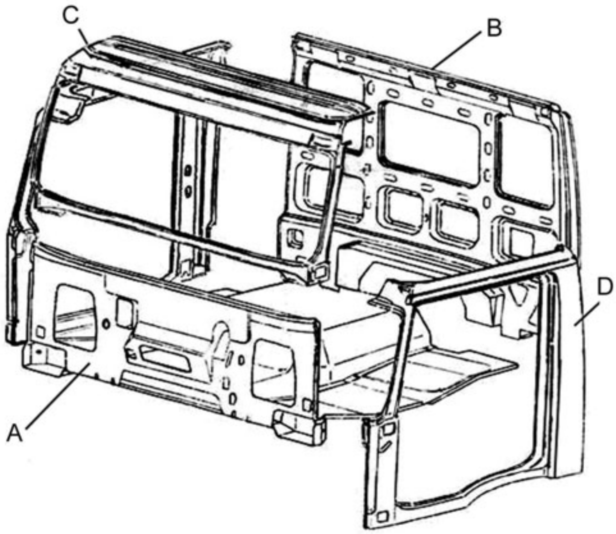


Fig. 4.103. Stamped sheet main sub-assemblies of a truck cabin: A) floor assembly; B) back panel assembly; C) windshield frame; D) RH and LH side frame.

- The engine compartment cover (central floor panel, as in Fig. 4.103) is unique as well as floor rails.
- The windshield frame has standard pillar outer panels, while cross members relate to cabin width.
- Cross elements, back panel assy and front cabin assy, are related to width.
- Different cabin lengths are obtained by adding cross floor panels relating to width and additional rail extension. Moreover, the rear side pillar is replaced by side stiffened panels, and assembled to the door opening and back panel.

Chassis

The chassis configuration is nominally ladder shaped, with two main longitudinal rails (usually constant cross section for small trucks and variable section for heavy duty semitrailers) and a number of cross members (Fig. 4.108).

The chassis rails and cross member can be steel cold or hot rolled or aluminum extruded profiles, welded in the case of tapered section. Rails and cross members can be joined using arc or spot welding, fasteners, bolts, screws. The assembling technology used is often not related just to engineering or design analysis but to the available plant facilities and common practice of the manufacturer. It should

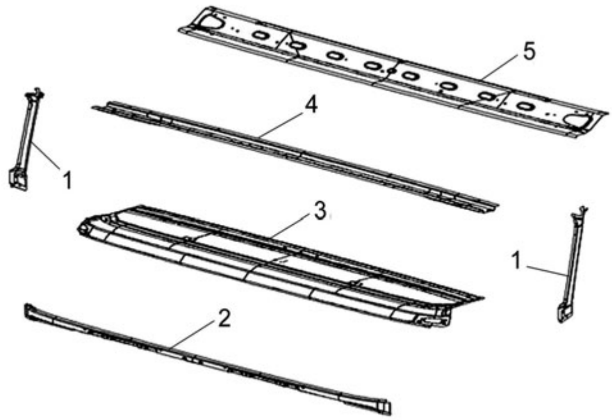


Fig. 4.104. Example of stamped elements for a truck windshield frame: 1) pillar outer; 2) top cowl; 3) windshield header; 4) header reinforcement; 5) header boxing.

be borne in mind that arc welding seams, mainly those between aluminum profiles, must be certified with x-ray images and 100% process parameters control.

Trucks specifications

The following list summarizes the most common specifications for these vehicles, according to commercial vehicles targets.

- Modal analysis of complete body: identification of resonance frequencies and associated torsion, bending and mixed vibration modes.
- Chassis acceleration measurement in vehicle mission targeted tracks and following frame fatigue test by bench three-axial loading: during durability testing, the cabin and suspended masses are missing.
- Chassis vertical acceleration in road targeted driving and following excitation in a climatic chamber, together with temperature cycling between –30°C and + 80°C, to verify cabin and trimming durability.
- Cabin frame resonances; resulting seats and steering wheel vibrations.
- Strength and deflection of roof composite panel under snow and concentrated mass load.
- Stiffness and strength of frame extensions, insert, reinforcement and rear pillar panel under concentrated load.
- Durability test of step sides, front fender and fender extension: verification of resistance to concentrated load and insert strength.

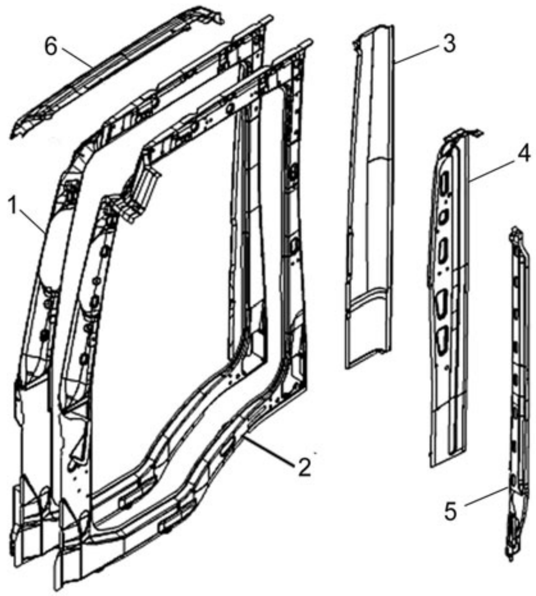


Fig. 4.105. Sheet stamped elements of a truck cabin side frame: 1) RH outer side frame; 2) RH inner side frame; 3) outer rear pillar; 4) rear pillar boxing; 5) rear pillar reinforcement; 6) RH upper side outer panel.

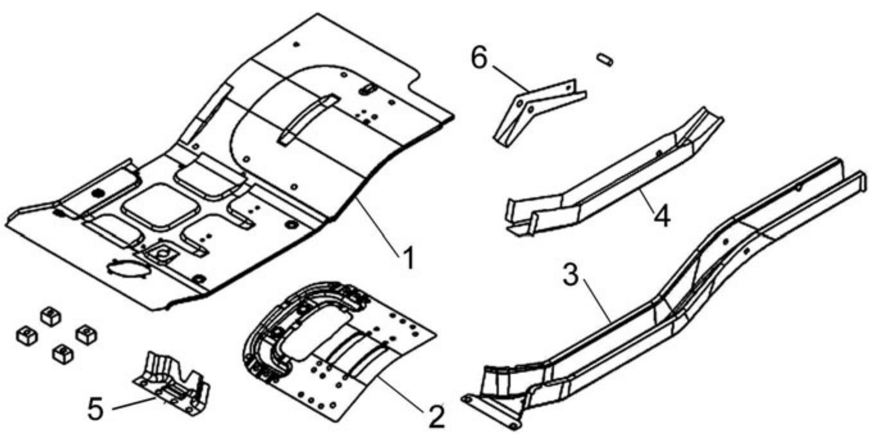


Fig. 4.106. Sheet stamped elements of a cabin RH floor: 1) RH side floor; 2) RH floor reinforcement; 3) RH rail; 4) RH rail extension; 5) RH rail front end brace; 6) RH rail rear end bracket.

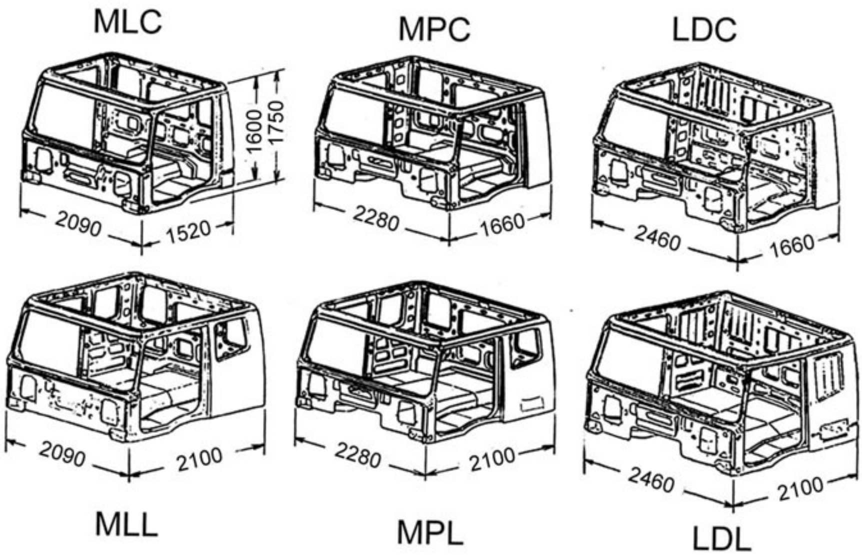


Fig. 4.107. Range of cabins assembled from modules of different length and width.

Fig. 4.108. Example of semi-trailer chassis with tapered section rails.

- Structural test on hood and front grille (local load resistance, insert pull-out loads, durability of gas lift anchorages and operation cycling).
- Aerodynamics add-on devices characterization.
- Test on roof trap-door (durability, effraction load, operation torque on opening handle, emergency device effectiveness).
- Strength test of transported cargo hooks and durability of luggage clamping devices (according to DIN 75410).
- Allowed noise level inside cabin.
- Fatigue strength of steering wheel (in torsion and bending), steering wheel adjustment device, steering column and handbrake assy mounting devices.
- Cabin door stiffness in all directions.
- Stiffness and fatigue resistance of sliding door in operation and slamming cycles.
- Performance and durability of door hinges, door brakes, door handle and roof handle.
- Performance and fatigue resistance of composite materials auxiliary doors and cabin console.

Of course, the body should also comply with all relevant regulations imposed in the country of the customer (regarding safety, visibility, etc.).

4.10.2 Pick-Up

These vehicles result from the union of a cabin for 2÷5 passengers (usually a derivation from a sedan or a SUV) with a rear bed for cargo (mostly open top with additional textile cover but sometimes sold in version closed by a hard cover).

A pick-up body relates principally to the reference vehicle frame: if based on a automobile platform, the underbody is not sufficiently stiff and strong to allow a complete separation of cabin and rear bed. Therefore an integral body side is needed incorporating the rear bed; this type is also called *coupe utility pickup*. If derived from a SUV or an off-road vehicle, usually the cabin and rear bed can behave as independent self supporting assemblies mounted on a common chassis.

The cabin can have 2 or 4 doors and short or long bed matching different chassis frame lengths.

The structural design of the cabin to bed union is the most critical detail of such vehicles, both in the case of integral and split body sides. In the first, the discontinuity of section and stiffness between the cabin and rear bed are the

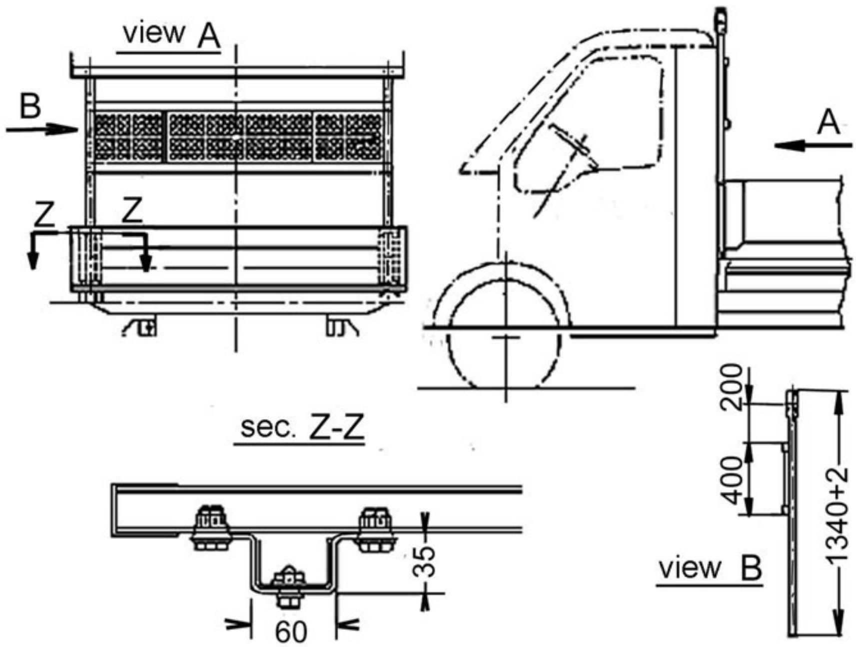


Fig. 4.109. Details of a pick-up or commercial cabin shielding frame, to protect the back cabin panel from forward freight motion.

most common cause of fatigue cracks on paved tracks; it is therefore necessary to avoid small radii and sharp stiffness change from boxed to open sections.

In the other case, due to lack in synergism of cabin and bed, the body stiffness in the interface region is conferred to the chassis frame, usually consisting in longitudinal rails and cross members and therefore the local stress is higher in this region.

As concerns the specifications and design criteria, the cabin has the same target as the reference vehicles, while the beds are similar to commercial vehicles and therefore have the following characteristic specifications:

- safety and stability of freight: for this purpose, the cabin back includes adequate trusses and shielding frames (Fig. 4.109) whereas the bed includes a number of hooks for goods clamping (Fig. 4.110);
- safety for other road users: side and rear protection bars are provided for this purpose (Fig. 4.111);
- warping and bending resistance of bed side walls and tailgate;
- absence of road noise, squeaks and rattles;
- resistance to environment-induced corrosion;

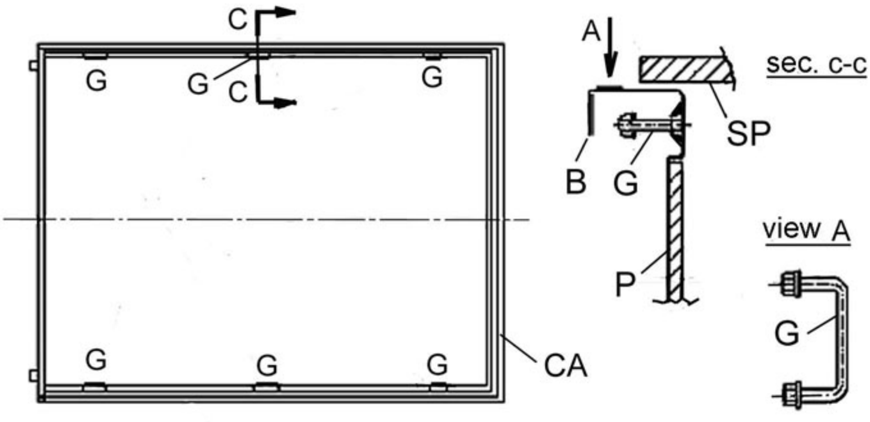


Fig. 4.110. Details of freight clamping devices in a pick-up bed: G) hooks; P) bed floor; B) frame; SP) bed wall; CA) bed.

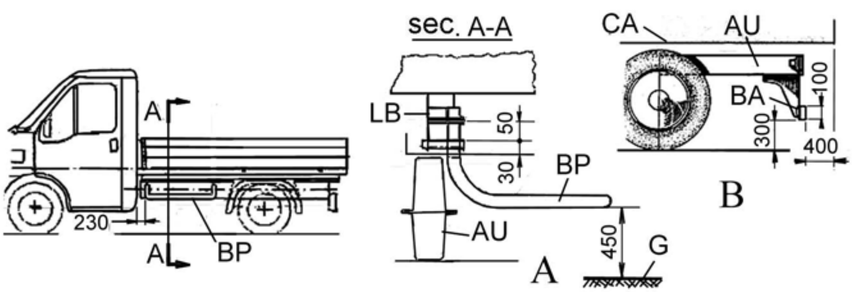


Fig. 4.111. Examples of side (A) and rear (B) protection for other road users. CA) pick-up bed; AU) chassis; BA) side protection bar; BP) rear protection bar; LB) underbody rail; G) ground.

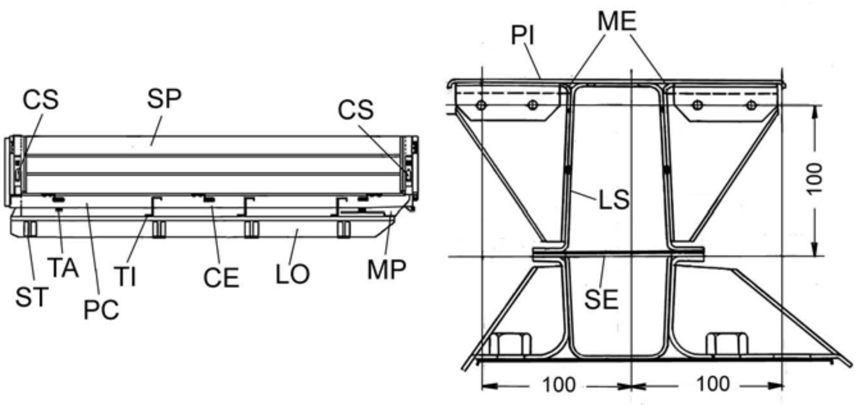


Fig. 4.112. Map of bed walls supporting devices and typical section of rail and cross member intersection. SP) side wall; CS) wall lock; CE) wall hinge; LO) platform rail; TI) intermediate cross member; PC) frame; TA) wall stop bott; ST) outer brace for platform fitting; PI) cantilever brace, one side zinc coated (cantilever side); ME) cantilever, one side zinc coated (interface with rail and brace); LS) upper rail, inner side zinc coated; SE) diaphragm between rails, two sides zinc coated.

- resistance to electrochemical or galvanic corrosion, mainly depending on the materials used for underbody, bed and fittings (Fig. 4.112);
- resistance to abrasion;
- fatigue resistance of rear bed to underbody fittings.

4.10.3 Commercial Vehicles, Vans

Vehicles belonging to this family are mid-sized vehicles in the range between cars and trucks, usually featuring a unibody offering performance closer to cars than to trucks.

The speed of these vehicles is similar to cars, while the cargo capacity and large side/rear opening dimensions cause an overall stress condition which is much more severe than in the automobile body. Underbody design is usually ladder shaped, with longitudinal rails and cross members welded to the floor; these parts are usually bent or rolled or stamped when required. The upper frame includes a cabin (usually featuring a line of three seats) and a cargo volume, separated from the cabin by a protection panel. The body side is made from a drawn outer panel and inner members stamped or curved as rings in the vertical plane, made from rolled or cut and bent steel sheets. The most critical part of this assembly is the rear end frame, ring shaped and strongly boxed.

The roof, commonly stamped in steel, is welded to the body sides with conventional automotive tools and stiffened by bows similar to cars. For some high or raised roofs, due to the lower production rate, fiberglass hand lay-up or resin transfer molding can be used instead of steel.

According to structural analysis, the most stressed areas of the body in these vehicles are the shock absorbers to underbody attachments (mainly due to the wide weight range of the transported goods which does not facilitate the optimization of shock absorbers setting), side door opening frame edges (due to door dimension and square shape, for comfort loading) and tailgate opening frame.

Another critical part is often the windshield glass, larger than in cars; the windshield opening frame stiffness, uniformity of bonding adhesive seam, adequate gap between body sheets and windhshield to avoid direct contact, are the most effective options to increase glass reliability.

With reference to materials and technologies, this family of vehicles has a more rapid rate of innovation and evolution than trucks and is more similar to that of cars: competition is fierce and customers are usually very attentive with respect to costs, insisting on added value provided by innovation. The annual average distance travelled is typically much higher than for cars and therefore, the durability of these vehicle must be higher than with automobiles; the renewal rate is no longer than 3÷4 years. As a consequence, innovation transfer from automobile to vans is frequent. In future more extensive use of aluminum in these vehicles body can be expected: in fact, the increase of payload with the same total weight due to a body weight reduction of 30% can quickly pay back the higher purchase price of an aluminum van.

Commercial vehicles specifications

- Torsional stiffness between axles (target specified by vehicle manufacturer).
- Bending stiffness between axles (as above).
- Dent resistance of outer panels, due to manual push or forcing, to snow load (hood and roof only) or to dynamic loads (hail, stones).
- Outer panel resistance to pumping (elastic instability under local pressure).
- Loaded cargo panels strength; absence of permanent deflection.
- Fatigue resistance of body and suspension, power train and auxiliary elements, under a four post paved road excitation.
- Fatigue resistance of suspension and power train attachments in a bench simulated mixed track, including brake, acceleration, curve and road bump loads.
- Fatigue resistance of suspension and power train attachments to underbody in a bench simulated urban track with heavy longitudinal stresses.
- Vertical elastic and permanent deflection of door, hinges and pillar system under static loading.

- Modal analysis of elastically suspended body without movable parts, with the purpose of finding torsion and bending, local and overall resonance frequencies, to face risk of interaction with suspension resonance frequencies.
- Inertance measurements on body in white subsystems attachments and verification of transfer functions from road to cabin through wheels and body frames.
- Static and fatigue resistance of tow device and related body attachments.
- Static and fatigue resistance of trailer tow hook, according to CEE 94/20 Directive.
- Static and fatigue strength of transport vehicle hooks and related body fitting areas.
- Static and fatigue resistance of fuel filler flap and related fitting devices.
- Static and fatigue resistance of roof rack anchorages in a bench simulated road track.
- Static door handles misuse and handles fitting strength.
- Hinges and door brakes resistance to strong wind blows.
- Door systems fatigue resistance to operation and slamming cycles.
- Static and fatigue resistance of all mechanical subsystems fittings (gear control, handbrake lever, steering column and gear, pedals housing).
- Static and fatigue strength of seats anchorage.
- Static and fatigue resistance of cargo clamps on body.

Of course, all existing safety regulations in the countries where the vehicles are registered must be respected as well as ratings related to lock effraction and insurance impact testing.

5
Body Components

5.1 Outer Body Components

5.1.1 Bumpers

Before the 1970's, bumpers were usually chrome plated or rolled and formed stainless steel leafs, the main function being aesthetic enrichment and protecting the car body against small impacts (Fig. 5.1).

Thanks to the Experimental Safety Vehicles (E.S.V.) (and later Research Safety Vehicle) Program , many studies and considerable research led to the definition of some basic design concepts of relevance such as:

- Front and rear end of vehicles should be able to absorb energy.
- The stiffness of body parts committed to energy absorption should increase as the passengers cabin is neared.
- The properties of traditional bumper leafs are completely opposite to those required, as they collapse in bending, with only low levels of energy absorbed.

As a consequence, the *soft nose* (Fig. 5.2) was born, consisting in: a) an outer flexible plastic shell (thermoset as polyurethane molded element by *R.I.M. - Reaction Injection Molding process* or thermoplastic injection molded as polyolephine or polycarbonate or blended thermoplastics); b) a metal support cross-member fitted to body frame through energy absorption devices; c) some polyure-thane or polyolephine foam insert in the space between.

L. Morello et al.: The Automotive Body, Vol. 1: Components Design, MES, pp. 207–437.
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Fig. 5.1. Example of steel stamped bumper (Cadillac).

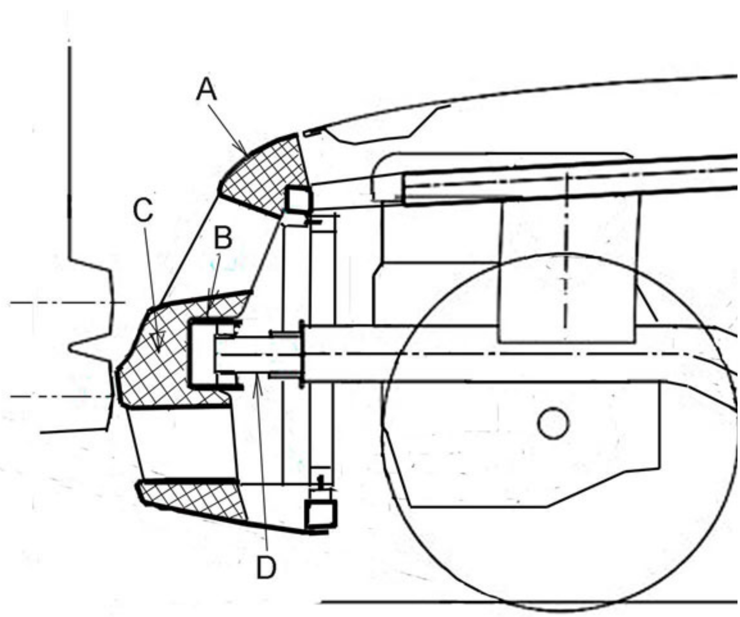


Fig. 5.2. Schematic section of high absorption front end: A) flexible skin; B) supporting bar; C) foam insert; D) absorbing/damping device.

The early design of this solution (Fig. 5.3) was proposed by research engineers and the overall appearance was bulky; since designers did not convert those shapes, such designs did not reach new models production. Later, a compromise was achieved which effectively lasted until the end of the 20th century, consisting in a plastic bumper considerably larger than the previous steel one, covering the entire lower part of body front and rear end.

This type of bumper is based on a shell (usually made by thermoplastic resin and therefore with low elastic modulus) of 3÷4 mm thickness which is easily deformable and therefore requires a large number of contact points with a steel or aluminum cross member support in order to absorb small impacts without permanent crushing (Fig. 5.12).

In the shrinking stage after molding, the thermoplastic material and molding process caused large random dimensional variations and consequent matching problems with adjacent parts such as fenders, hood, liftgate and decklid. Therefore the preferred matching design used stepped joints or significant play; bumper section in the X direction usually protrudes from the body and front grille by between 50 and 100 mm, this being needed in the first absorption step in order to avoid contact with more critical components such as lamps, radiator grille and movable parts.

Between bumper shell and support cross-member, foam could be inserted, as can be seen in some typical production sections.

The step of the bumper section with respect to the adjacent body profile represented an issue from an aesthetics viewpoint since designers aimed at flush surfaces. This problem was finally solved, thanks to the concurrent improvement of materials and molding process; in practice, on more recent cars, the bumper skin surface has been extended in height, so that relevant body parts have been covered without aesthetic discontinuity, both in front and rear body extremity (Fig. 5.4).

In practice, in the most recent models, the traditional bumper function is not achieved just by the bumper perimeter (as it cannot be distinguished from other body parts) but is developed under the skin, through absorbing, support and load transfer devices, positioned where needed and performing their task through a soft surface in order to reduce the risk of injuries in case of contact with pedestrians.

Table 5.1. Plastic bumpers evolution. For reference, see Fig. 5.5. Tp: thermoplastic; Ti: thermoset.

		plastic	absorption	color		
STEP	Years	type	insert	mass	painted	Fig.
1	70	Tp/Ti	no	x	specif	A
2	80-90	Tp>Ti	yes/no	x	grey	B
3	90-2000	Tp>>Ti	yes	x	as body	C
4	>2000	Tp	yes		as body	D

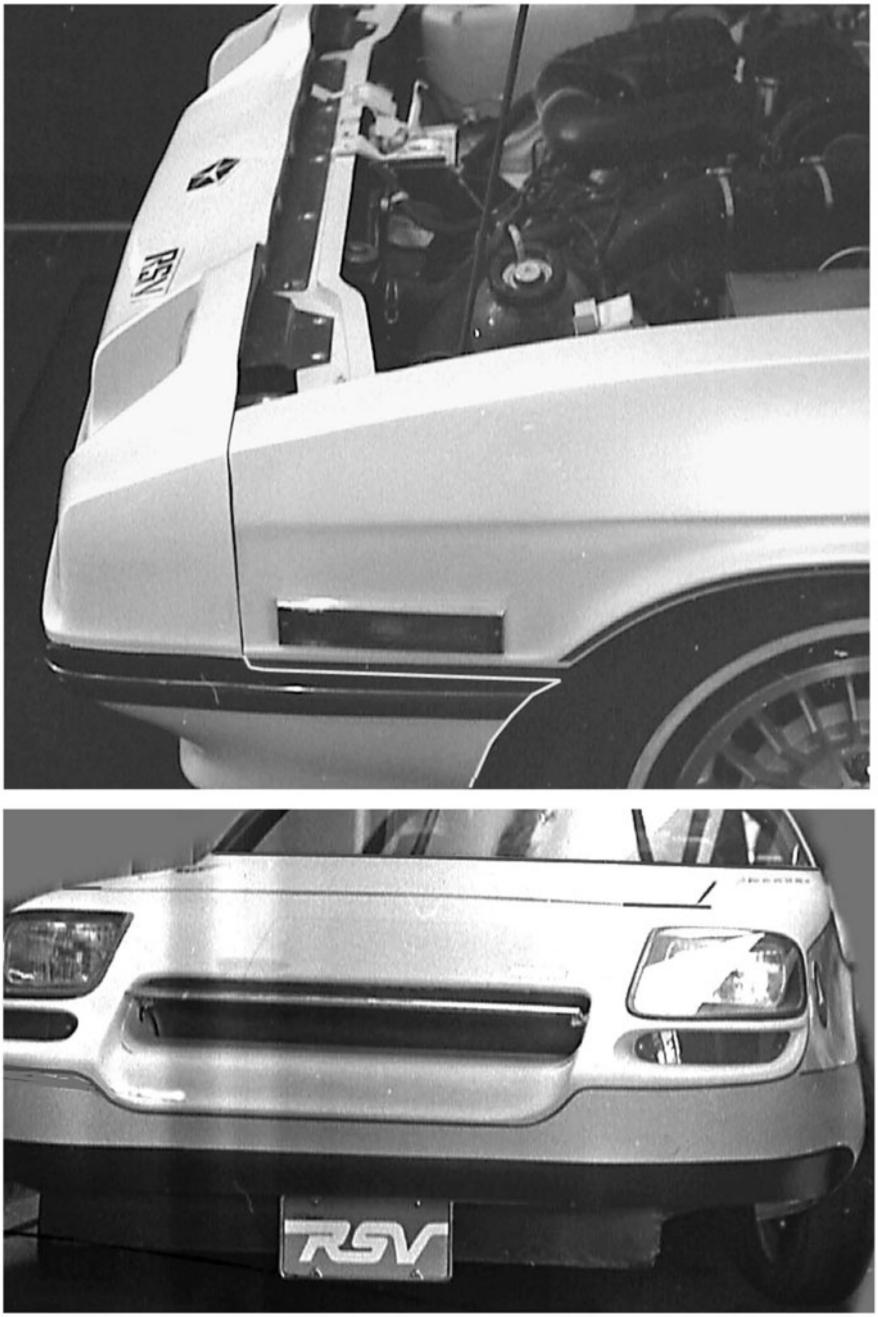


Fig. 5.3. Absorbing front end of R.S.V. vehicles (1973-75): Calspan (above) and Minicars (below).

Fig. 5.4. In most recent front end, as in Porsche *Cayenne,* the bumper skin is extended to bonnet contour, with aesthetic continuity.

It can be concluded that, following a rather complex and on-going process of evolution (Tab. 5.1 - Fig. 5.5), the design of bumpers is once more determined by its aesthetic properties, while the protection function in case of impact, originally less important, is now achieved by specific devices hidden under the bumper itself.

Consequently, the bumper of today is really an integrated body part (even made of a different material, despite being body colored), while before the 1970's it was essentially a component added for cosmetic purposes.

The mission of the bumper

The main bumper tasks include the following:

- aesthetics;
- overall body protection in parking impact (up to a speed of 4 km/h) or according to individual State safety rules;
- energy absorption and controlled transfer of stress to body frame, when impacted at 15 km/h (*insurance impact test*);
- aerodynamics;
- friendly contact (or absence of injury) in case of pedestrian's impact;
- support of winches or tow hooks for off-road vehicles (fig. 5.6).

Today most production vehicles have plastic bumpers painted in the same color as the body; in the case of special mission (e.g. use of bumper to tow or lift heavy masses as in case of off-road vehicles), metal painted or plastic coated

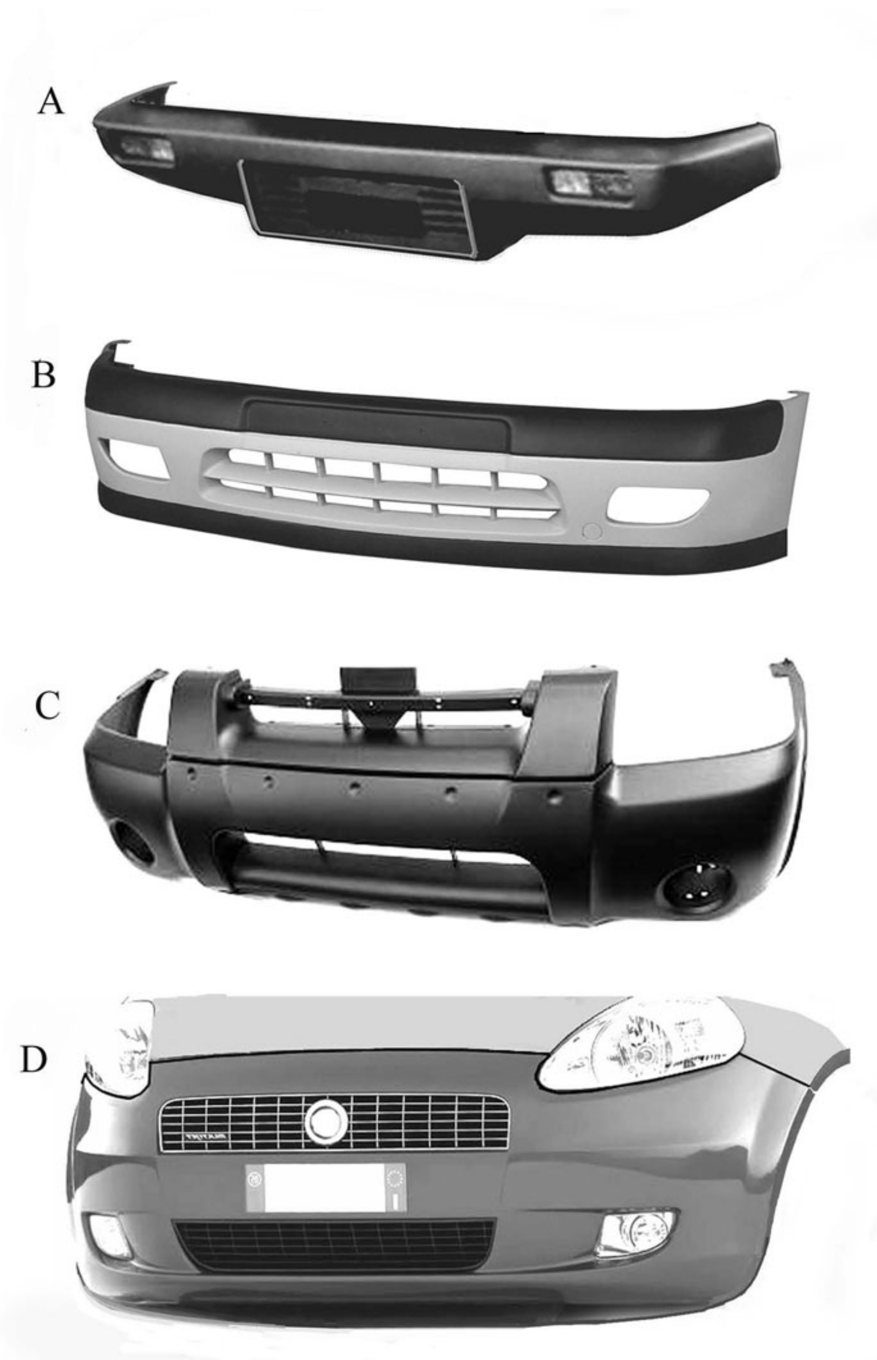


Fig. 5.5. Examples showing the evolution of bumper appearance (see A,B,C,D in table 5.1).

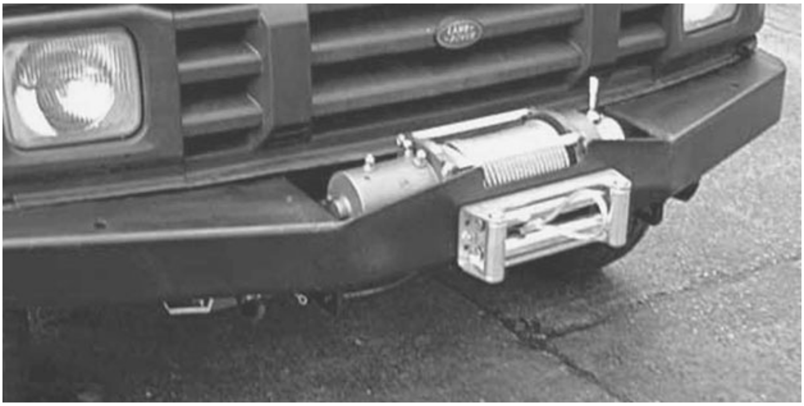


Fig. 5.6. Example of off-road steel bumper with integrated winch housing.

bars are in use, strongly connected to body; cheap vehicles, to reduce cost and chromatic body matching troubles, feature a different color for body and bumper (in this case bumpers are mass colored, usually grey or black).

Regarding crash tests required for the mandatory homologation, different regulations are applied in different countries; for instance, for years Canada and U.S. have required car components protection at a higher speed than in Europe, resulting in different designs of bars and absorption devices.

Fig. 5.12 shows a view of most common solutions in Europe, Japan and Korea.

Aesthetics (Style)

Bumper shape, gaps with respect to adjacent parts (lamps, fenders, radiator grille, bonnet), color, roughness (skin grain) are properties relevant to the aesthetics of the vehicle and are therefore modeled and specified by the styling centre. Skin radius must comply with the regulation limit of > 2.5 mm (in some areas > 5 mm) for all surface points that can be contacted by a 100 mm sphere.

Even the plastic blend used to mold the bumper should have a mass color not so different from the final bumper painted color in order to keep any abrasion or surface marking less evident. In some cases, only zones less exposed to damage are painted, while most zones with high risk of contact such as bumper fascia are left grey or black.

Protection in low speed crash (parking)

International regulations are explained in depth in Volume II.

Here it is appropriate to recall that, for European and Arabian State Rules (ECE 42), bumpers, both front and rear, must enable permanent functional damage to the vehicle to be avoided when impacted by a pendulum of mass equal to the vehicle curb weight, in three different transverse position and at a height of 445 mm from the ground.

The vehicle should be tested in three load conditions (curb weight, three people and full load).

Pendulum impact speed is 4 km/h or 2.5 km/h, depending on the impact position.

U.S. and Korea rules (U.S. Std. 581) request similar tests, with two different ground distances (406 and 508 mm) and no functional or aesthetic damage (*zero damage target*); the car is in curb weight. Moreover, front car behavior must be tested also in a barrier crash at 4 km/h speed: in such conditions some minor damage is allowed, but the vehicle must still be able to operate.

For Canada (Std. 215), the testing procedure is the same as the U.S. although the pendulum speed is 8 km/h or 4.8 km/h, depending on the impact position; the front barrier crash speed is 8 km/h.

These tests must be run also at low temperatures (–20 °C ÷ –30°C, depending on the State regulation). In this case the vehicle, or at least the relevant parts to be tested, is conditioned first in a room located close to the test facility.

Repair cost reduction

Most of road crashes are at low impact speed; if the equivalent barrier speed is higher than 8÷10 km/h, it is usual that the damage to those cars not equipped with special devices is relevant and the cost of repair is high. This is due to structural deformation even in the body main frame (for instance, front rails and engine compartment). As a consequence, repair requires not only replacement of the part, but even the complete removal of the power train and accessories in order to reshape or replace the deformed body frames. Also, it must be remembered that parts reshaped by stretching, hammering and welding no longer exhibit their original strength.

Due to the significant relevance of these issues, German Insurance companies were first to determine the premium of fully comprehensive insurance policies also as a function of repair costs. In order to evaluate those costs, cars must undergo some barrier impacts at 15 km/h (speed known as *insurance impact speed*) and consequently insurance experts evaluate the repair cost, according to *body shop standards* in order to determine the car rating.

In this context it is appropriate to consider some numerical evaluations of energy, load and deformation for bumpers involved in different crash situations.

The energy to be absorbed by a vehicle of mass m= 1,000 kg (in case of completely anelastic crash) while impacting a fixed barrier at speed V=15 km/h, is:

$$E_p = \frac{1}{2}mV^2 = 500\left(\frac{15}{3.6}\right)^2 \cong 8,680 \text{ J} \tag{5.1}$$

If the impact involves only a part of bumper (eg. an asymmetric barrier), so that only one body rail reacts, maximum rail resistance must be considered and compared with the body resistance in rail to body connection.

For example, such resistance can reach 50,000 N per rail in order to yield an adequate deformability and absorption capacity in high speed crashes.

If the target is to avoid permanent body crushing, the bumper should transfer to the rail, at 15 km/h speed, a maximum load lower than say 40,000 N (or 80% of rail strength, for example).

During load application, the reaction of the body is not constant, but increases up to a peak before decreasing: for simplicity, if we imagine a triangular load curve, the average value shall be one half of maximum peak, or 20,000 N.

Under such conditions, the bumper-rail-body system, compared to a spring, should be compressed of a d_p amount, without any other body to barrier contact:

$$d_p = \frac{E_p}{20,000} \cong 0.43\text{m} \tag{5.2}$$

Acceptable deformations for the elastic body and rail are of a much lower amplitude, meaning that the bumper alone would need to be deformed approximately by 40 cm! Clearly 40 cm of bumper guard, referred to the body contour, would be unacceptable not only for aesthetic reasons but also in terms of vehicle efficiency and handling.

On the other side, we have seen that a bumper must offer protection in low speed parking crashes ($V = 4$ km/h), against a free pendulum of same mass; in such conditions, the energy to be absorbed, E_0, is approx. 1/28 of the 15 km/h barrier impact energy, ie. 308 J.

Considering a bumper-absorber system with constant stiffness k, reacting with a load increase proportional to crush, for a 4 km/h pendulum impact, the system overall deformation is given by:

$$d_0 = \sqrt{\frac{2E_0}{k}} = \sqrt{616(\frac{0.43}{40,000})} \cong 0.081\text{m} = 8.1\text{cm} \tag{5.3}$$

And the corresponding maximum load F_0 will be:

$$F_0 = 2\frac{E_0}{d_0} = \frac{616}{0.081} \cong 7,605\text{N} \tag{5.4}$$

Correspondingly the design goal is to construct a bumper load transfer system that, for a 4 km/h pendulum impact, is loaded by 8,000 N and deformed a few centimeters, while at higher impact speed absorbing devices between bumper and body intervene, transferring five times higher loads without collapse and without permanent crushing of the rails.

Some different designs have been conceived to solve this problem, but conceptually all use either a metal or composite bar between the bumper and the body. This member provides support and reaction to the bumper over a wide surface (through a plastic, high-density foam insert, dimensioned for a 4 km/h impact). On the other side, the same member is screwed or welded to highly efficiency absorbing devices (offering a high mean collapse load to maximum load ratio), located between the bumper bar and the body rails. These devices are called *crash boxes* (Fig. 5.7), as

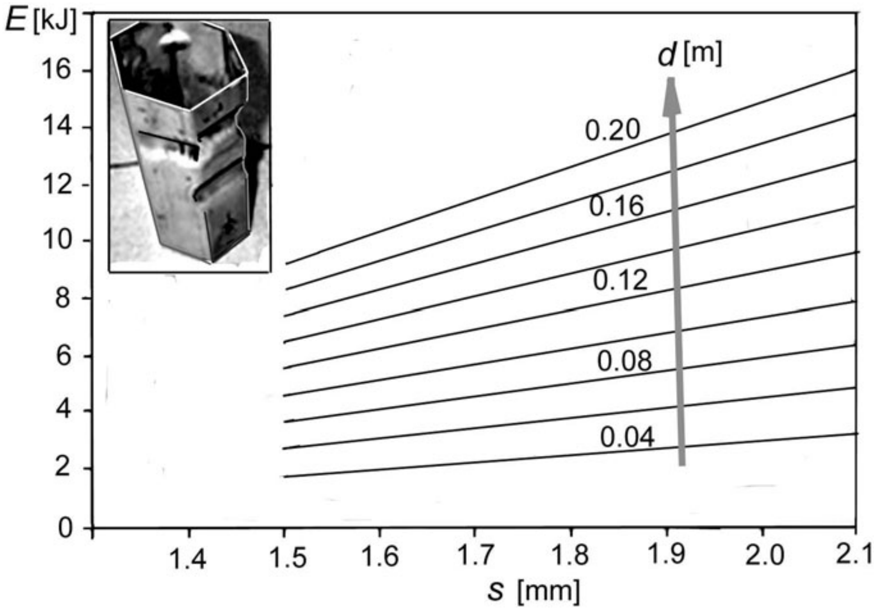


Fig. 5.7. Parametric properties of a typical crash-box. E: absorbed energy; d: total crush; s: wall thickness.

already mentioned in the chapter on *Bodywork*. The properties of these absorbers are controlled deformation and high efficiency, limited maximum load (so rails do not deform permanently) and minimized body crush, in order to prevent damage to vital components such as the radiator and engine pulleys. Their actual goal is to reduce repair cost rather than avoiding damage altogether mostly by avoiding removal and remounting of the power train.

In these solutions, bumpers share their function with a subsystem which is not crushable at impact speeds slightly exceeding 4 km/h which becomes a filter capable of absorbing energy in the speed range 5÷15 km/h. This subsystem is usually integrated in a front assembly module or a rear assembly module called respectively *front end and rear end* (Fig. 5.8).

Aerodynamics

Bumpers perform two main aerodynamic tasks: the first, as a body shape part influencing both drag and lift, the second, as flow conveyors or extractors both for the engine compartment and underbody.

In detail, the front bumper usually features a spoiler or *dam*, extending to the underbody (Fig. 5.9), having the purpose of accelerating the underbody air flow. In this way, negative pressure variation is generated, thereby decreasing front lift and, at the same time, the air suction from the engine compartment is facilitated. This process causes a change in the lift contribution of the different

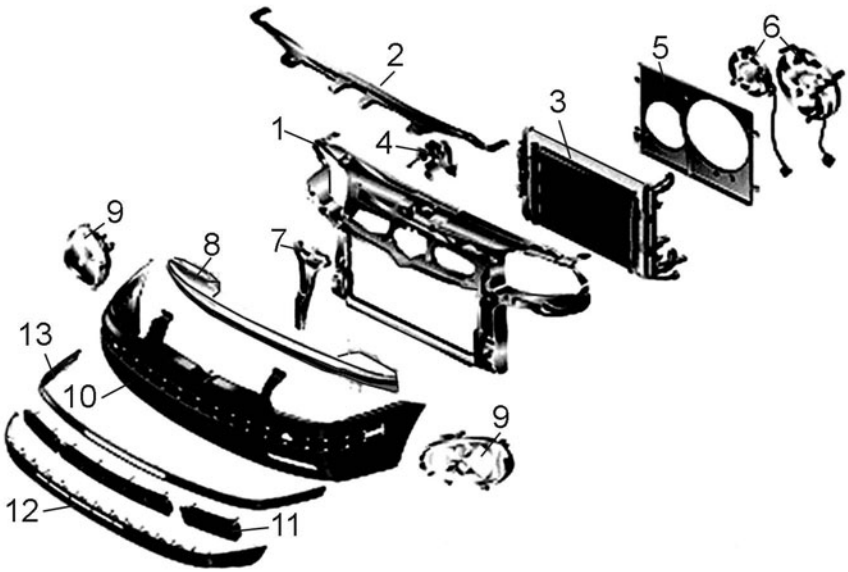


Fig. 5.8. Split view of the components usually assembled in a front-end module: 1) frame; 2) upper cross member; 3) radiators; 4) bonnet lock; 5) air flow channel; 6) fans; 7) central brace; 8) bumper bar; 9) projectors; 10) bumper; 11) foam energy absorbers; 12) dam; 13) fascia.

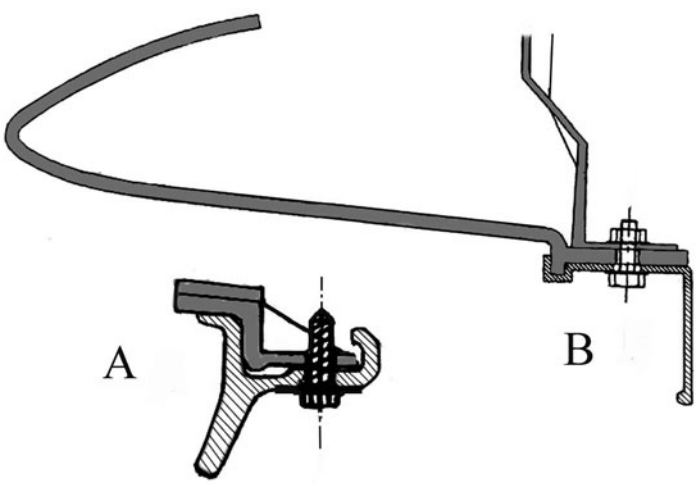


Fig. 5.9. Examples of front *dam* and fastenings.

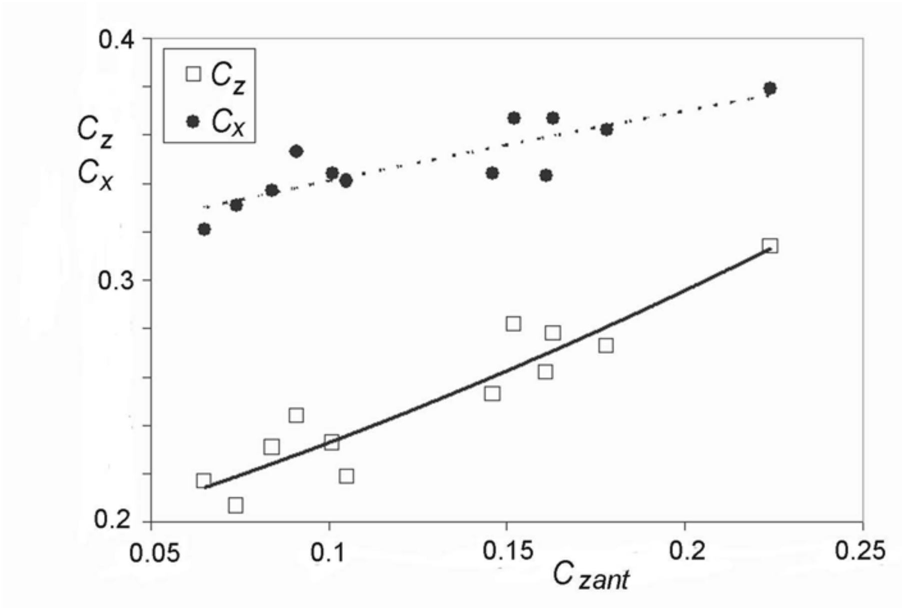


Fig. 5.10. Influence of front lift coefficient C_{zant} on overall lift coefficient C_z and on drag coefficient C_x in relation to different spoilers tested on the same car.

body zones, as it usually increases rear lift, resulting in a downward *pitching moment*. Nevertheless, the induced rear lift is usually less than the reduction in front lift, the combination being lower overall lift. The additional result is lower induced drag; therefore the advantage of an optimized front spoiler is reduced lift as well as drag coefficient.

Fig. 5.10 provides an example of the explained effect: the reported values have been measured with different front spoilers mounted on the same vehicle without other modifications.

Moreover, the bumper hump at the pendulum impact position, together with the front spoiler, determines the effectiveness of the radiator air intake. According to the aerodynamics of today's cars, the air intake is usually positioned in the lower bumper area, because here the peak aerodynamic pressure is exhibited, while over the hump and below the spoiler a negative pressure can often occur.

The dimensions and position of the air intake should be investigated in detail for a new model during the pre-engineering stage; later in the process it is much more difficult to change the style model while more powerful engine and air conditioning systems could require larger radiators that may not be compatible with the engine compartment space available and the car weight target. Therefore, an adequate virtual and experimental analysis is needed, both for air intake and ejection.

Fig. 5.11. Examples of openings in rear bumpers providing air extraction from underbody.

Sometimes, the rear bumper features air extraction from the underbody area (Fig. 5.11) to both control the wake and induce a reduction in rear pressure and consequently rear lift .

The aerodynamic performance of bumpers cannot be split from general body criteria; therefore usually no specification or aerodynamic design target, apart from the overall body development target, is set for them .

Low risk of injury to pedestrians

As explained in Volume II, specific regulations have been proposed in this area and currently the *EURO NCAP Rating* is applied; as a result car manufacturers are forced to develop front bumper design and softness that can achieve a good score in such a rating.

Today the bumper rating criteria are established by analysing the dynamic behavior of a system made by two articulated metal segments which represent a leg of a pedestrian hitting the bumper at a given speed.

Measurement parameters are accelerations, loads, bending moment, bending angles and shear between the segments. The consequent body design criteria are not specified. Correspondingly, virtual analysis and testing of impactor against the bumper are performed via an iterative process, the goal being to determine a compromise in terms of the behavior of the car and pedestrian during impact.

Other legislation constraint

In addition to the constraints cited which are specific for bumpers, often mandatory rules exist in individual countries requiring a specific solution; the consequence in terms of standardization is that the same solution is often adopted in other countries assuming no specific objections from customers arise. Some examples of this include:

- Wheels shielding, according to a defined perimeter (general rule).
- Splash shield dimension (Czech Republic, Poland, Hungary).
- Lamp installation (position and limits; general rule).
- Lamp wiping/washing (general).
- Licence plate housing – size 525x165 (general).
- Ramp angles and front overhang (Europe).
- Plastic parts marking (national laws).
- Cadmium and chlorine-fluorine-carbonate removal (general).

Common processes and materials

Fig. 5.12 shows a statistical comparison between different structural types and materials used in bumpers developed in Europe, Japan and Korea over recent years.

According to reasons explained in the paragraph on *the mission of the bumper*, the most rational solution uses high pressure injected thermoplastic material.

Thermoplastic materials, due to their high flexibility (low elastic modulus) and elasticity (deformation proportional to load) are able to absorb small impacts without any body damage and with only minor damage to the counterpart; moreover, the good moldability also makes these materials appropriate for practically all shapes, as required for reasons of aesthetics and aerodynamics.

High flexibility makes mold extraction from the die easier, even in presence of undercuts, without the need for movable die parts.

For this purpose, it is worth noting that extraction from a die is conditioned by the surface grain of the piece; when a plastic part is embossed, ie. when its skin is moulded in a die with embossed surface, the draft angle should be consistent with grain depth (Fig. 5.13).

Among the different thermoplastic materials, selection is conditioned mainly by the required thermal mission; in fact some materials are more resilient at low

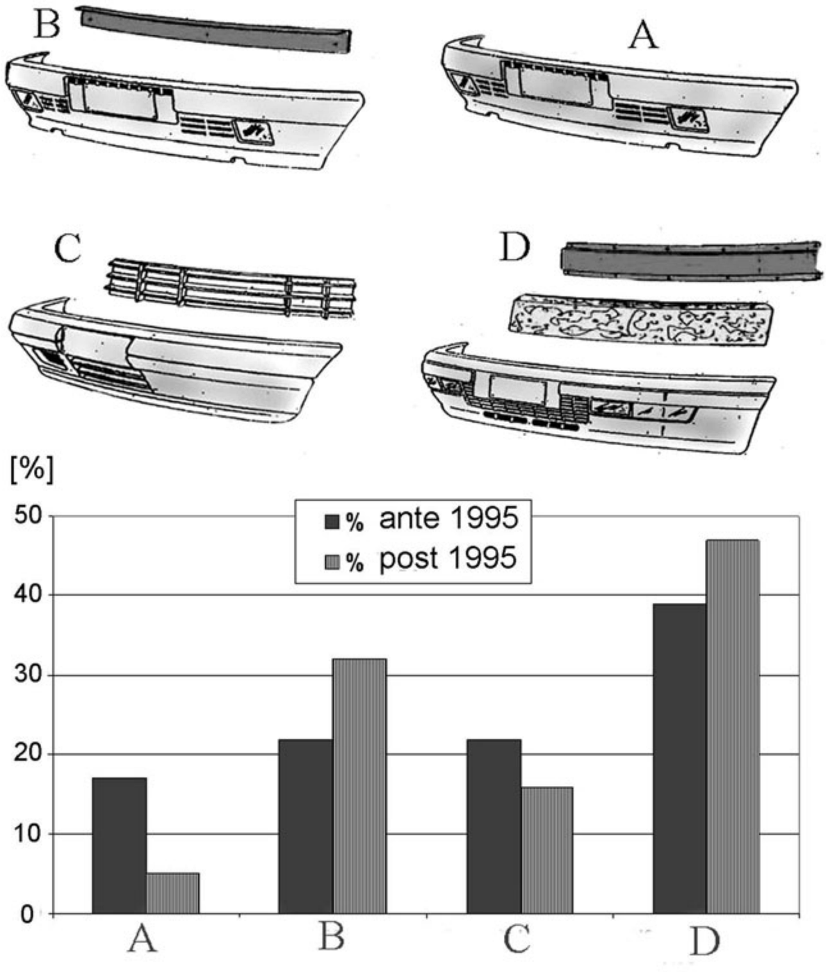


Fig. 5.12. Market analysis of different bumper types. A: self supporting shell; B: with metal supporting leaf; C: with plastic boxing; D: with foam insert and metal supporting bar.

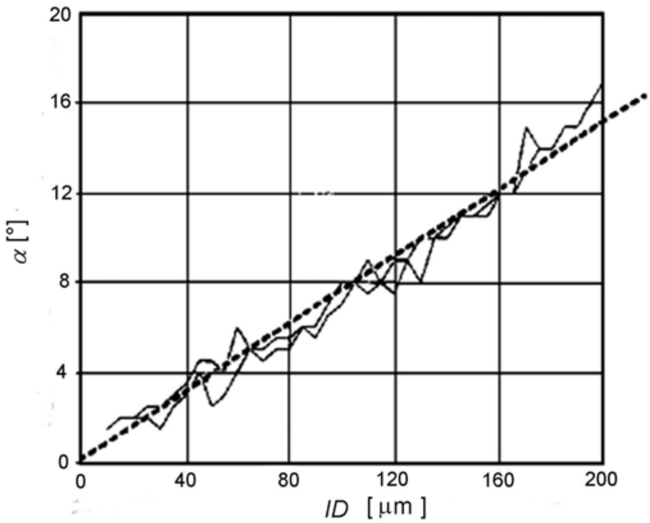


Fig. 5.13. Influence of embossed grain depth ID on bumper extraction requirements: α is the draft angle required.

temperature (<–30°C), a property which is clearly a priority for the bumpers of cars sold in very cold countries (Fig. 5.14).

With some exceptions, today polyolefin are used for most applications, even of large size, due to lower cost and substantially adequate properties in each of the salient tests (impact, chemical and aging resistance, moldability, paintability).

A persistant problem for all thermoplastics is the presence of unevenness or waviness on flat surfaces, due to cooling after moulding and aging under load (*creep*). These waves are unacceptable for class A parts and sometimes can be reduced by using ribs which must be very thin (otherwise sink marks can arise); otherwise support metal blades can be snapped on to the bumper.

High pressure injection is the most effective process, both in terms of the material properties and production cost (when production volume is consistent with higher die and press investments).

For small production volumes, low pressure injection of thermoplastics can be used or *Reaction Injection Molding* of thermoset (mostly polyurethane) plastics; in the latter case, the blend can be stiffened by adding short glass fibers (*R.R.I.M. process*).

Polyester and vinylester thermoset resins are not recommended due to their higher stiffness and lower resiliency. Moreover all thermoset materials face the problem of recycling.

Regarding energy absorbers for low speed crash, foam inserts (polyurethane or polypropylene or polystyrene) are used as well as plastic honeycomb injected

	DENSITY	FLEXURAL MODULUS (Mpa)	ELONG. AT BREAK (%)	BRITTLE TEMPER. (°C)	THERMAL EXP. COEF. X10-5/°C	ROCKWELL HARDNESS	SOFTEN. TEMPER. (°C)
TPO	0,97	1100	35	-40	11	65	80
PC/PBT	1,22	1700	120	-40	8	120	145/180
PA/PPO	1,07	2000	80	>-40	9,5	>100	130-175
RIM	1,05	200	250	-45	18	20	—
RRIM	1,13	500	100	-30	5	20	—

Fig. 5.14. Typical bumper materials properties in the 1990s.

polypropylene or polystyrene blocks, full of thin ribs; the selection is made according to cost and weight (Fig. 5.15).

Design criteria, materials and technologies

As explained above, the design specifications are related to:

- Impact, for contact with pendulum or barrier and fitting areas.
- Dynamic stress, where openings and notches can weaken the bumper.
- Thermal and mechanical stress in proximity of hot parts (eg. engine, exhaust system).
- Abrasion or break for ground contact, against ramps or platforms.

Size is related to material choice (in Fig. 5.16, materials used recently are shown): for polyolefin (polypropylene, polypropylene with EPDM) the recommended outer skin is 3÷3.5 mm, if a support metal blade exists; 3.5 mm, if a plastic boxing is welded to the outer skin; 4.0 mm if the bumper is self supporting. Plastic boxing requires at least 3 mm thickness.

The highest thickness is needed with low flexural modulus polypropylene (550÷800 Mpa), the lowest if high modulus is used (up to 1800 Mpa). In Fig. 5.14 the mechanical and thermal properties of frequently used materials are compared.

For energy absorbers, polyurethane or polypropylene foam with a density of 40÷50 km/m^3 are commonly used.

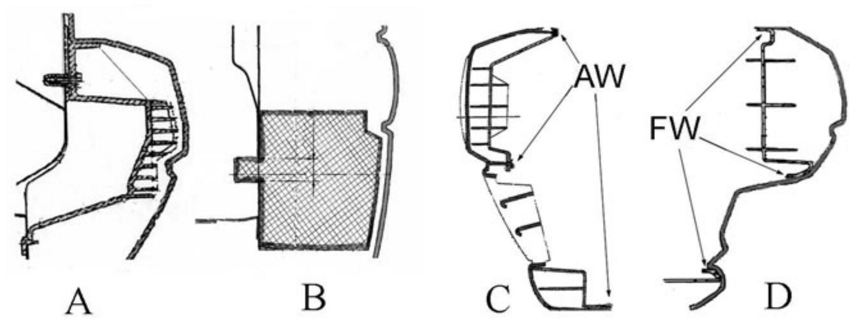


Fig. 5.15. Examples of energy absorbing insert and boxing technology. A) rigid plastic insert; B) foam insert; C) boxed plastic molding, fitted to the bumper by local heat staking; D) boxed plastic molding, friction welded to bumper. AW) heat staking; FW) friction welding.

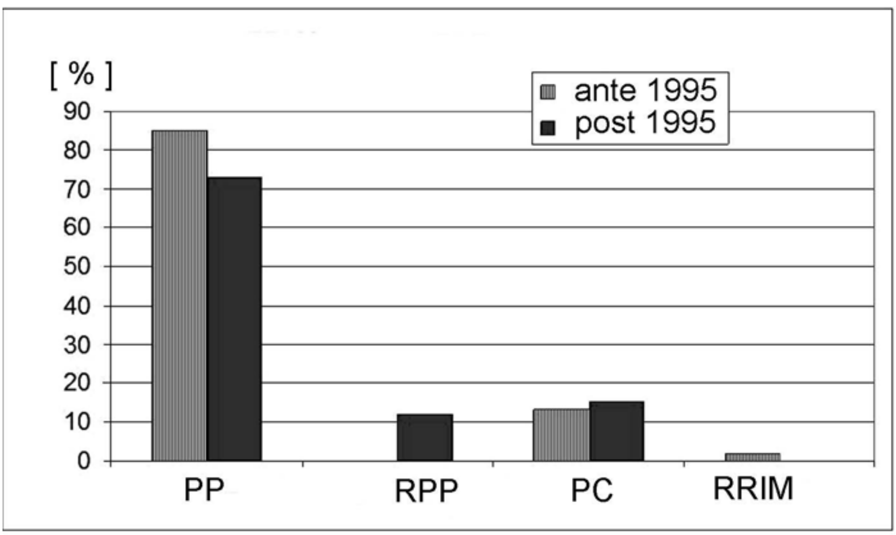


Fig. 5.16. Market share of the most-used bumper skin materials in the 1990s: polypropylene PP, reinforced RPP, polycarbonate PC, RRIM.

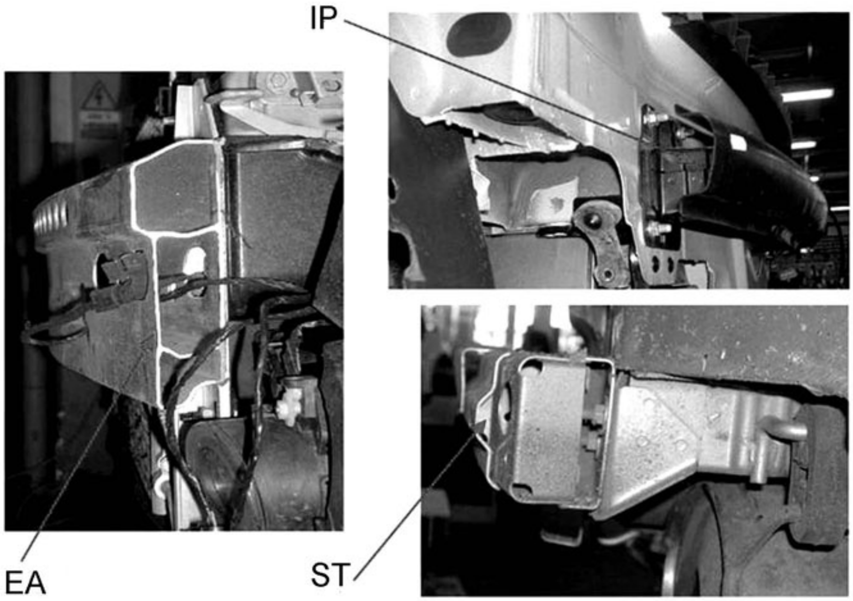


Fig. 5.17. Examples of different materials and technologies for bumper cross member. IP: injection molded thermoplastic; EA: extruded aluminum; ST: steel.

For pedestrian protection purposes, the local dynamic stiffness should not exceed 150 kN/m and the allowed deflection space behind the bumper should be not less than 100 mm.

Fig. 5.17 illustrates some front bumper cross-members in aluminum, plastic and steel. Assembly of different bumper parts can use a variety of processes (welding, embedding, plastic pin staking, as shown in Fig. 5.15).

5.1.2 Grilles

The main technical goal for a radiator grille is air flow control through an adequate intake duct, between the radiator grille and radiators (usually the air-conditioning condenser is coupled with the engine cooling radiator). When the sealing of the intake duct is missing or poor, due to local leakage air can escape from holes where pressure loss is lower than through radiators and air recirculation around radiators is possible, causing an increase in air temperature instead of cooling.

Today the air intake for the passenger compartment has adequate dimensions, leading air flow through the heat exchangers of the conditioning system. Instead originally they were simple, direct louvers between cabin and environment,

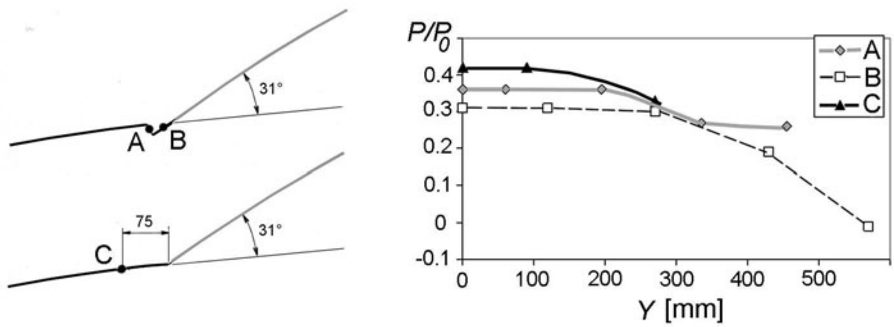


Fig. 5.18. Aerodynamic pressure close to lower windshield boundary, recorded on a clay model in the wind tunnel. P/P_0 is the ratio between local pressure in 3 different clay points and dynamic head, measured at different Y distance from mid vehicle longitudinal section.

usually small, often hand operated and only capable of capturing air flow layer adjacent to the body surface.

Air outlets have been introduced successively to supply a washing flow through the cabin, in order to eliminate internal humidity which causes the misting of glass. Originally the preferred position for outlets was on the rear side pillars, completed by louvers and labyrinth ducts, to avoid water and noise ingress.

Thanks to significant experience matured during road testing and in wind tunnels, different solutions have been abandoned or re-oriented towards the following solutions which are now widely adopted on different cars:

- air intake in front of windshield (being a zone of maximum aerodynamic pressure – Fig. 5.18), with aesthetic louvers or under the hood, with a simple shielding cowl louver;
- air outlet in the back body angle area (negative pressure), for example in side liftgate drain channels, or hidden under rear bumpers (see Fig. 5.19). Adequate verification is needed to ensure that no exhaust gas recirculation toward the luggage compartment exists.

Design specifications

Aesthetics and performance are the principal targets: flow effectiveness (not only in terms of pressure losses and flow rate, but also noise, recirculation and water ingress); resistance to small impact stress, snow loading and contact with external bodies; resistance to chemical agent deterioration, UV rays, thermal variations; resistance to painting and chrome coating, no whitening of black mass colored grilles; radii according to international safety standards.

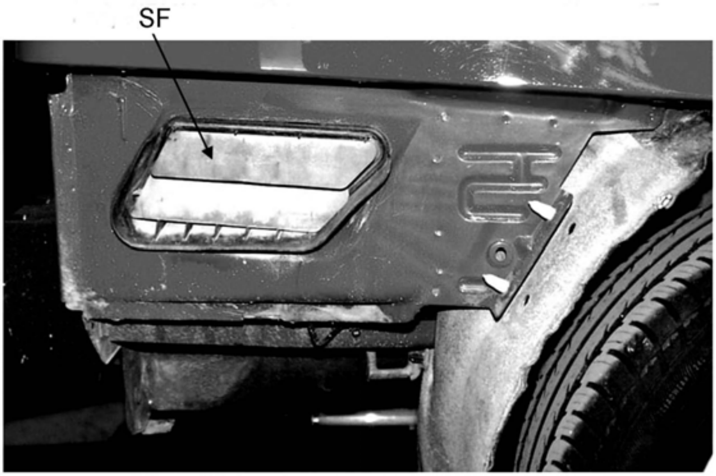


Fig. 5.19. Example of cabin air outlet featuring rubber flaps SF, positioned in the rear portion of quarter panel, below rear bumper.

In aerodynamic model analysis, the most effective body areas for air intake and outlet are selected. In the following stage of aerodynamic full scale verification in wind tunnel, prototypes of grilles are installed (made from wood or fast prototyping materials) at the entrance of the ducts, with dimensions to yield the same pressure loss through:

- the engine compartment, in the case of the radiator grille
- the passenger compartment, in the case of the cabin air intake and outlet.

In the stage of detailed component design, a mathematical model of the grille is analyzed in terms of structural and aerodynamic performance; prototypes are then verified during road and wind tunnel testing. In most cases, road testing suggests design changes for radiators and intercooler air intake, with consequent design changes for radiator grille and duct. Even water spray tests in rain chambers often exhibit lack of drain or protection against water overflow in ducts connecting the grilles to the passenger compartment.

Grille materials and technologies

Usually grilles are injection molded. The choice of material is conditioned by the following parameters:

- Thermal elongation; for instance, the cowl louver is as wide as the car and therefore is often split into two halves. (Fig. 5.20 – B)

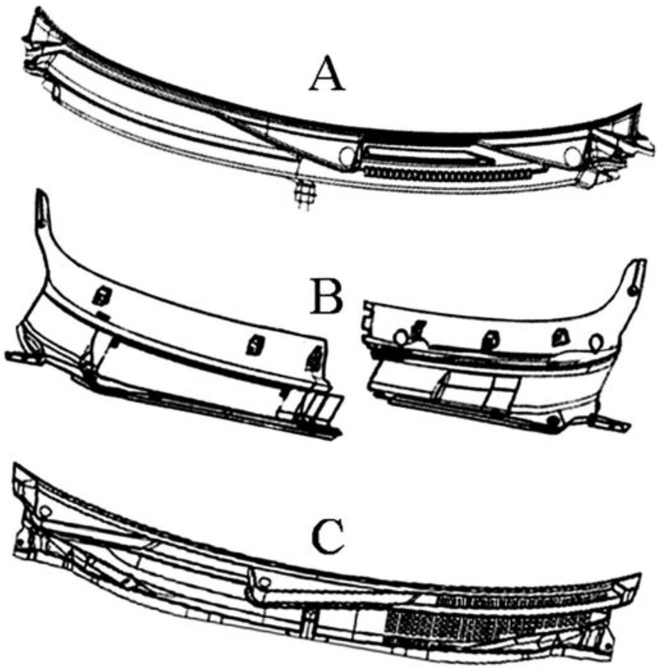


Fig. 5.20. he most common windshield grille designs. A: one piece grille, screwed to body; B: split grille with screw and snap fittings; C: one piece grille with continuous windshield side fitting.

- Thermal resistance, due to the grille being positioned close to the radiator or in the rearmost upper engine compartment zone where the temperature can reach 90 °C.
- Surface finishing (painting or chrome plating) by chemical deposition process or by simulation through special painting or hot pressing.

In table 5.2 the most commonly used grille materials and surface finishings are listed, both for single piece and split grilles. As regards fittings, less than 10% of grilles are simply screwed on, about 30% are snapped on and 60% adopt a mixed fastening solution.

Regarding the cowl louvers and the presence of boundary seals, common alternatives are shown in Fig. 5.20. It can be noticed that sealing under grille contour is recommended when the grill can contact the windshield, both for aesthetic reasons and to avoid windshield abrasion.

In Fig. 5.21, a grille section is visible using three different ways of fastening: snapped on (in the windshield sealing area); by self threading screws and plastic clips (in zone of the cross-member sheet); by interference (below the hood gasket). In the same figure, the grille tooth that is embossed in lower windshield

Table 5.2. Material, finishing and morphology of most common radiator grilles. I: Italy; E: Europe.

		one piece				split		
RE	material	chrome	black	color	total	chrome	color	total
E	ABS	9%	13%	17%	39%	26%	9%	35%
	ASA			9%	9%			
	ABS+PC					9%		9%
	PA					4%		4%
	BMC			4%	4%			
	total	9%	13%	30%	52%	39%	9%	48%
I	ABS				5%			53%
	ABS+PA							25%
	PP				17%			
	total				22%			78%

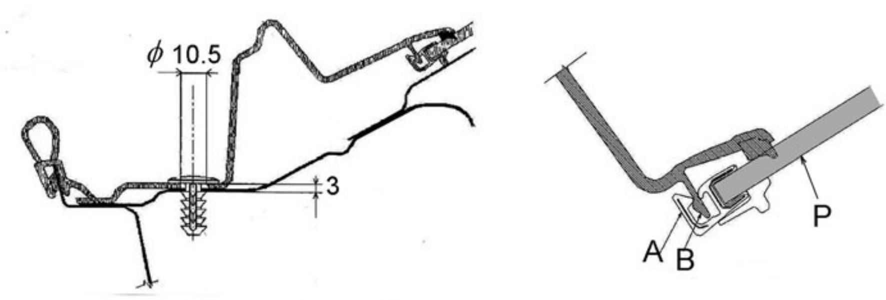


Fig. 5.21. Example of grille below the windshield with different types of fittings. On the right section, a flexible lip fitting to the windshield is shown. A: armed lower windshield gasket; B: grille fastening tooth; P: windshield.

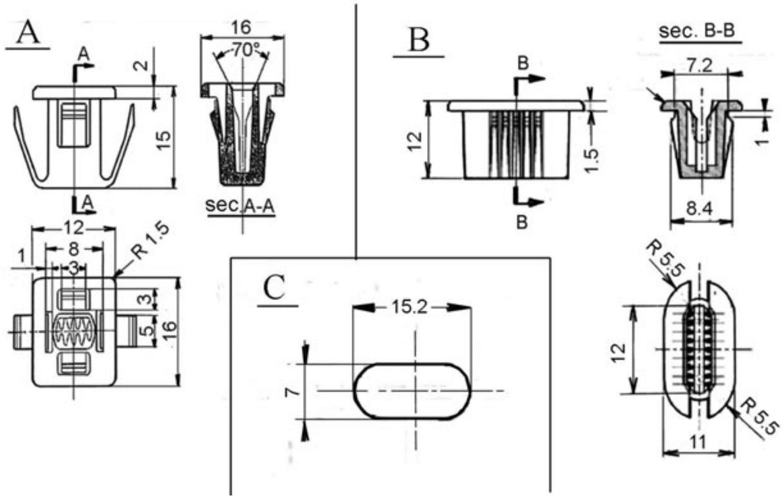


Fig. 5.22. Examples of plastic clips for self threading screws (A and B) and slot design for supporting sheet (C).

gasket is detailed as well as the flexible lip applied to the grille in the windshield contact area.

Regarding the plastic clips for self threading screws, a wide range of types is available.

Two of these are shown in Fig. 5.22.

In Fig. 5.23, sections of production cars are shown, together with their different fastener types including screws, plastic clips, nuts and the required slot size for metal sheet.

The allowed grille play can be computed starting from reference body hole (usually on mid car section), by the thermal elongation coefficient α of grill material and the maximum temperature range in car use (commonly from –30°C up to +80°C). If the grille reference production temperature is 20°C and grille span is l=1500 mm, the dimensional variation Δl at the grill farthest from the mid-car section will be:

$$-\Delta l = 0.5\alpha l(-30 - 20) = -25\alpha l \quad (5.5)$$

$$+\Delta l = 0.5\alpha l(80 - 20) = 30\alpha l \quad (5.6)$$

For instance, with the most critical material (Polypropylene), assuming a value of α=15x10^{-5}, the expected dimensional variations are as follows:

In cold condition: Δl= – 5.6 mm

In warm condition: Δl= +6.7 mm

Table 5.3 reports some statistical data concerning the different types, materials and fasteners commonly used by car companies.

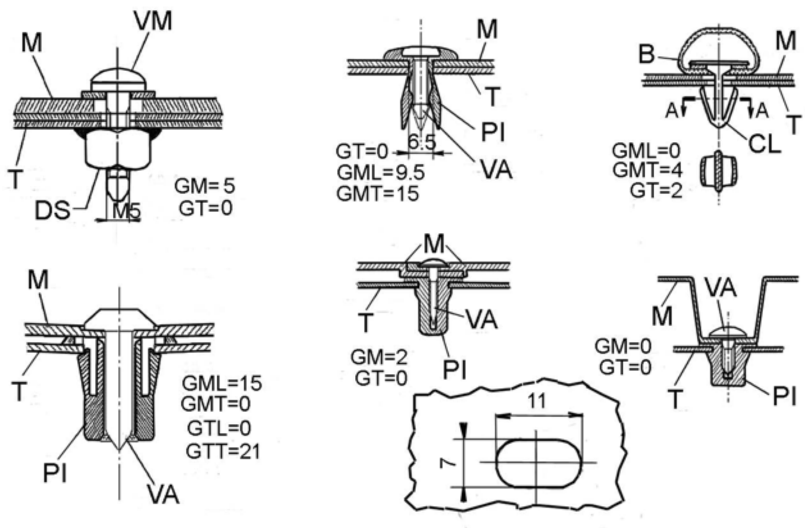


Fig. 5.23. Examples of plastic inserts for grille fitting and play needed on grilles and metal sheets. M) grille; T) upper cowl; PI) plastic insert; CL) clip; VA) self-threading screw; VM) metric screw; DS) weld nut; B) bulb; GM) grille play; GML) longitudinal grille play; GMT) transverse grille play; GT, GTL, GTT) slot plays.

Design criteria

For a radiator grille, the most important performance parameters are: the incident angle of blades referred to the local air flow vector, blades shape (profile, distance between clamps, thickness, length), radii and frame design, influenced by dynamic stresses (aerodynamic pressure, vibrations, small impacts) as well as by the air flow channeling task. Together with the structural strength of grilles, it is very important to keep the air intake energy loss as small as possible and therefore optimize grille profiles (Fig. 5.24).

A similar concept applies to the cowl louvers.

For outlet grilles, usually located in hidden zones, the design of the rubber flaps (when present) is performed according to the pressure difference between the passenger compartment and external environment and to the correct opening direction.

Today, air extraction from the cabin by the correct positioning of outlet openings in a de-pressure zone is rather less important in terms of achieving good reduction in cabin humidity since the commonly used air conditioning systems are very effective and rapidly dry the air; nevertheless outlets are still useful in whatever position for easier door closing. In fact, when the windows and outlets are closed, door closing causes a light overpressure in the cabin. Experience on

Table 5.3. Common windshield grille (cowl louvers) properties.

MATERIAL	Japan	Germany	France	Italy
PP	100%	67%	37%	72%
PP+EPDM		8%	38%	
PC-ABS		17%		
ASA		8%	25%	
MPPO				14%
PUR				7%
METAL				7%
GASKET				
no one		10%	25%	29%
comoulded		20%	38%	18%
foam	50%			12%
bonded	50%	60%	37%	41%
snapped		10%		
FITTING				
screws		8%	49%	65%
clips	50%	25%	38%	6%
mixed	50%	42%	13%	29%
on windshield		25%		

cars without outlets has shown that it is easy to reduce the energy of door closing simply by opening a window a little. This can be explained in terms of the transformation of kinetic door energy into work during gaskets deformation and cabin air compression.

At first contact with the locking device, the door must still have enough energy to firmly clamp the locking ratchet. If energy consumption for cabin air compression is reduced, because air can escape from partially open windows or from open outlets, the residual door energy to clamp the ratchet is higher or, instead, a lower launching energy is needed to achieve door locking.

A simple mathematical model of first approximation can be used to evaluate the outlet opening size influence on door closing loads (Fig. 5.26).

Let J be the door moment of inertia, A the door surface surrounded by the weatherstrip, L the distance from latch to hinge axis, φ the door opening angle, starting from designed closed position, V_0 the starting cabin volume full of air of density ρ and ambient pressure p_0. Let the total cabin air outlet surfaces be A_s.

If we suppose to launch the door with a starting angle φ_0, linear speed v_i in latch position and therefore with a starting angular speed $d\varphi/dt = v_i/L$, the door will be slowed by the elastic and damping weatherstrips reaction, resulting in a braking moment $M_G(\varphi)$, theoretical value of which is shown, as an example, by Fig. 5.25.

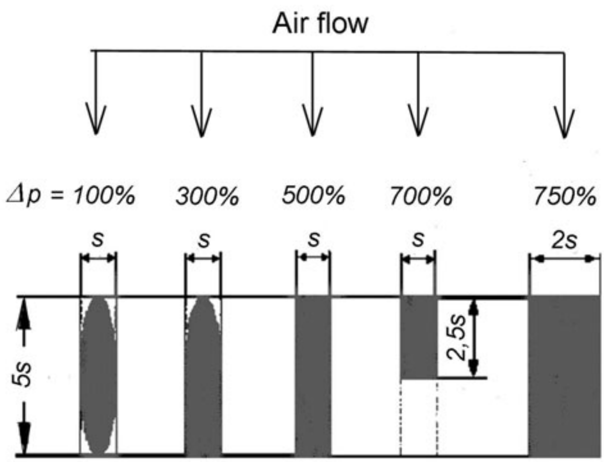


Fig. 5.24. Influence of grille profiles shape on aerodynamic pressure loss Δp, related to the reference profile ($\Delta p = 100\%$).

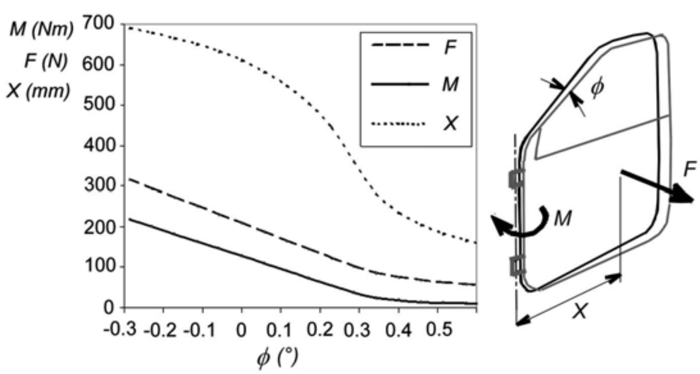


Fig. 5.25. Load F, moment M and load leverage x, caused by the primary door weatherstrip, displayed as a function of door operating angle φ. When the value $\varphi = 0$, the door is in closed design position.

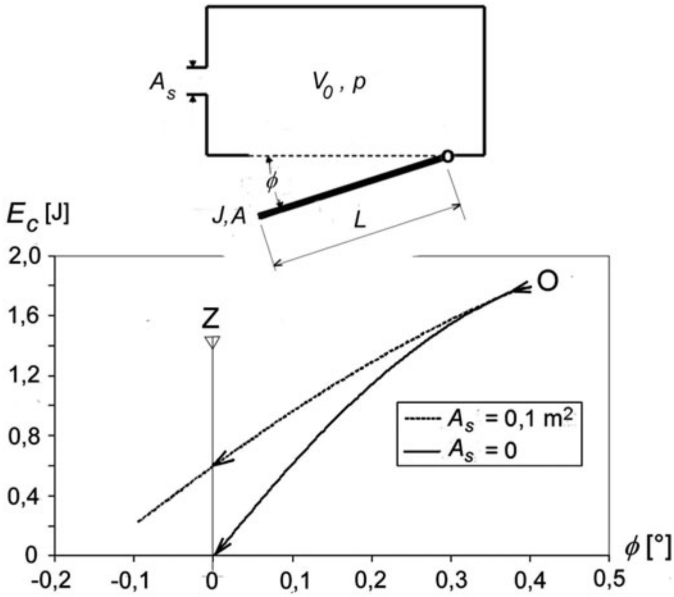


Fig. 5.26. Computed graph of kinetic door energy E_c while closing, in two conditions: a) without cabin air outflow; b) with outlet open section $A_s = 0.1\ \text{m}^2$. Starting point: O; first lock contact point: Z.

In the time interval Δt, the air mass

$$\Delta m_e = \frac{\rho A L \Delta\varphi}{2} = \frac{\rho A v_i \Delta t}{2} \tag{5.7}$$

shall be pushed into the cabin, causing an overpressure Δp that, in absence of outlets, can be computed as an adiabatic transformation (k being the adiabatic exponential coefficient):

$$\Delta p = p - p_0 = p_0 \left[\left(\frac{\rho V_0 + \Delta m_e}{\rho V_0} \right)^{\kappa} - 1 \right] \tag{5.8}$$

In the case of openings, the cabin overpressure due to an additional air mass Δm causes an air escape with speed w which can be computed by the adiabatic duct outflow expression:

$$w = \sqrt{2 \frac{k}{k-1} p \frac{V_0}{(\rho V_0 + \Delta m)} \left[1 - \left(\frac{p_0}{p} \right)^{\frac{k-1}{k}} \right]} \tag{5.9}$$

The escaping air mass $\varDelta m_u$ over the time interval $\varDelta t$ is therefore given by:

$$\varDelta m_u = \rho w A_s \varDelta t \tag{5.10}$$

In the presence of outlets, the resulting cabin pressure variation due to air ingress $\varDelta m_e$ and air escape $\varDelta m_u$ shall therefore be:

$$\varDelta p = p_0 \left[\left(\frac{\rho V_0 + \varDelta m_e - \varDelta m_u}{\rho V_0} \right)^{\kappa} - 1 \right] \tag{5.11}$$

And the additional slowing moment (due to weatherstrips) shall be M_p:

$$M_p = A L_p \varDelta p \tag{5.12}$$

where L_p is the distance of pushing force from hinge axis, close to $L/2$. Correspondingly the differential equation of the door dynamic balance is:

$$J \frac{d^2\varphi}{dt^2} + M_G(\varphi) + M_p(\varphi) = 0 \tag{5.13}$$

Step-by-step application of these formulae to a door model, leads to the graphs presented in Fig. 5.26 using the following parameters:

J = 8.8 kgm^2; L = 1.1 m; A = 1.2 m^2; V_0= 2 m^3; v_i = 0.7 m/s; ρ = 1.29 kg/m^3; κ = 1.4.

In this figure two different air outflow conditions have been considered:1) outlet closed; 2) outlet size = 0.1 m^2, similar to a part opened window glass; in both conditions, the simulations start from the beginning of the weatherstrips reaction.

The choice of the weatherstrip stiffness and damping, starting door angle and launch speed have been made, for illustration purposes, such that in the closed outlet solution, no energy is saved at the first locking position. As can be seen from Fig. 5.26, in the same position the other solution, with an outlet size of 0.1 m^2, still retains sufficient energy to enable the latch (second lock) to be clamped firmly .

Therefore, using the simulation model shown, it is possible to evaluate the influence of total outlet size A_s both on the residual kinetic energy and on the slowing moment applied to door (Fig. 5.27).

It is appropriate to remark that air outlet provides two concurrent benefits: a greater amount of kinetic energy is saved when approaching the door latch, while the braking moment, that contrasts full door locking, is reduced.

It can be noticed that, in the model, an opening surface of 0.04 m^2 can cause a relevant reduction of door braking moment and still leaves some kinetic energy for locking.

According to several simulations, consistent with car testing, an outlet air surface of at least 0.02 m^2 can be recommended.

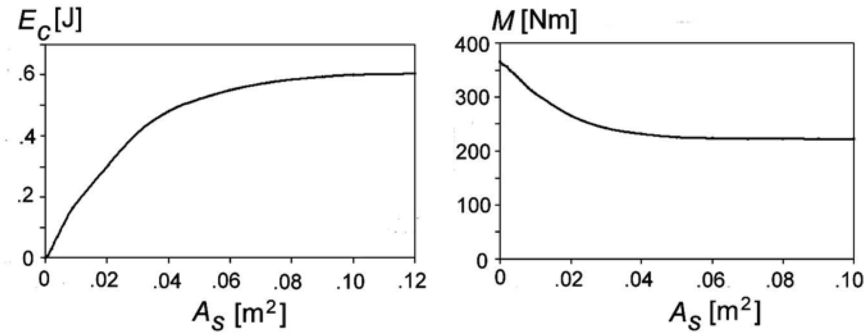


Fig. 5.27. Computed influence of cabin air outflow surface A_s on residual kinetic energy E_c of a door, at first contact with locking device and on overall braking moment M, applied to door.

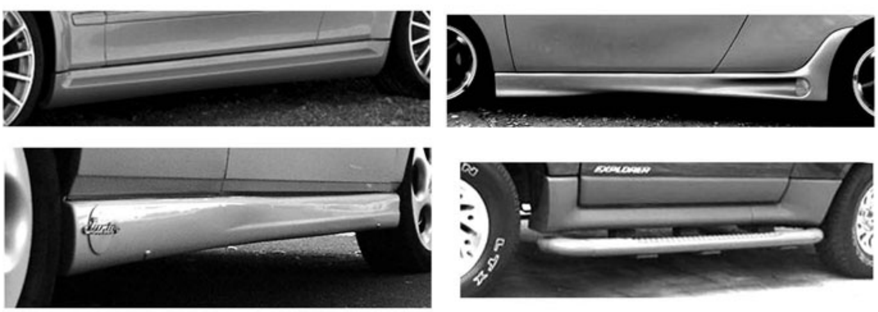


Fig. 5.28. Some examples of colored sill covers for saloons, high performance cars and SUVs.

5.1.3 Sill Covers and Side Airdams

These devices have been installed on cars since the end of the 1970's, the main purpose being to protect the lower body side (rocker panels and doors) from corrosion caused by abrasion due to stones, salt and mud projected from the wheels. At that time, body sheets were never zinc coated and therefore abrasion of paint layers could expose steel sheets to rapid rusting and deterioration, mostly in countries affected by icy winter climate and widespread salt spraying on roads to contrast icing.

Other advantages of sill covers include the opportunity to model more freely the lower body side, usually conditioned by the forming process of the upper side and by its size, improved protection of door opening from dust, mud and powder, and possible influence on vehicle aerodynamic properties (Fig. 5.28).

Table 5.4. Typical properties of material families used in sill cover.

PROPERTY	PP/Talc	RRIM 20% glass	PC/ABS	PBT
Density (kg/dm3)	1,06	1,2	1,18	1,3
Flex. elastic Modulus (MPa)	2600	1100	2500	2200
Break strength (MPa)	36	26	50	56
Elongation at break (%)	35	30	50	40
IZOD notched resiliency (kJ/m2)	4	6	7	5
thermal elong. coeff. (10^{-5}/°C)	5-8	5-8	7-8	6-10
softening temp. VICAT B (°C)	90	-	110	120

Nevertheless sill covers are additional components in any case, therefore increasing costs, investments and weight (from 2 to 4 kg per car).

In recent years, widespread use of zinc coated steel, under floor PVC spraying during the paint cycle and polyurethane transparent film application on the painted body, have caused sill cover advantages and their adoption to be reduced especially on smaller, economy class cars.

Materials and technology

Manufacturing of sill covers commonly uses high pressure thermoplastic injection or reaction injection of polyurethane resin filled with short glass fiber. The most used thermoplastics are blend of Polycarbonate and ABS (as *Bayblend*®), Polybutylenterephtalate PBT and Polypropylene with EPDM. Typical properties of these materials are shown in table 5.4.

Originally most sill covers were black, whereas later some began to be body colored. In recent years, body colored sill covers have become predominant. Mounting is made on the painted body using plastic snaps such as pine-tree clips and self threading screws with plastic inserts, as explained later.

Design specifications

The main technical properties of these components are:

- amount of sill surface covered and therefore protected;
- position, type and number of fasteners;
- absence of interference with jigs and fixtures used to lift the vehicle;
- mechanical strength and environment resistance;
- when possible, aerodynamic performance.

In Fig. 5.29, some sections *yz* of production sill covers are shown. As can be seen, cover to sill fittings are preferably supplied by clips or snaps on the visible

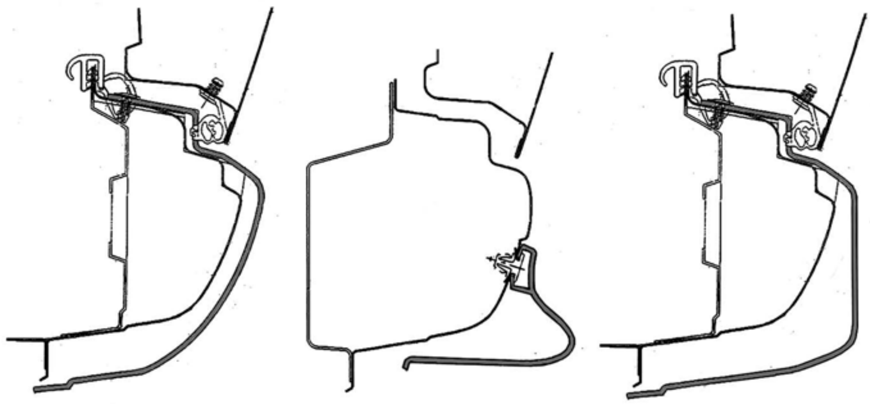


Fig. 5.29. Typical sill cover sections, where snaps to sill and cover overhang are visible.

side, fitted in adequate slots in order to allow thermal differential elongation. The length of the cover is usually between 1.5 and 2.0 m, and the temperature variation in the area can reach 80 °C (from – 30°C to + 50°C). The thermal linear elongation coefficient of the materials used are in the range $5 \div 10 x 10^{-5}/°C$. As a consequence, if one end of the cover is screwed to the sill (see, for example, Fig. 5.30), the other end could have a length reduction in the range $3.75 \div 10$ mm (depending on length and material) and an elongation between 2.25 and 6 mm.

Sill covers are made of resilient plastic materials with the lowest thickness allowed by the technology used (about 2.5 mm), while at the same time being sufficient flexible to avoid the risk of breakage by contact with obstacles or platforms. Therefore they must be supported by a wide number of fasteners, usually screws and plastic inserts located in the lower cover surface. (Fig. 5.31).

In the lower part of sill covers, some openings are featured in order to provide access for lifting devices, in some cases closed by mudguard flaps. Moreover, every sill cover has a front and rear closing wall or shield, a number of slots and small bridges for fittings, stiffening ribs and windows with flaps.

Delivery tests are used to verify matching gaps, stiffness in loading conditions, fasteners fatigue resistance and easy access to lifting devices.

Regarding the aerodynamic properties, since the ground distance of the underbody is much higher than the *boundary layer* thickness, the sill cover has a low influence. Some wind tunnel test have been published [1], as shown in Fig. 5.32: in the cited example, it can be noticed that the sill covers induce a low down force in straight motion and lift in a curve.

[1] H. Ohno, I. Kohri, *Improvement of Aerodynamic Characteristics of Passenger Car by Side-Airdams,* JSAE Review Vol. 12 No. 3, July 1991.

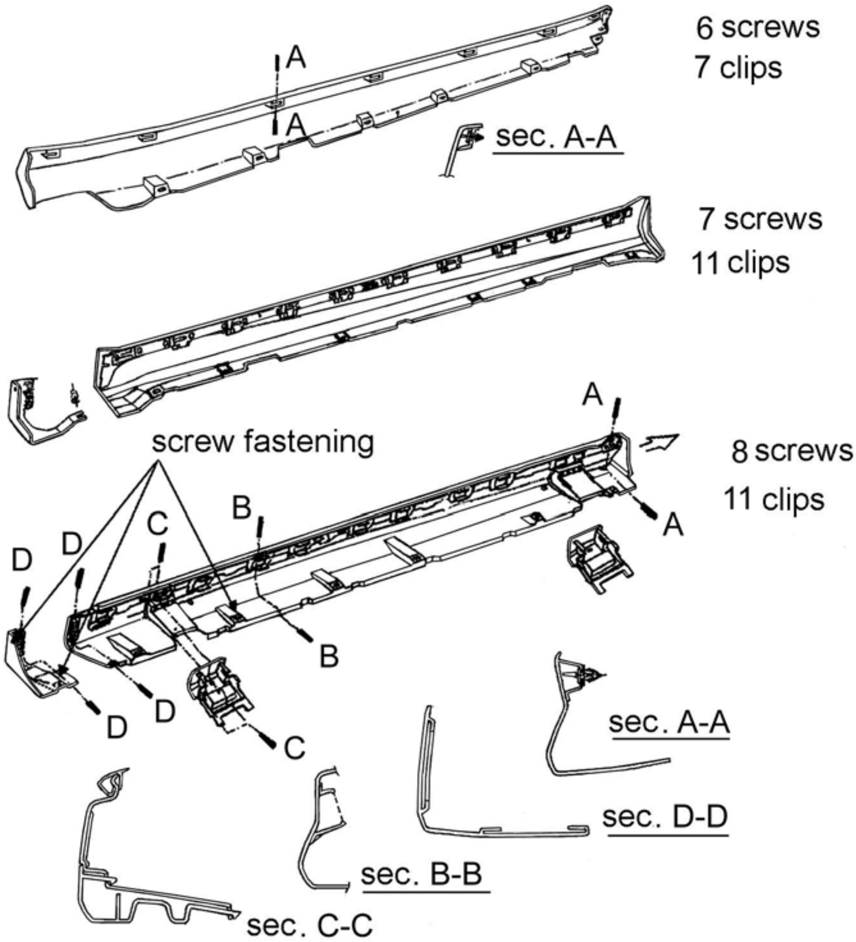


Fig. 5.30. Examples of sill covers and details of fasteners type and movable connected parts.

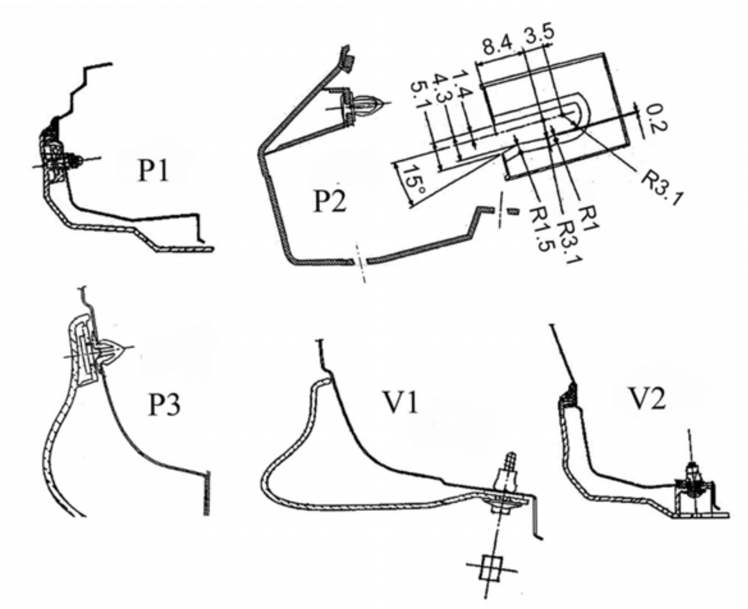


Fig. 5.31. Examples of sill covers fastening by screws (V1 and V2) or by snap pine-tree plastic clips (P1, P2, P3).

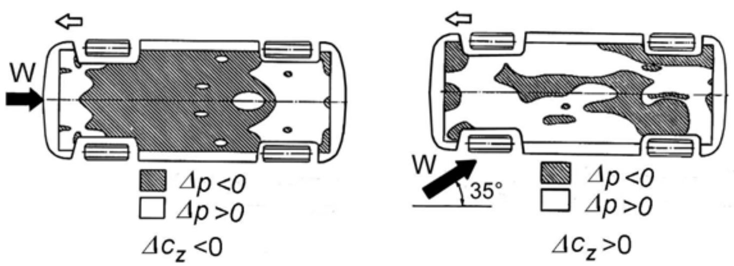


Fig. 5.32. Influence of underbody air pressure in a car with side air-dams, both in front wind and wind at an angle (from JSAE Review Vol. 12 No. 3). W shows wind direction.

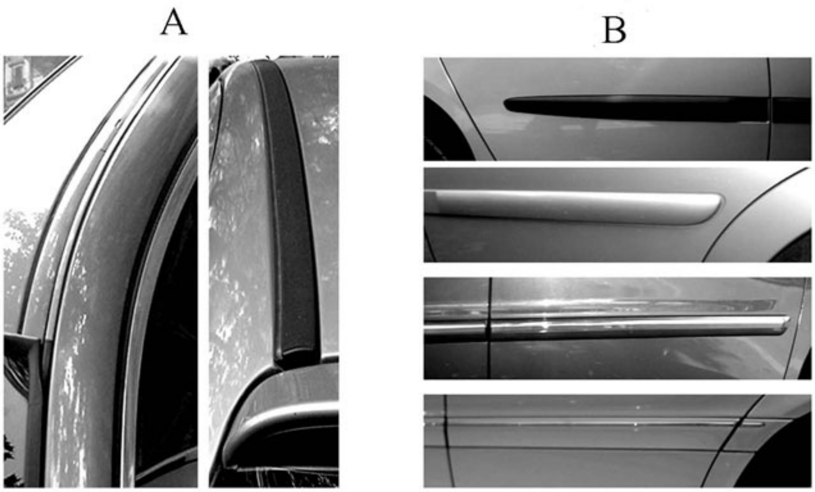


Fig. 5.33. Examples of roof outer moldings (A) and side moldings (B).

5.1.4 Outer Moldings

These components fall into two main families: the first relates to shielding of aesthetic defects such as unsatisfactory sheet joints, the second is designed to protect body painted sheets from small impacts. The first family includes roof moldings, typically constant section and small size if compared to molding length. The second includes doors and body side moldings, constant section or shaped (Fig. 5.33).

In the case of roof moldings, the superposition of side outer panel and roof panel, whatever the assembly process used, could put in evidence the trimmed sheets, requiring protection against corrosion and waterproof sealing.

In the case of doors, moldings supply a local protection against little damage occurring in parking operations (for instance, due to door opening contact) or in narrow entrance manoeuvers.

In the case of the roof, sealing is the primary goal, followed by aesthetics and fitting ease; in the case of doors, protection effectiveness, resistance to extraction and scratching are the main goals, but aesthetics still represents an important target.

In the case of the roof, the technical reference parameter is the section size to be filled by the molding, usually determined by body side and roof assembly process and commonly not narrower than 12 mm. In the case of doors, protection effectiveness of the molding is a complex parameter to evaluate as it is strongly influenced by design, stiffness and resistance of the hosting door itself.

In both cases, a relevant property is the type and number of fasteners.

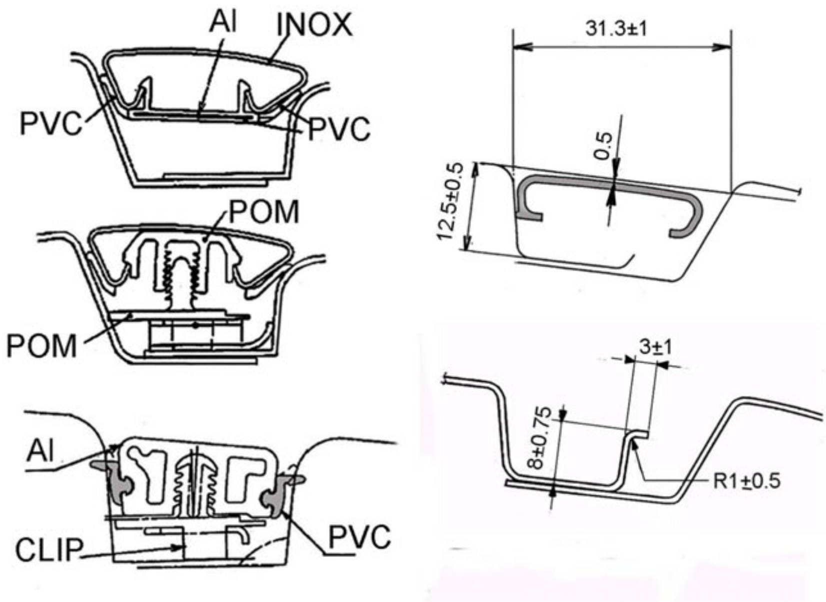


Fig. 5.34. Examples of metal roof outer moldings: materials for any function are described.

Materials, production and assembly process

A) Roof moldings

The most used families are:

A1) PVC molding with glass fiber insert.

A2) PVC molding with metal insert.

A3) Metal profile (aluminum, inox steel).

A4) Thermoplastic rubber molding with metal insert.

Both plastic and metal moldings can be fitted protruding or drowned.

Fig. 5.34 shows some typical sections of moldings with metal top surface (inox steel or chromed aluminum in some cases), but most frequently body color matched by painting. In these solutions, in order to fasten a roof rack or sky rack, the molding is designed to have an opening flap with recovery spring (Fig. 5.35).

Fig. 5.36 shows some typical molding sections with PVC or rubber top finishing, usually black.

Fig. **??** summarizes the trend in fitting systems and edge molding process.

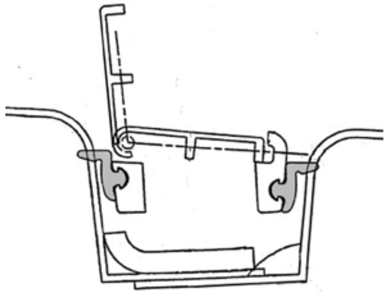


Fig. 5.35. Roof molding section at roof rack bracket housing, with hinged flap.

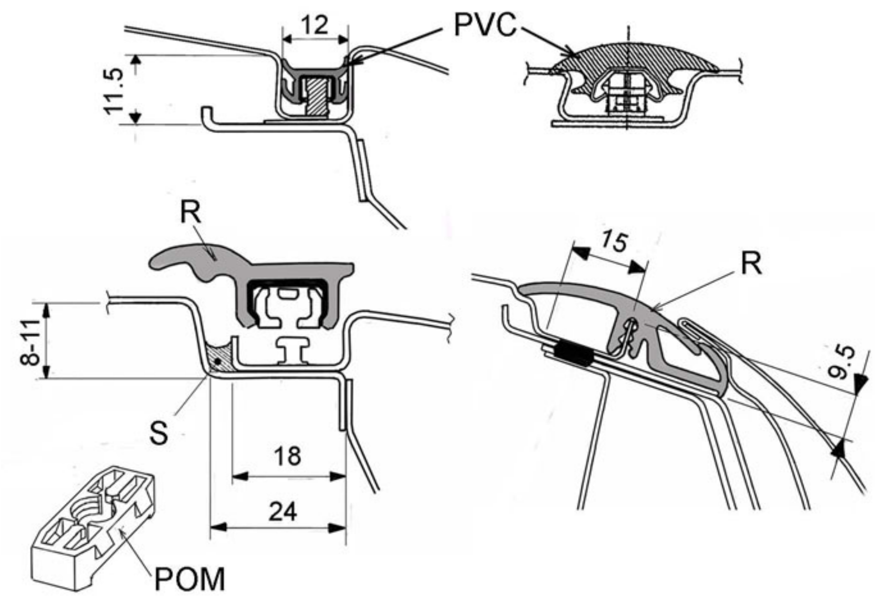


Fig. 5.36. Examples of plastic outer roof moldings and details of fitting devices. R: rubber; S: sealant.

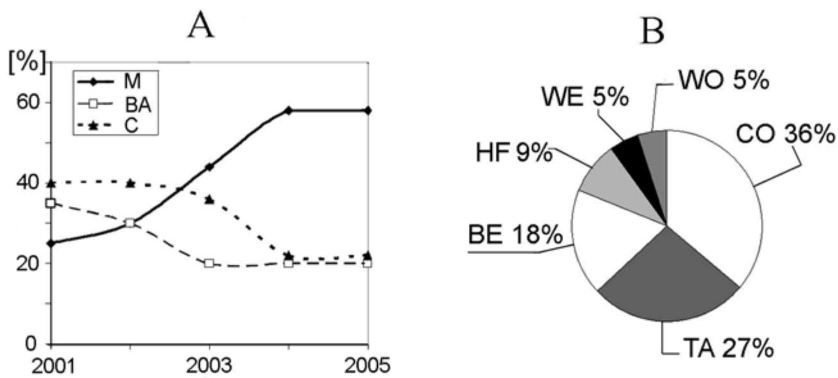


Fig. 5.37. Technology trends for fasteners type (A) and end design (B) of roof outer moldings. M: springs; BA: biadhesive; C: continuous; WE: welded; WO: machined; CO: co-molded; TA: plug; BE: bent; HF: hot formed.

B)Side and door moldings

The most common families are:

B1) PVC molding with metal insert.

B2) PVC molding with glass fiber insert.

B3) Polypropylene.

B4) PC/ABS.

PVC moldings are usually mass colored, but Polypropylene or PC/ABS body colored moldings are the most diffused.

Fig. 5.38 shows some typical sections of side moldings with different types of fitting.

On some cars, side moldings are replaced by plastic large covers or *impact guards*, injected or reaction injection molded, most frequently body colored and fitted to door outer panel with the same fasteners used for moldings (Fig 5.39).

Molding specifications

Moldings and impact guards should be:

- perfectly fittable to surfaces and housing designed for their insertion. For this purpose, adequate flexibility and ease of elastic fitting are required, without permanent deformation. Fitting positions usually require marks or edges (meaning reference surfaces on panels, additional to reference holes if present) in order to support a precise manual fitting even when fitting fixtures are provided;

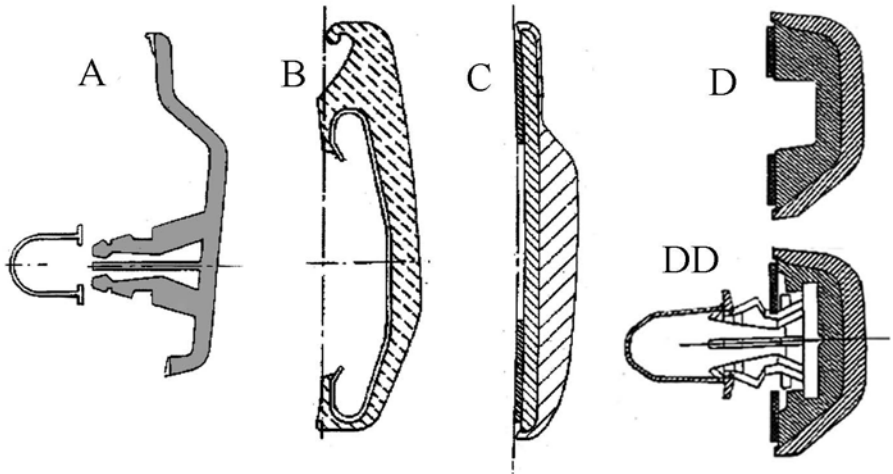


Fig. 5.38. Typical side molding sections with different fasteners: A) snap fitting by a plastic appendix injected in molding die; B) snap, on metal profile; C) by biadhesive and plastic insert; D) by biadhesive; DD) end section of D solution, with additional plastic clip.

- made by material which are resilient even at low temperatures, scratch resistant, non aggressive, and resistant to chemicals, to UV rays, and corrosion;
- without metal sharp edges, responsible for marking or direct metal-to-metal contact with panels, in order to avoid body corrosion;
- featuring preloaded elastic fasteners with additional semistructural adhesive, when required in order to avoid beating and vibrations while traveling.

Sometimes, moldings are fitted by bonding only; in this case, bi-adhesives are used overall, with some additional semistructural bonding, preferably at each molding end, to fix the molding while curing and to avoid *peeling* , the most critical type of stress for adhesives.

Anyway it is recommended to add mechanical fasteners at both molding ends.

5.1.5 Spoilers

In the chapter on bumpers, some front spoilers, fully integrated in the car front end, have been shown.

Rear spoilers are not usually integrated with body parts, unless small size and their shape allows integration; usually rear spoilers are add-on devices,

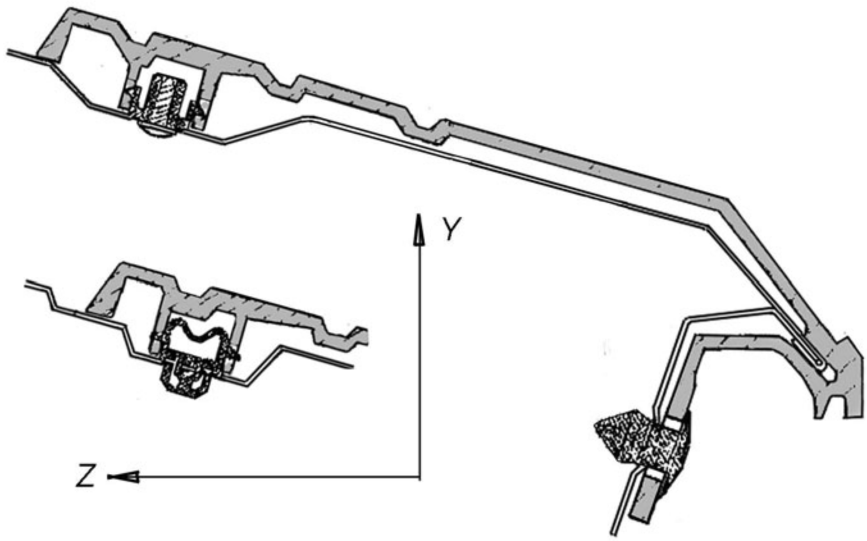


Fig. 5.39. Example of side guard obtained by *RIM* (*reaction injection molding*) process - Alfa Romeo 164 (1987).

fitted to the body mainly for aerodynamic purposes. In many cases, mostly when mounted at the rear end of the roof or on the liftgate upper cross-member, the aerodynamics task is mixed with the intention to create a sporty image and the requirement to protect rear passenger area from sun rays.

Two sections of liftgate mounted spoilers are displayed in Fig. 5.40, where glass fitting is shown.

In the following explanation, spoilers with a relevant aerodynamic function will be considered, featuring large size, adequate wing profile and strong attachments to body, usually on the decklid. These spoilers are adopted to reduce rear axle lift or even induce a down loading on rear axle, mostly on rear wheel drive high performance cars.

As already explained in the *body* and *bumper* aerodynamic chapters, lift causes two main effects: to reduce ground load or wheel-road adherence and increase induced drag. Regarding the wheel-ground contact, the problem is strongly dependent on speed, as the lift increase is related to the square of speed, for a defined lift coefficient; therefore high speed cars are the most affected.

For standard cars, it would be reasonable to choose a zero lift design, to minimize drag and speed influence on road holding. High performance cars normally feature improved wheel-road contact through down load, even despite an increase of drag (as is the case in racing cars).

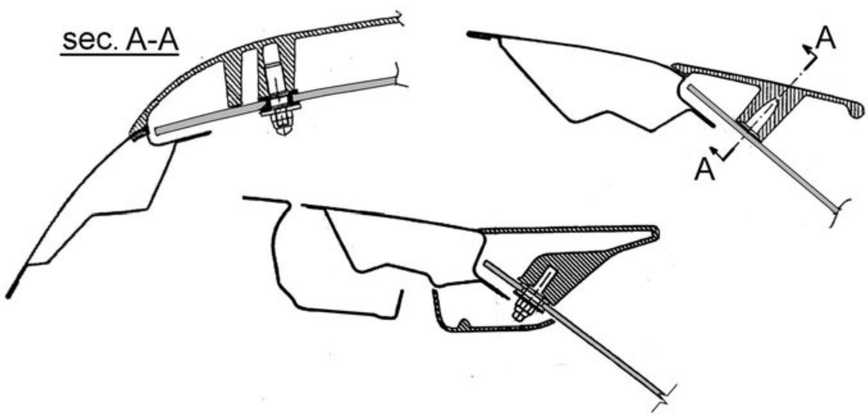


Fig. 5.40. Examples of liftgate spoiler with sections on glass fittings. Their task is to remove the air flow from the roof and destroy related vortices responsible for lift contribution.

Most cars without any spoiler are affected by some degree of lift, despite the research and applications already mentioned in the chapter on *body aerodynamics*; to cut lift, add-on devices should therefore be fitted to alter the body natural lift attitude.

Rear spoilers have this property: their shape can change the air flow in such a way so as to generate a down force and their position, behind rear wheels, has a leverage factor with a relevant change in lift distribution between the front and rear axle. To balance the pitching moment that affects front wheels adherence and to lower overall lift, also the front end shape should be changed (for instance, by integration of a dam in front bumper).

In practice, as already stated, aerodynamic add-on configurations should be defined and optimized interactively and concurrently in order to balance the overall body behavior.

Technology and materials

Due to their large size and slim shape with cantilevers and wide span among clamps, rear spoilers are stressed mainly in bending and torsion. Moreover, they can be subjected to misuse when hand pressed to push the car or close the decklid. Their xz sections, usually wing or pseudo-wing shaped are already boxed for aerodynamic needs and therefore can easily be soft or hard skinned, while molded in appropriate process.

If skin is not stiff enough to face local pressure without crushing, the closed volume can be filled with foam and/or reinorced by a support frame.

A common solution consists in one piece polyurethane integral skin foam, stiffened by a metal frame featuring welded screws or threaded bushes for fitting

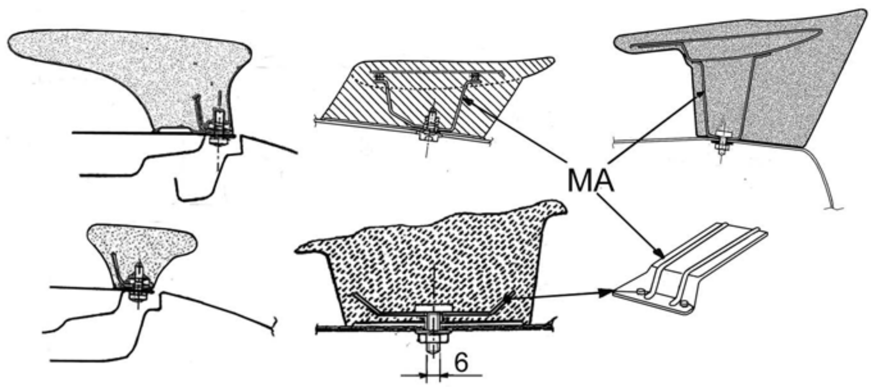


Fig. 5.41. Examples of spoilers made by poliurethane integral skin foam, with metal frame (MA). Sections at decklid fittings.

operations (Fig. 5.41). In this case the spoiler is perceived as being smooth and soft: this property is considered to be very convenient in terms of low aggressiveness with respect to potential pedestrian contact.

When the spoiler is slim, a stiff skin may be required which can be obtained by two bonded or mechanically joint thermoplastic pieces, injection or reaction injection molded (Fig. 5.42) or one *blow molded* piece, depending on the cost and investment balance and therefore on production volumes.

A statistical analysis of spoilers on the market in the year 2000 demonstarted a clear predominance of one piece thermoplastic injection molded solutions (60%), followed by two bonded pieces (20%) with just a relatively low proportion of foam and blow molding types.

Two piece bonded spoilers were commonly made by *Bulk Molding Compound B.M.C.*, using a *low profile LP* low shrinkage thermoset composite reinforced with approximately 20% of random glass fiber.

Specifications and delivery tests

In addition to the legal requirements concerning the outer surface shape (minimum radius 2.5 mm) and the usual environment resistance of plastic components, spoilers must comply with a number of performance criteria typical for their mission, including:

- overall resistance to maximum dynamic loads;
- attachment stiffness, including supporting metal sheets contribution to flexibility;
- yield strength and fatigue resistance of fasteners in repeated decklid or tailgate operations;

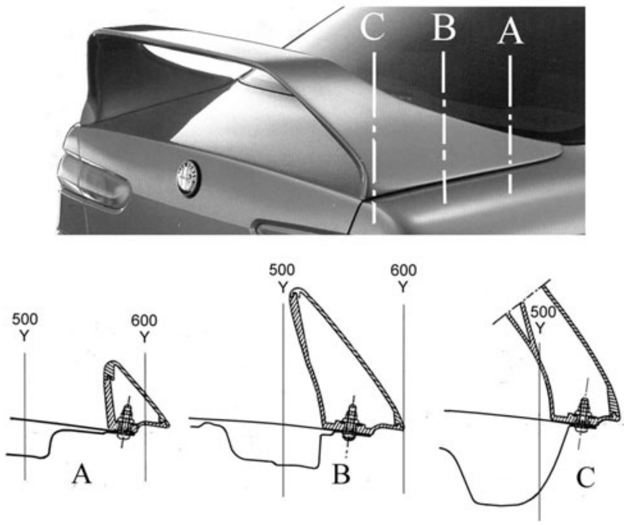


Fig. 5.42. Boxed spoiler Alfa Romeo 156 made in *B.M.C. (Bulk Molding Compound)*, a thermoset composite with random glass fibers. Sections A, B, C at the 3 side fitting positions.

- geometrical body fitting quality in contact areas;
- absence of permanent mark or deformation in contact areas;
- resistance in decklid misuse testing;
- absence of beats and vibrations on rough roads.

5.2 Weather Strips

The main mission of weather strips is to seal passenger and luggage compartment from noise, air, water, snow, mud, powder and engine compartment from mud, water and snow. In particular noise transmission due to leaks is a critical factor.

Referring to body components, the required matching precision is of a lower order than in engine or other mechanical components, the usual range being 1 mm. On the other hand, a degree of displacement between linked parts can be tolerated, and in some cases is required (for instance between doors, hood, liftgate and the body, or between window glass and door).

Therefore, body weather strips should comply with elastic (reversible) deformations in the order of millimetres: allowed flexibility is only limited by the dynamic seal capability, ie. the ability to match quickly and completely the surfaces to be sealed.

For all kinds of seal, an optimum value of stiffness exists: above this value, sealing continuity in presence of dimensional changes becomes critical and closing loads become too heavy. Below the optimum stiffness value, sealing pressure and dynamical adaptation are not adequate.

Therefore the design contents of weather strips concern:

- seal housing configuration;
- kinematic approach of linked parts to be sealed;
- weather strip design;
- weather strip manufacturing and materials;
- weather strip surface coating and/or finishing.

5.2.1 Mission and Delivery Criteria

In addition to sealing ability, other important mission criteria are required:

Aging resistance

The sealing properties must remain unchanged for the entire vehicle life, meaning that weather strips must cope with aging promoted by environmental, physical and chemical agents, including sun radiation, humidity and temperature variation, contact with hydrocarbons and many types of gas, powder, sand, etc.

This is achieved predominantly through the appropriate choice of material, that once was natural rubber and today is mainly compound rubber, especially *EPDM* (*Ethylene Propylene Diene Monomer*) and *Santoprene* (a blend of thermoset rubber and thermoplastic polymers).

Aging is tested in laboratory tests on weather strip samples, in climatic chambers filled with chemical agents, in repeated fatigue test on body subsystems or on the complete car, in climatic chambers and also on the road.

Acoustical insulation

The first step of the delivery criterion is a static laboratory test, in which a completely trimmed body side is submitted to a permeability measurement, both in design conditions and fully sealed on weather strip gaps, in order to make the joint similar to an uninterrupted surface.

This test is then integrated with road and wind tunnel tests in order to measure global compartment permeability.

Then, individual measurements in insulated rooms and with specific tools are performed in order to measure local joint sealing; in these tests, also rustles due to molecular flow on outer surfaces and in body side boxed frames are evaluated (Fig. 5.43).

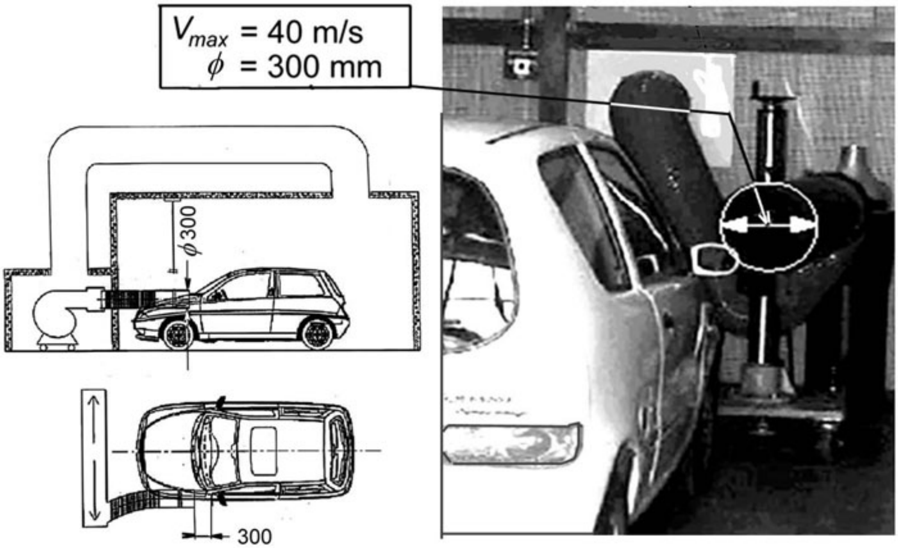


Fig. 5.43. Chamber for air and noise infiltration evaluation, featuring a controlled rustle generator.

Air and gas infiltration

The delivery criterion requires the comparison of weather strip contribution to air and gas leakage with respect to the allowed flow through cabin outlets which must be at least an order of magnitude higher. This measurement can be made in wind tunnel or in a static test, in which a measured air flow rate Q is blown into the cabin, and the stationary pressure difference p–p_0 between the cabin and outside is measured. The average speed of the escaping air is given, as a first approximation, by Torricelli's law for an uncompressible fluid of specific weight γ:

$$V = \sqrt{2g\frac{(p - p_0)}{\gamma}} \tag{5.14}$$

The equivalent opening surface A, from which the flow rate Q is escaping, is given by

$$A = \frac{Q}{V} = \frac{Q}{\sqrt{2g\frac{(p - p_0)}{\gamma}}} \tag{5.15}$$

The measurement is made by comparison between a test with all gaps fully sealed and a test with the design solution under investigation. Cabin air outlets can be kept closed or open in both tests.

Investigation to find leaks is made by full seal removal, zone by zone; equivalent section calculation is repeated for each position.

Gas sealing of the baggage compartment, liftgate and rear lights gaskets is verified with specific attention in order to avoid exhaust gas recirculation and infiltration as a consequence of de-pressure and vortex conditions close to vehicle rear end.

Water seal

Delivery criterion consists in a high pressure water spray test in a special chamber, where each wheel of the car is mounted on a vertical actuator in order to simulate different road attitudes for a duration of up to 30 minutes, while water spray is directed towards all vehicle surfaces including the underbody. In the test, no water infiltration must be noticed.

During a new model development, prototypes are repeatedly submitted to this type of verification, putting linked parts in extreme conditions with respect to real life environments (as regards body attitude, temperature, vibrations, rain intensity and duration, high pressure local sprays).

In fact, the aim is not only to adopt conceptually right solutions, but also verify effectiveness against production deviations (tolerances, subjective mounting operations).

Moreover, every car leaving the production line is verified in a rain chamber; any single water leakage noticed in the test even in a single car is investigated in terms of being a systemic defect by a root cause analysis in order to find design and production criticalities (often concurrent).This is considered to be the only way to reach an acceptable level of reliability due to the extremely relevant number of possible leakage causes and conditions.

Powder and snow seal

Delivery is conditioned by a static test, in which a special fine powder is sprayed on lower vehicle parts while the passenger compartment is under de-pressurised conditions. A visual analysis of passengers and engine compartment surfaces is performed.

Body joints finishing

Weather strips are usually snapped on to flanges, double sheet lips, U profiles, rivets welded to body, clip holes: therefore finishing for these body zones is also required. For this purpose, weather strips usually feature coloured PVC or *flocked lips*(flock is a layer of bristles with a smooth perception and low friction coefficient) or even ribbed, to obtain a trim effect which is perceived positively (Fig. 5.44).

Where the body joint is too wide or perceived negatively, it is common to use an additional co-molded connecting weather strip (for instance, in the upper door back edge, Fig. 5.52).

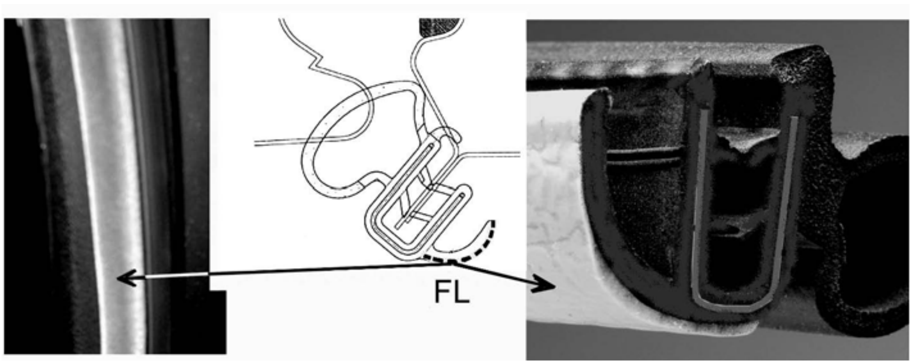


Fig. 5.44. *Flock* (FL) provides a perception of smoothness of the weather strip inner lip or foot.

Glass run

Window channels and belt weather strips, usually flocked, are used to check window drop and enable the window glass to slide easy in addition to providing adequate insulation. Window channels can have symmetrical sections (ie. symmetrical sealing strips on both sides of channel) when metal supporting sheets exist on both sides (Fig. 5.45).

Instead, when flush windows are required, meaning that the window glass is flush with the body outer surface, the outer metal sheet is not present and the thickness of the outer strip should be as low as possible: in this case, seal outer strips are very short and sometimes supported by an internal strip frame (Fig. 5.45). For some types of window regulators, any glass displacement in the X direction should be avoided: this goal is achieved by using a pin fitted on the rear vertical glass side and guided inside a drop window rail.

Belt weather strips are split in two parts, one snapped onto the inner door panel and the other onto the outer door panel (Fig. 5.46); their lips (at least one inner and two outer) are usually flocked.

Delivery tests for glass run strips consist in window drop cycles, operated by window regulators, inside climatic chambers where water with sand and salt, to increase surface abrasion and breaking stress of strip lips, is sprayed.

Vibration damping

Doors, hood, decklid and liftgate (the movable parts) have maximum vibration in correspondence to resonance frequencies, which can be excited due to the unevenness of the road surface.

Due to their elastomeric nature, weather strips exhibit hysteresis, and hence usually provide some degree of damping of the vibrations of movable parts; nevertheless the energy which can be dissipated is usually not sufficient to attenuate the vibrations completely. If this effect is perceived and judged to be

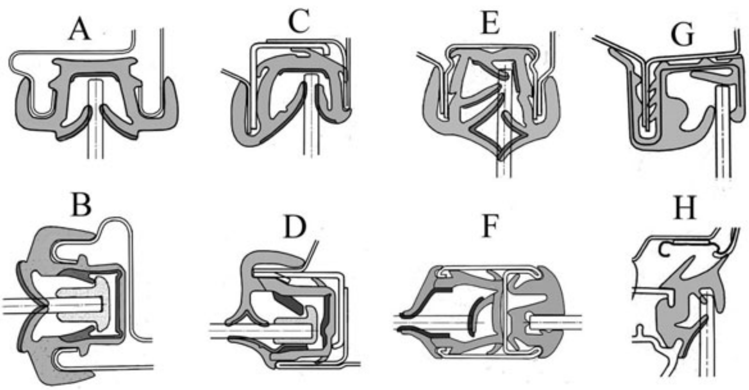


Fig. 5.45. Examples of window run channels: A) symmetrical; B) symmetrical with pin guide rail; C) asymmetrical; D) asymmetrical with pin guide rail; E) asymmetrical with multiple lip; F) double channel for rear door glass and quarter glass; G) flush armed channel; H) flush, without armature.

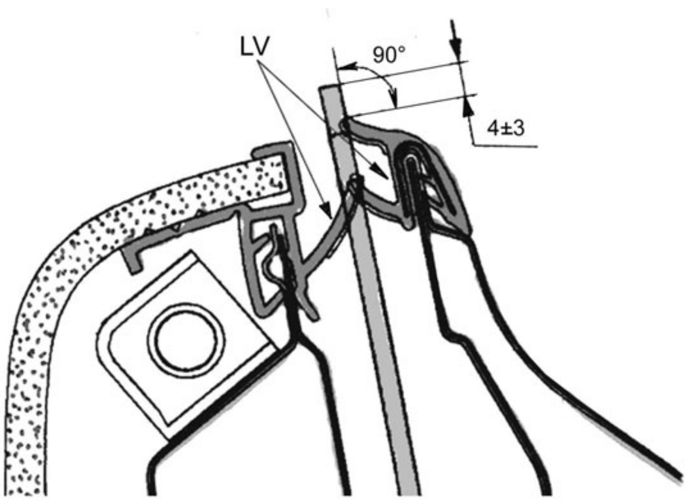


Fig. 5.46. Examples of extruded belt strips (LV).

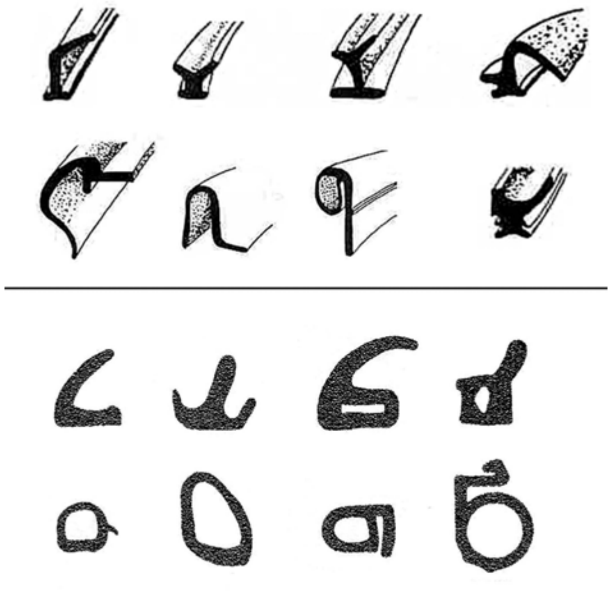


Fig. 5.47. Examples of historical door weather strip sections. Above: compact rubber sections; below: foam rubber sections.

unacceptable by the driver, specific vibration modes of movable parts may be changed through re-design, for example, by adding rubber pads positioned between the body and the movable part, in order to help block vibrations and define their final closed position.

Common technological solutions

The historical evolution of weather strips has taken a series of steps which naturally has not completed its entire course. Originally strips were simple open lip profiles in compact rubber, that was hard to compress (Fig. 5.47).

A relevant innovation was introduced with the tubular closed strips, still using compact rubber. Another relevant step was introduction of foam rubber in open sections and later the extrusion of tubular foam rubber strips (Fig. 5.48).

More recently, evolution has led to multiple cavity sections and to co-extrusion of different blends. Of course, this increasing complexity requires a closer control of production process; for instance, it is much more difficult to obtain a constant section extrusion with foam than with compact rubber.

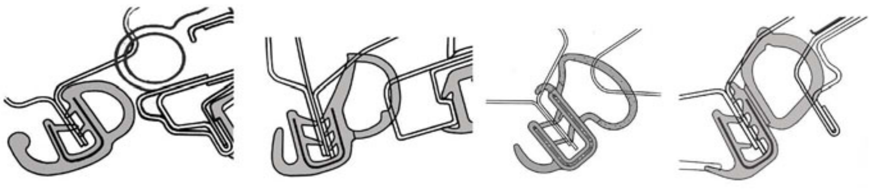


Fig. 5.48. Some example of primary single bulb door weather strips.

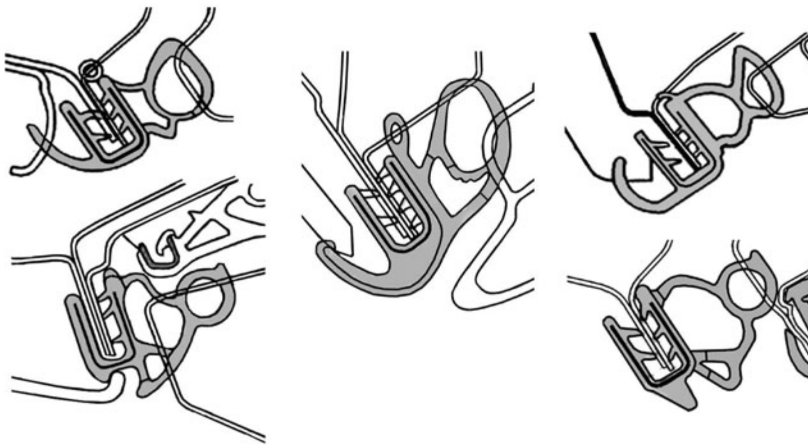


Fig. 5.49. Examples of door primary double bulb weather strips.

Moreover, until now co-molded parts have a series of geometrical constraints: for instance, a molded zone connecting two extruded tubular parts cannot have a boxed section due to die extraction. Also the sealing effectiveness of a weather strip is influenced not only by strip shape and sections, but also by geometry (i.e. curvature) and surface continuity among sections: if continuity is lacking (for instance, due to brazing or to metal sheet steps), strip choice must be oriented towards uneven fittable strips.

For this reason strip sections including two co-extruded rings (see for example Fig. 5.49) have been successfully introduced since they offer a better fitting attitude to adjacent stiff surfaces (for instance, featuring less wrinkles in curved sections) and lower overall size; moreover, two coupled cavities provide an improved barrier against noise transmission.

The difference in behaviour between one bulb and double bulb strips can be better understood by examining the conceptual deformation of two schematic sections, through door compression in two orthogonal load directions (Fig. 5.50).

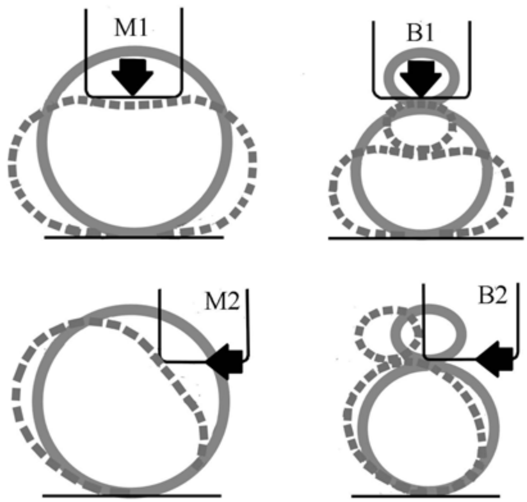


Fig. 5.50. Schematic illustration of deformations caused by loads applied along the main axis and a transverse axis, on two types of weather strips (one bulb and double bulb strips)of nominally the same size. The smaller bulb of the two bulbs solution has a higher shape stiffness and doesn't undergo relevant local deformations.

Strips to be snapped on stiff sheet flanges, feature a U-shaped foot with steel spring insert and small teeth to clamp the flange, to increase friction and avoid water ingress. This foot must be much stiffer than the seal bulb, and therefore must be made of compact non foamed rubber: this explains why weather strips should be co-extruded with two or even three different materials each with a different function (Fig. 5.51).

Extrusion is the most common weather strip production process, enabling a constant section design which is generally preferred. If the section needs to change at some point, the strips must be molded causing an increase in cost. As an example, constant sections along the door frame usually need to be integrated with a molded insert (overmolded or co-molded, or bonded to extruded parts) in the back edge of the upper door frame, if the central pillar has a sharp intersection with the body side upper rail (Fig. 5.52).

Strips fitting devices can vary according to the fitting position. If there are sheet lips or flanges, as in the body side, luggage compartment or liftgate openings, weather strips are snapped on to a metal flange (see, for instance, Fig. 5.51). When strips are fitted to the door sash, they are clamped by special U profiles or by pine-tree nylon clips inserted into holes in the door.

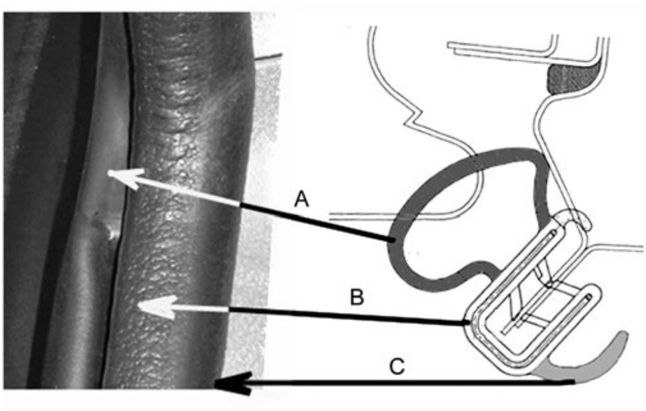


Fig. 5.51. Example of a three blend extruded strip. A: foam rubber; B) compact rubber; C) PVC.

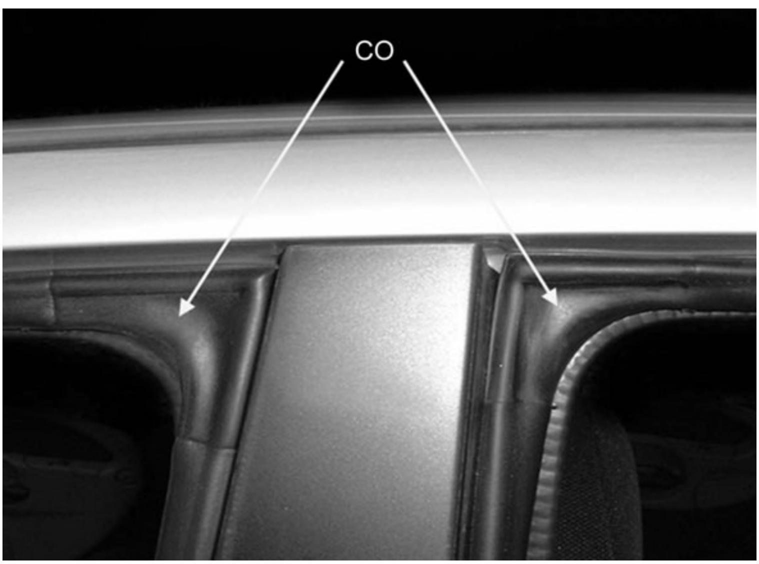


Fig. 5.52. Often the upper door back angles of weather strips, matching the central pillar, are co-molded (CO).

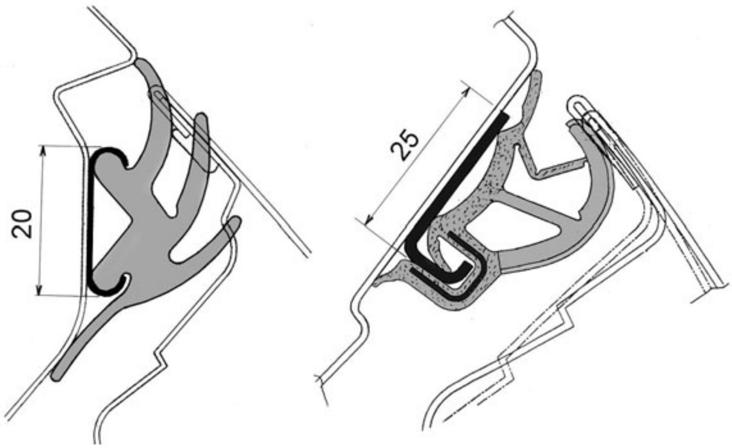


Fig. 5.53. Examples of secondary strips fitting, clamped by U or L shaped profiles, welded to body side.

On side roof rails, for anti-rustle purposes, secondary seals are used, clamped by rivets or U shaped retainers welded to the body (Fig. 5.53). Adhesive bonding is not recommended, unless combined with additional mechanical fasteners.

Specific properties of different weatherstrips

In the following section, shape and size of different strips for different applications are explained.

5.2.2 Door Weather Strips

These are the most complex car seals, due to the constraints imposed by the door, related to its shape and its multiple functions, and by the proximity of passengers to doors, requiring good insulation from environment.

Three main areas exist each with different needs:

1) door contour, that requires a continuous seal ring, as for a shaft-hole seal (primary seal area);
2) upper door frame, hosting the door glass and close to the passengers ears, where weather strips with anti-rustle properties are required (secondary seal area);
3) lower door contour, usually where any incoming water from belt area must be drained, without allowing powder ingress (sealing against powder).

The primary seal can be snapped onto body side sheets or onto the door frame. The principal advantages of both solutions are shown in Table 5.5.

Table 5.5. Comparison of door weather strips advantages as function of fitting place.

FIT TO DOOR	SNAP ON BODY SIDE
more effective matching kinematics	lower cost in case of co-moldings
stiffer reaction surfaces	lower investment
more design freedom	lower door manufacturing cost
	lower body joints cover cost

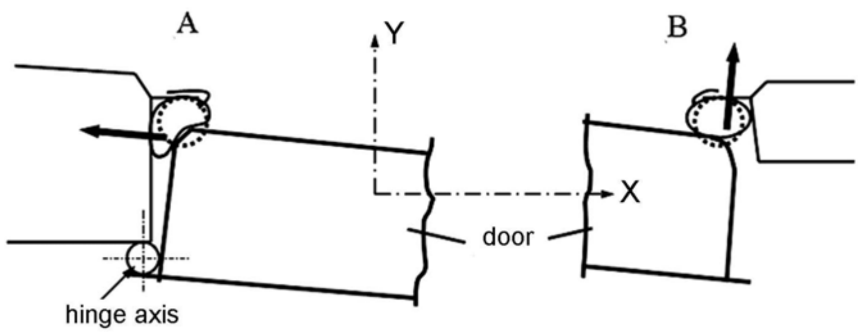


Fig. 5.54. Door to body approaching direction while closing. A) hinge side B) latch side. The different deformation mode of snap-on bulb weather strip can be noticed.

Regarding the kinematics of door closing , Fig. 5.54 shows the typical problem exhibited by weather strips snapped onto body sheets, with a mainly vertical hinge axis:

- far from hinges (for instance, along the back door side), the displacement of the door is substantially orthogonal to the body side and therefore the weatherstrip bulb is compressed in the Y direction;
- close to hinges, the main component of the door frame displacement is in the X direction; therefore it shuffles against the strip bulb and drags it against side pillar, in an angle where the reaction is much higher and door closing becomes harder.

The situation across the world regarding the solutions used is mixed although, as a general trend, in Europe and U.S. the primary seal is often fitted to the body side, mostly for reasons of cost. Instead in Japan, the most widely used solution is the primary seal fitted to door; in this case, a secondary seal is always fitted to the body side to shield body sheet joints, featuring also an additional seal (Fig. 5.55).

As regards the upper door weather strips (secondary seals), a wide range of design types of seal cavity exist (Fig. 5.56):

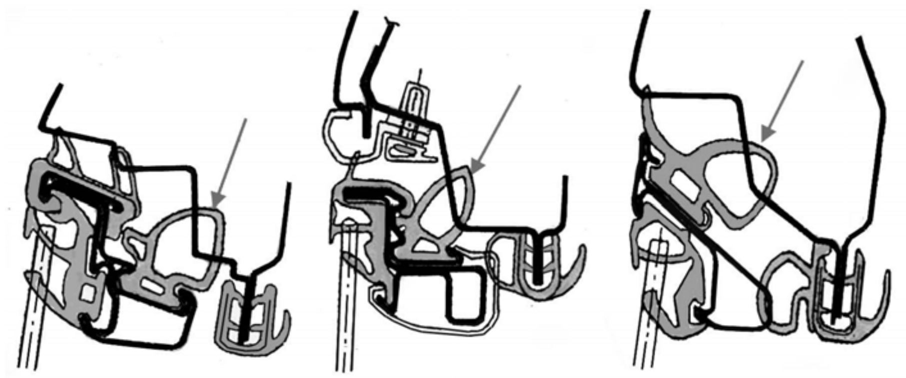


Fig. 5.55. Some examples of primary door seal (indicated with arrows) for Japanese cars.

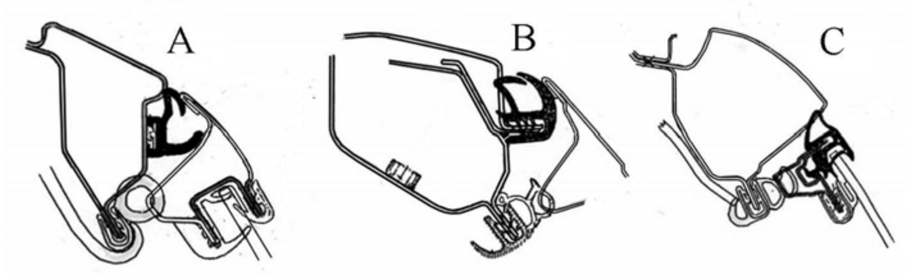


Fig. 5.56. Examples of secondary seal families.

A) with two lips that close the cavity when contacting the counterpart;

B) with two lips that overlap while closing the door;

C) with a single or multiple ring bulb.

In cases A) and B), one or both lips can be replaced by closed bulbs, with the benefit of increasing insulation between the cavities. The rubber for these bulbs (usually extruded) can be a compact elastomeric blend or elastomeric foam (the elastomer family being one of the types cited).

Depending on the roof-body side design, the secondary seal can be fitted to the upper door or the roof: in this case, styling governs the weather strip choice. In Fig. 5.57, some typical applications are displayed.

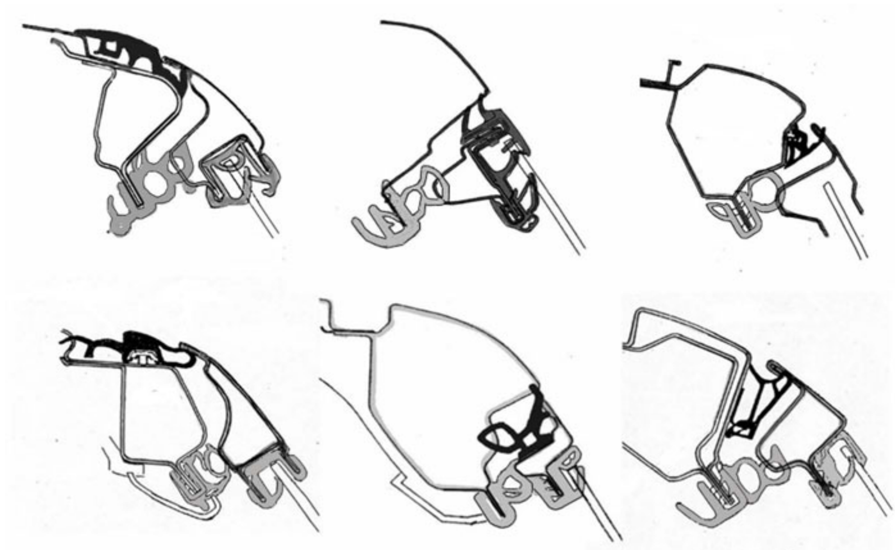


Fig. 5.57. Secondary seals for drap-over doors and enclosed doors.

As concerns sealing against powder, the most common application is on door panels, as it is used to free drained water when the door is opened and to seal the door when closed (fig. 5.58).

On some cars, this weather strip even provides some benefit with respect to insulation from rolling and exhaust noise coming from the underbody region.

Some door frames are not extended above the belt line and the upper glass seal is made directly using a body fitted weather strip (f*rameless windows doors* – Fig. 5.59). In this case, seal performance is very critical in the node where the glass meets door frame: water ingress in this area can be avoided only by using complicated molded weather strips (Fig. 5.60).

Design and delivery criteria

Weather strips design is based on some general rules:

- Bending or deflection of the weather strip engaged must be within a range of values consistent with its size when free; for instance, a bulb deformation should not exceed 50% of its original diameter in designed working condition and never exceed 70% in the worst tolerance condition (Fig. 5.61).
- In the lightest working conditions, seal pressure on metal counterpart should not be less than 30% of design pressure, included tolerance effect.
- Permanent deformation after fatigue and aging test should never exceed 30% of design deformation.

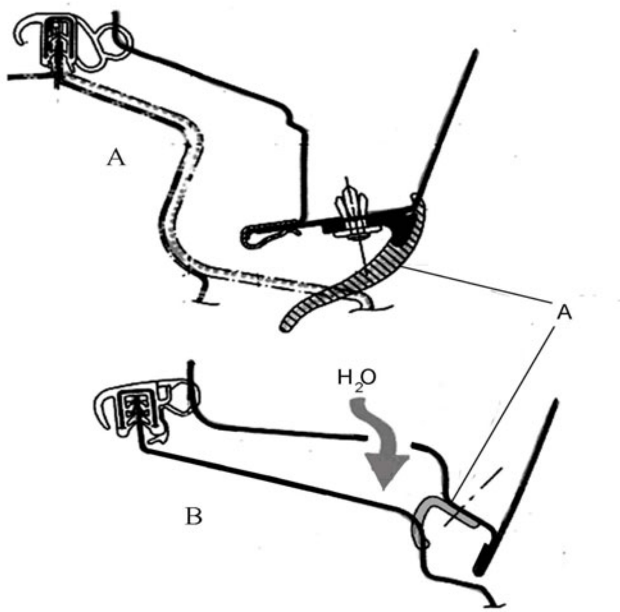


Fig. 5.58. Weather strips against powder, fitted to door outer (A) and inner (B) panel.

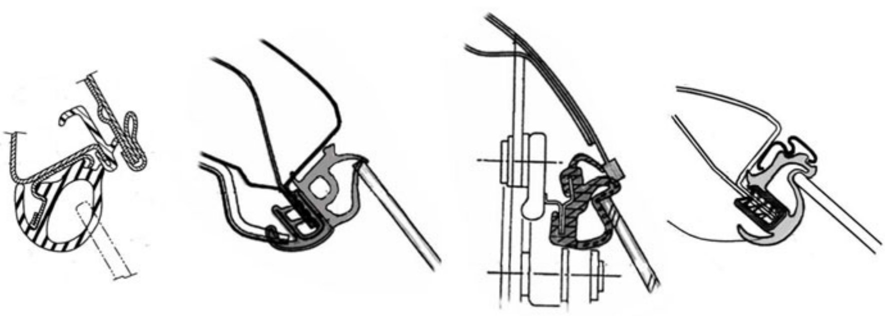


Fig. 5.59. Sections of frameless window weather strips for coupés and convertibles.

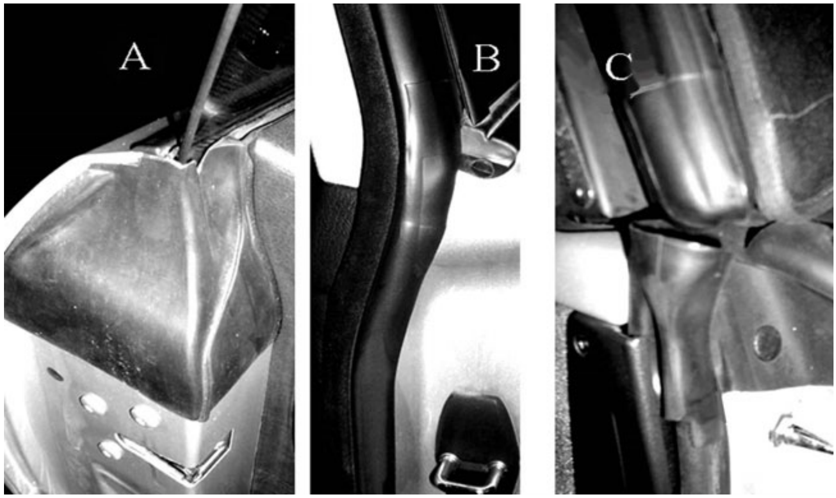


Fig. 5.60. A: molded weather strip node on frameless window door; B: in the connection area between glass and door inner panel, weather strip snapped onto the body pillar undergoes relevant curvature changes; C) a molded funnel to collect and drain water entering between glass and body side is included in primary seal.

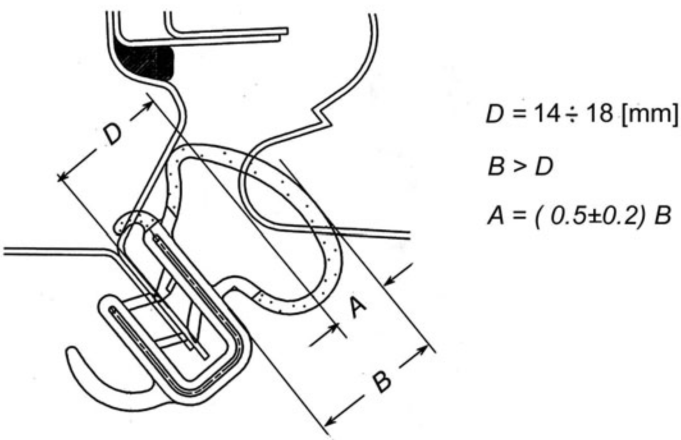


Fig. 5.61. Design criteria for a single bulb weather strip. A: recommended tolerance range; B: free bulb size; D: design gap between door and body side.

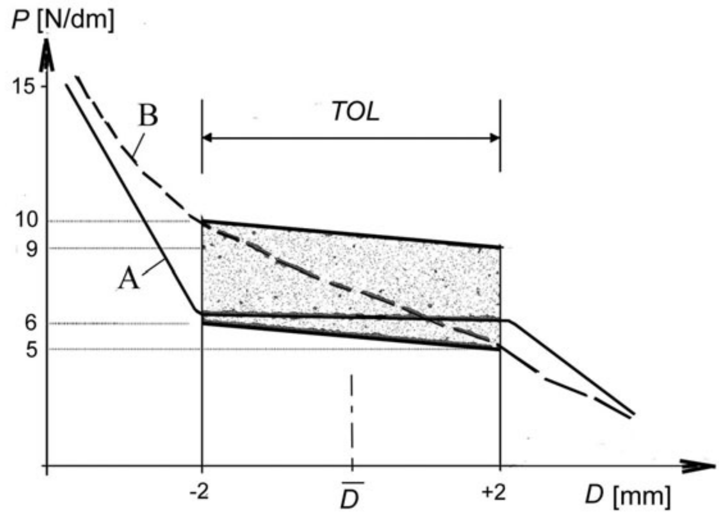


Fig. 5.62. The figure shows lift P of two door weather strip types in a bench compression test where the door to body contact is simulated. Contact length: 100 mm. The dotted field is the target for weather strip work, according to designed tolerances.

- Weather strip lift (i.e. the load corresponding to a defined seal deflection) should remain within a target range: as an example, a typical target for a primary door seal is illustrated in Fig. 5.62. In this figure, the recorded properties of a common weather strip (curve B) are compared with an ideal weather strip (curve A), featuring a constant lift in the dimensional tolerance range of door housing.
- In the vulcanized or co-molded zones, weather strip portance should never exceed 20% difference with respect to the remaining zones.
- Curvature weather strip radius should never exceed the targeted values, related to seal size, with respect to its clamping foot and to the kind of metal inserted in the foot, the purpose of which is to keep the weather strip in its designed position. This rule is intended to preserve the seal from wrinkles and section reduction which causes contact loss. The smallest recommended radius around an axis parallel to seal flange is 40 mm, while around an axis orthogonal to seal flange should never be less than 150 mm.
- In the weather strip clamp section, some teeth must be designed to stop water leakage.

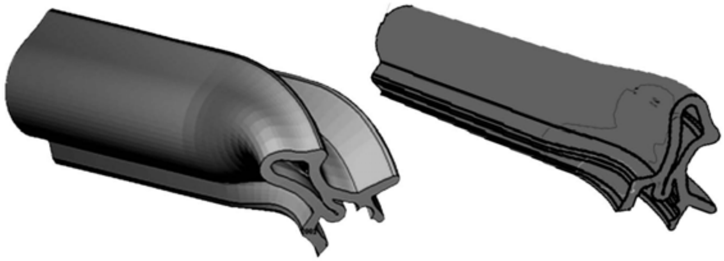


Fig. 5.63. CAD 3D model enables to check local deformations as wrinkles and waveness caused by installation design (for instance, too small radius).

Development process

Weather strip design is currently supported by a number of virtual analysis tools. From the initial steps of a new model development, the door contour is defined in relation to door rotational kinematics. Starting from these constraints, the typical node and frame sections of door openings are studied and matched door–body sections are designed.

The first step in weather strip design requires a 2D check of door approach to body side while closing: finite element models are used to evaluate weather strip sections deformation and stresses.

The following step is a 3D finite element simulation, mainly to check curved weather strip zones, affecting the risk of wrinkles and section reduction (Fig. 5.63). These analysis help sections shape tuning and co-molding needs investigating.

Following that, extrusion matrices for straight weather strip profiles are machined and small fast prototyping dies for molded connection of straight parts, using simulated rubber, are manufactured.

The prototype resulting weather strip is tested and tuned on prototype cars; after delivery, it is then supplied in a limited number of samples, manufactured by production dies, according to the common plastic components construction and tuning process.

Experimental delivery tests on road and in climatic chamber, listed in previous *mission and delivery criteria* paragraph, are performed partly by using simulated rubber prototypes, and partly with first production samples.

These production samples are manufactured with production tools using a respresentative production process and material, and therefore are completed with flocking and coating against friction and squeak.

In fact, none of the weather strip blends used today should resist to abrasion stress and to local sticking to metal sheets in ice condition. Under vibration, and in some climatic conditions, the contact of elastomeric material to painted sheet causes a stick and slip phenomenon perceived in terms of squeak and rattle.

This event can be avoided, or at least reduced, by flocking of the elastomeric surface (but still a risk of ice sticking remains) or, more often, by applying specific coatings.

Testing of individual weather strips is used to verify:

- aesthetic properties, including colour, gloss, waveness due to metal inserts;
- mechanical and chemical properties, such as the surface friction coefficient, friction coating adhesion, abrasion resistance, chemical resistance, snap on load, extraction load, foot breaking load.

5.2.3 Liftgate and Trunk Lid Weather Strips

The same mission, materials, technologies and development process, already mentioned for doors, are also applied to liftgate and trunk lid weather strips.

In fact, the goal in this case is to seal the passenger compartment or cabin-linked compartment, using a cover part, rotating around a fixed or movable axis and matching a weather strip boundary.

Compared to doors, two main differences exist :

- weather strip seal contact is mainly laid on a horizontal surface and therefore water flow rate is higher;
- weather strips seal surface is often designed with small radiuses in three dimensions, due to rear light and back glass style.

The resulting design has therefore the following constraints:

a) weather strips should feature specific devices to avoid water ingress: sealant inside, dam against water rise, guard teeth (Fig. 5.64);

b) all around seal zones, adequate drain channels must be provided;

c) weather strip sections and mostly their clamp configurations should be consistent with the lowest possible curvature radii. Usually, buckling deformation is directly related to the ratio of weather strip size to flange radius in the curve plane: in this case, the design strategy consists in choosing the strip of minimum width, for instance by positioning trim lip parallel to weather strip foot instead of serial to it. In any case, the radii should never be smaller than the values displayed in Fig. 5.65, otherwise typical buckling defects, visible in the same picture, arise.

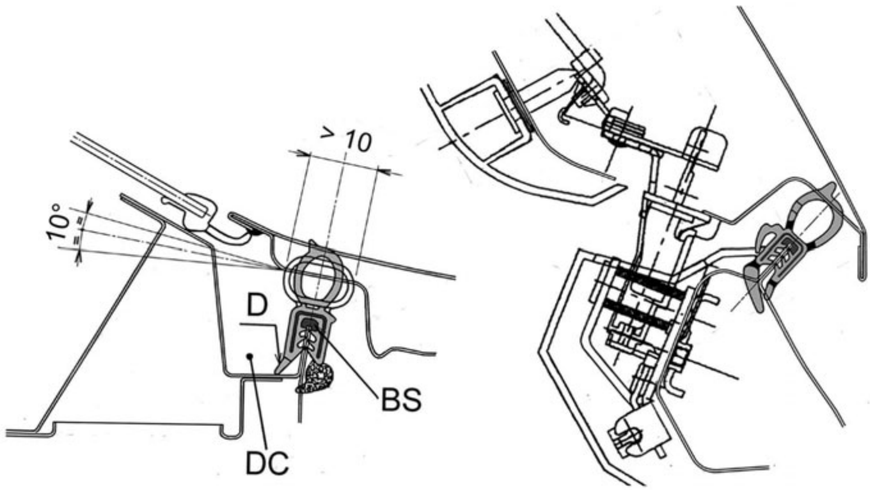


Fig. 5.64. Section of single bulb weather strips for luggage compartment: to the left, a section below back glass; to the right, on latch. DC: drain channel; D: dam; BS: butyl sealant.

Design and delivery criteria

The same criteria explained for door weather strips, regarding the maximum and minimum compression levels and the permanent deformation after durability test, are recommended.

The lift allowable values are a little higher than for doors (+ 10%), while the tolerance play range is the same.

5.2.4 Hood Seals

These weather strips are required to seal the upper part of the engine compartment only, with the following main purposes:

- to contrast snow, water and mud ingress, in order to avoid failure of the engine and electric systems;
- to keep the passenger compartment free from any odour or gas caused by engine components that could pollute air intake from the cowl louver;
- to reduce air-borne noise from the hood area to cabin contour;
- to restrict air flow through the radiator grille from undesired run around radiators, resulting in poor cooling effects.

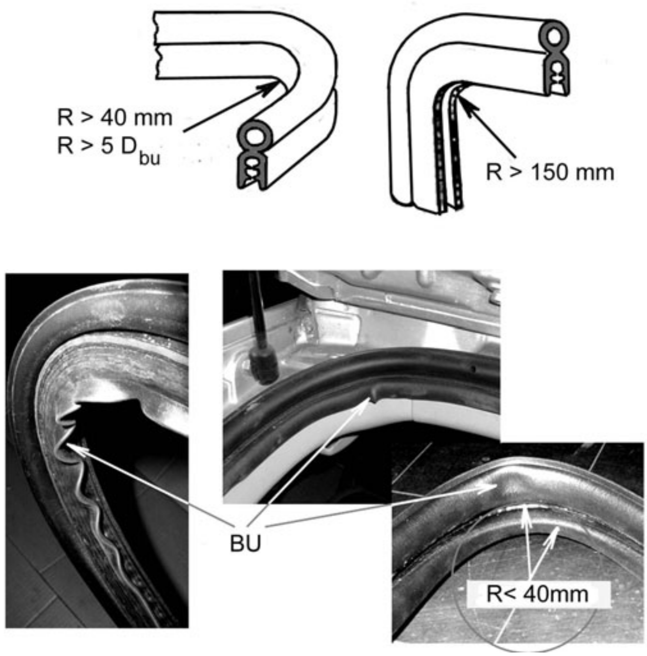


Fig. 5.65. Design radius to avoid buckling; below, some pictures showing the effects of wrong radii. BU: buckling; D_{bu}: bulb diameter.

These seals are usually large sized and foam extruded, to mate easily any housing tolerance and unevenness, due to their positioning in relevant variable section zones.

Usually hood seals are laid transverse to the engine compartment, one in front (close to radiator cross member) and the other below the rear portion of the hood, on cowl top cover and close to air box, when present (Fig. 5.66).

Sometimes, two longitudinal seals above the front rails on the engine compartment side are added to avoid water sprinkling.

Delivery and design criteria are the same as for doors weather strips, both in terms of the highest and lowest compression levels allowed and the maximum permanent deformation after durability test.

Materials and technologies are similar to those of the door: the difference is due only to the operating temperature in the engine compartment (up to 90 °C) and to the chemical contact with engine oil and gas. Moreover, as the required seal is limited to some areas, these weather strips are simply extruded, without co-molding or splicing.

Fig. 5.66. Examples of weather strips for engine compartment, fitted to the hood (left) and to cowl top cover (right).

5.2.5 Opening Roof Seals

Reference is made to three types of roof openings:

1) sliding roofs (above or inside roof frame), narrower than the roof panel;

2) multi-panel sliding/tilting roof;

3) soft and hard tops used in spiders and convertibles.

Dimensional accuracy of matching components generally decreases as the roof size increases; as a consequence, the size and problems of weather strips increase with opening roof size.

In case 1), simple bulb strips can seal the movable part, even due to the usual drain channel and to the inside roller blind that contributes to cabin insulation (Fig. 5.67).

In Fig. 5.68, the critical dimensions for a glass sliding roof and the recommended lift values are shown.

In case 2), the strips concept is similar to the previous one, even with additional problems for the multiple connection.

In case 3), due to soft top segment break down, even seals must be split into a number of strips, made by large size bulbs with male/female shaped splicing to improve the interference while closed (Fig. 5.69).

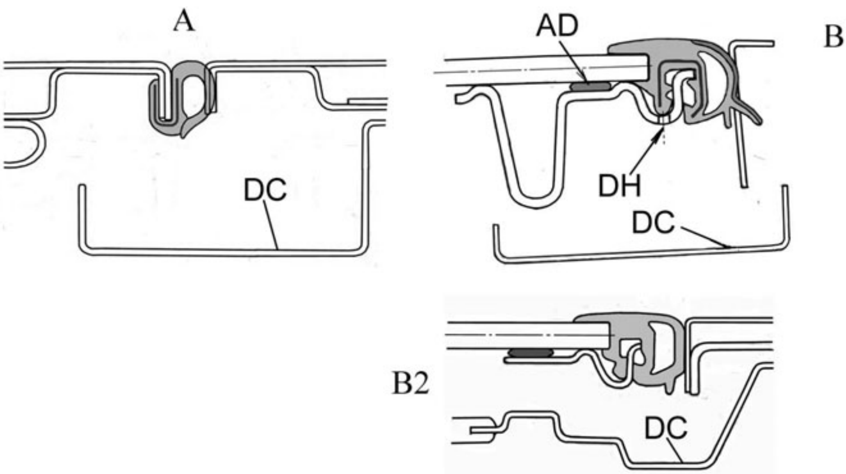


Fig. 5.67. Weather strips for sliding metal (A) and glass (B1, B2) roofs. Drain channel DC, below roof frame, is always present. DH: drain hole.

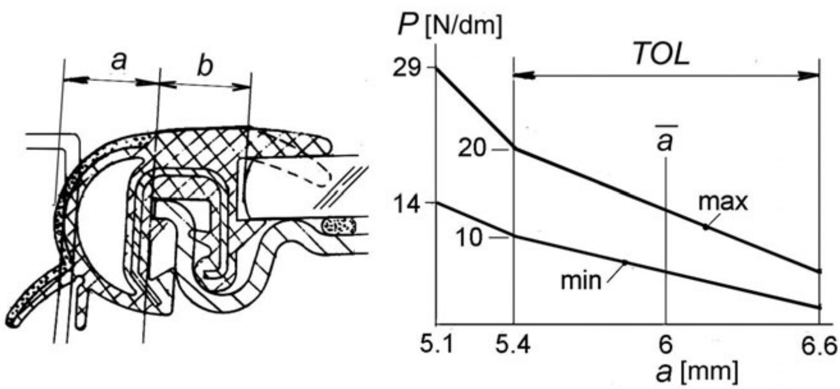


Fig. 5.68. Sliding roof seal section and related lift P specification. *a, b*: critical values; *TOL*: sliding roof-roof housing play tolerance.

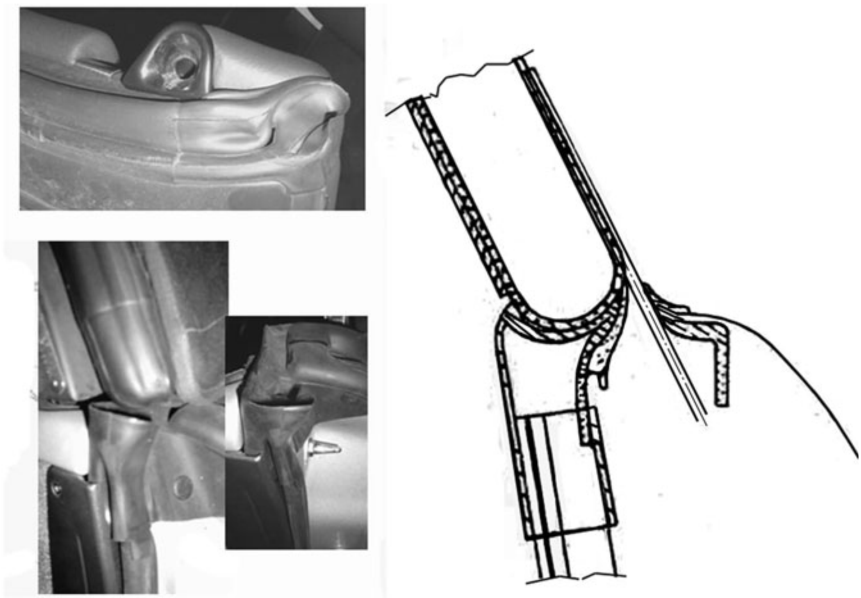


Fig. 5.69. Examples of connection between soft top weather strip and door seals, with drain channel.

5.2.6 Glass Seals

As concerns glass sealing, it is necessary to distinguish between fixed glass (windshield, back glass, quarter glass) and movable glass (typical for doors, but even liftgate, quarter glass and sunroof).

For fixed glass, two families of gaskets are used: one as primary seal, inserted in widshield opening together with the glass (Fig. 5.70), the other as a contour molding with aesthetic and protection function only for body bonded glass (Fig. 5.71).

Seal gaskets on fixed glass are no longer used on new cars, despite the relative ease of the manual tool-free installing process. The main inconvenience of such a solution was windshield water leakage which increased with aging, against which none of the solutions invented was entirely effective; moreover, shape constraints, such as the relevant size and angle radii without molding, would make the aesthetics of such a weatherstrip unacceptable today.

All fixed glass are today glued and bonded to the body; this process halts water leakage completely. In this case, the protection strips already cited are mounted on the glass contour to save glass edges and avoid contact with water of the plastic layer inserted in laminated glass.

In movable glass, two weather strip families are present, depending on the kinematics of the glass:

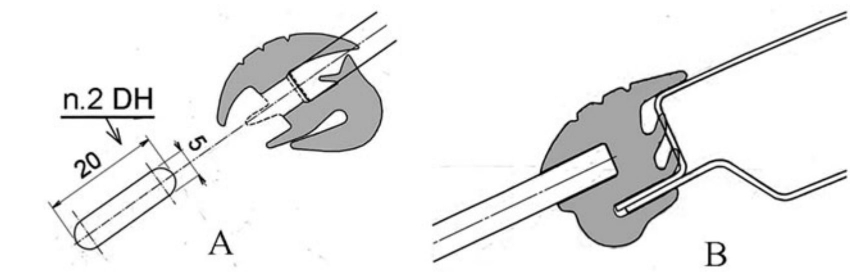


Fig. 5.70. Section of snapped traditional windshield gasket. A: lower side; B: upper side; DH: drain slots.

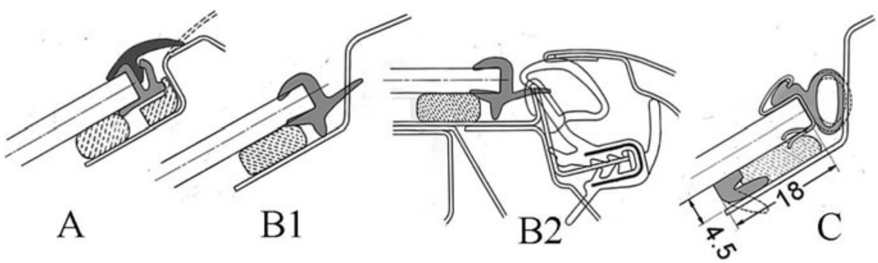


Fig. 5.71. Examples of weather strips for bonded windshield. A: with rubber constant section snap-on molding; B1, B2: single strip with centering lip (upper and side sections); C: bulb strip with metal molding.

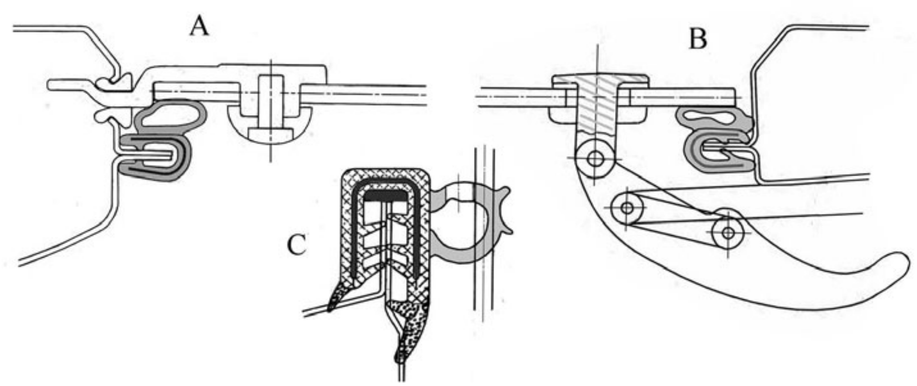


Fig. 5.72. Examples of weather strips for pivoting window. A: glass hinge zone; B) opening clip handle zone; C) side zone.

a) window drop weather strips (run channels and belt weather strips), featuring a number of flexible lips which usually are flocked to avoid ice sticking (Fig. 5.45 and 5.46);

b) bulb seals, usually featuring small lips or teeth to stop water, for quarter glass or cases with glass to body rotation (Fig. 5.72).

Innovation

Window drop channels with an *anti-trap device* have been developed (Fig. 5.73): when a sufficiently stiff body (i.e a finger) is put between glass and channel, a sensing device inserted in the channel records a pressure higher than a certain value, reverting the electrical powering to the window regulator in order to result in a retraction of the glass .

5.3 Glass and Mirrors

In early vehicles, transparent parts were cut from annealed flat glass sheets, with relatively low strength and creating the risk of injuries due to the typical occurence of sharp edges following breakage.

Successive developments saw the introduction of a temper hardening process (mainly thermal, but also chemical), resulting in a relevant permanent stress distribution in the tempered sheet, with strength increase and a mode of breaking that frees the elastic energy and causes splittage into a great number of fragments without splinters.

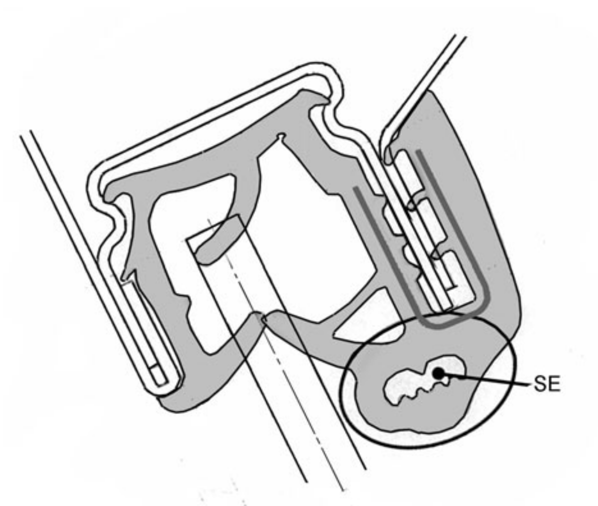


Fig. 5.73. Example of window channel with additional cavity (SE) for anti-trap sensor.

A further improvement, adopted in windshield for many years, was *differential tempering* that, in the case of breakage, results in bigger fragments where required, ie. usually the vision area to enable adequate visibility to be preserved.

In the meantime, glass sheet bending had been developed, both by simple gravity effect and using press molding, preserving the same optical performance of flat panes within a sufficient range.

However the most effective step in this evolution process has been the introduction of the *laminated glass process*, comprising two glass panes assembled with one or more transparent plastic layer in between. The required properties of this plastic layer are firstly to keep the glass sheets together in the case of breakage, effectively preserving almost full visibility in practice except through crack lines; moreover, depending on the type of layer used, the capacity to introduce other benefits including the filtering of some radiation, heat reflection, glass heating and demisting, tinting, electromagnetic signals receiving. These properties have been mainly exploited for windshields and partially for back and side glasses.

Also glass panels production process has been improved significantly over recent years, in particular as regards the finishing process, contour encapsulating, and surface coating to reduce mist and rain drop adhesion.

Nevertheless, car glasses of today still exhibit some critical issues, especially as concerns strength; correspondingly it is relevant to discuss about the glass structure and the cause of certain specific properties of glass.

While molten metallic materials tend to adopt, during the solidification process, a regular ordered 3D organization of uniform crystals (termed crystallization), glass hardening at adequate speed tends to retain the behavior of a ultra

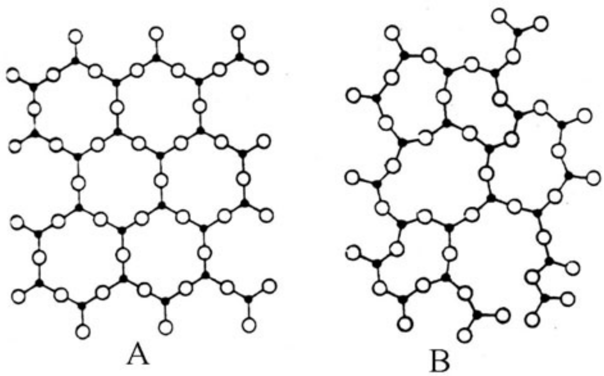


Fig. 5.74. Structural configuration of individual silica crystals in a crystalline (A) and vitreous (B) condition.

Table 5.6. Phisical and mechanical properties of a soda-lime glass.

PROPERTY	UNIT	VALUE
Young's Modulus	MPa	73000
Poisson's coefficient		0,22
Density	kg/dm^3	2,5
Thermal elongation coefficient	$°C^{-1}$	9x10^{-6}
Specific heat	J/kg$°C$	795
Thermal conductivity	W/m$°C$	1,16
Traction break strength	MPa	40
Compression break strength	MPa	1000
Bending break strength	MPa	40

high density liquid and therefore a non regular *vitreous* crystal structure (Fig. 5.74).

Below the so-called *vitreous transition temperature*, glass does not exhibit plasticity: instead it behaves as a linearly elastic material until suddenly breaking (brittle fracture). The distributed presence of micro structural defects across the entire glass surface does not enable a deterministic forecast of breakage conditions and position. Instead the only way to predict the breakage event is through a probabilistic analysis, as explained later .

Moreover, glass can brake due to *static fatigue*, a typical property of glass, due to progressive growth of cracks started by micro defects in the surface, under the combined effect of mechanical stresses and environmental humidity.

Tab. 5.6 summarises the physical and mechanical properties of a soda-lime glass, for which strength values must be considered to be an indication of the average order of magnitude. Regarding the surface glass defect rate, in addition to that caused by the non homogeneous and impure molecular structure, also the effects of manufacturing, chemical reactions and thermal stresses must be considered.

In most cases, breaking is caused by surface defects derived by mechanical scratches, grooves and marks caused by hard contact, where glass stresses are amplified by a stress intensity factor K, related to the material and to the geometrical parameters of the cracks.

In practice, glass which is stressed, for instance, by a traction load, exhibits an overstress peak at the edge of each surface crack; in order to calculate the overstress value, some expressions have been proposed[2], in which the starting crack length is included as primary parameter. According to the studies of Inglis and Griffith, even with different criteria to calculate the critical stress that enables uncontrolled growth of the the fatal crack, breaking stress is in any case inversely proportional to the square root of the major initiation crack dimension.

Assuming, therefore, that only cracks longer than a defined value can initiate the breakage of glass, it is necessary to identify the main stresses capable of causing crack growth up to the critical length. This analysis includes the investigation of fracture lines and surfaces, stress simulation via structural modelling, sample and full size glass bending tests, impact and indentation tests, durability tests and methodologies for result integration to specify design and delivery criteria.

Fracture lines and surfaces (fractographic analysis)

Observing the initiation points and patterns of a crack propagation, it is possible to notice that usual mechanical stresses cause straight, sometimes branched tracks, while residual or thermal stresses give rise to crooked tracks. Moreover, on the glass boundary, a fracture due to thermal shock or traction has a 90° angle referred both to border and to the surfaces of the pane, while a fracture mainly caused by bending has angles different from 90° (Fig. 5.75).

Usually, the broken surface around the critical crack exhibits three concentric regions. The center, around the position of the starting crack caused by an external mechanical action, with smooth and reflecting surfaces on the pane section and straight traces if the crack has been advanced by traction stress or pseudo-elliptic traces if advanced due to bending stress (Fig. 5.76). The surrounding region is characterised instead by quick and confused crack propagation, with a rough and opaque aspect. Then, in the external region, cracks tend to display an increase in the number of split branches.

It has been proved that, for a defined material, the distances of each region from the crack initiation point are inversely proportional to the stress σ_f corresponding to the same crack. This stress can be calculated empirically by using the expression:

[2] Enrico Faccio, *Caratterizzazione meccanica del comportamento strutturale dei parabrezza per autovetture,* Tesi di laurea - Università degli Studi di Padova, Anno accademico 1997-1998.

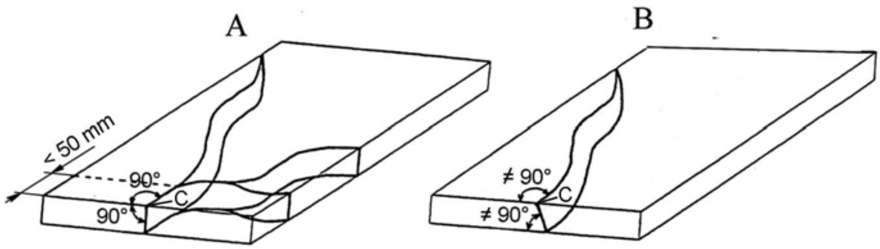


Fig. 5.75. Glass typical fracture patterns. A: caused by traction or thermal shock; B: caused by bending; C: start crack point.

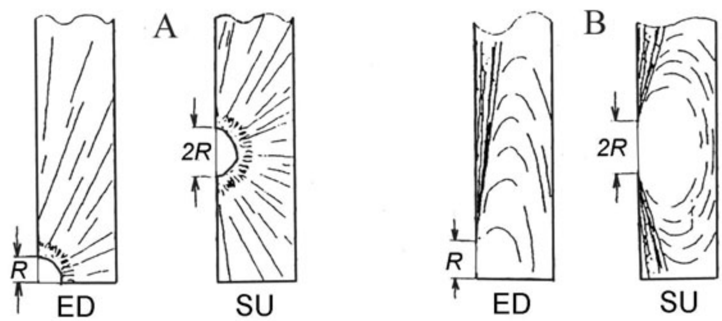


Fig. 5.76. Typical fracture traces on ED sections and SU surfaces, in case of traction (A) and bending (B).

$$\sigma_f = \frac{0.59 \pm 0.03}{\sqrt{c}} \text{ [MPa]} \tag{5.16}$$

Where $c = \sqrt{ab}$ is the crack size in [m] compared to an ellipse of semiaxis a and b.

In practice, assuming a typical crack dimension of 2 mm, a stress $\sigma_f = 13.2$ MPa should be sufficient to initiate the breaking process.

Defect growth process – Static Fatigue

It has been demonstrated that air humidity consistently causes a reduction in breaking stress, and this event can be explained by a quick increase of micro-defects already existing in every pane, due to chemical reactions between water and glass, and accelerated by the stress condition: this phenomenon is called *stress corrosion*.

Crack growth is relatively slow in the first step and is related both to the level of humidity and applied stress; when the crack reaches its critical dimension, the fracture proceeds at high speed mostly depending on the composition of the glass. Consequently, glass durability without breakage is dependent on the initial step growth speed of the crack (*static fatigue step*, also called *subcritical growth phase*): humidity and stress conditions are the factors that must be controlled.

In order to understand the meaning of static fatigue, it is useful to make a comparison with traditional metal fatigue where a variable, repeated cyclical stress can cause a specimen to break in a defined time, while the same stress, if constant in time, could never cause failure.

For glass, in certain environmental conditions, under constant applied stress conditions, time alone can give rise to breakage of a specimen. Moreover, in traditional fatigue, there are: a) an upper limit stress value corresponding to static strength and still respected if fatigue cycles are less than 1000; b) a lower stress value (*fatigue strength*) below which the specimen can be stressed for unlimited cycles, without breakage.

In the case of glass, an upper strength similar to metals does not exist because the strength of a pane is not related simply to its chemical composition but also to its history of stress, abrasion, and environmental influence, and therefore differs from sample to sample. Moreover, a static fatigue limit for glass cannot be defined in practice, as it decreases as far as the test duration increases; in any case, a criterion exists that states as static fatigue limit the stress value corresponding to crack edge curvature unchanging.

The speed of growth of cracks in the first step is proportional to air humidity and temperature level, but its sensitivity is different depending on glass composition. For a soda-lime glass, if humidity changes from 10% to 100%, the increase factor of growth speed is approx. 10; if temperature changes from 22 °C to 60 °C, the speed increase factor exceeds 20. Also deterioration of the condition of the glass surface (abrasion) is damaging, while the stress rate (dynamic fatigue) has a beneficial effect.

Table 5.7. Stress recorded on a windshield by estensimetric gauges.

TEST CONDITION	MPa
before and after installation	21
windshield de-icing	15
on road simulator	18
on heavy paved track	10
at maximum speed	13

The most important goal in design practice is to forecast glass durability in conditions of standard use. Through experimental testing, it is possible to relate duration time with applied stress to obtain fatigue life curves.

The number of tests, the need for many samples and long test times can require an exceptional commitment in terms of testing. By chance, Mould and Southwick[3] experiments with liquid nitrogen have proved that the fatigue strength is independent of the duration of load application. Regarding different crack types, it is possible to collate characteristics in a family of curves, related to the material *inert strength*, ie. the original material resistance before contact with atmospheric humidity. Then, by superposition of these curves through a timing referred to inert strength halving time, the following rule is obtained: all fatigue testing results can be included in one mathematical expression, given by:

$$\frac{\sigma}{\sigma_N} = f(\frac{t}{t_{0.5}}) \tag{5.17}$$

(*universal static fatigue expression*), where σ is fatigue strength, σ_N is the inert strength of the material, t is the duration, $t_{0,5}$ is time corresponding to condition $\sigma = 0.5\ \sigma_N$.

The universal static fatigue expression (Fig. 5.77) is valid for all types of abrasion, provided that breaking times are sufficiently long and not too close to the fatigue limit.

Stress measurement and break tests

The stress conditions of a car glass are variable in time and intensity; therefore a number of estensimetric strain gauges have been placed on a windshield and strains have been recorded in both a set of production process and operational conditions.

Unfortunately the applicability of such recordings is limited for a number of reasons: firstly, gauge size gives an average result for the covered area and does not allow border values to be recorded; gauge positioning is not exactly aligned with principal strains (even by a previous computer simulation); internal glass

[3] R.E. Mould and R.D. Southwick, *Strength and static fatigue of abraded glass under controlled ambient condition; II: effect of various abrasions and the universal fatigue curve*, J. Am. Ceram. Soc., 42-1959.

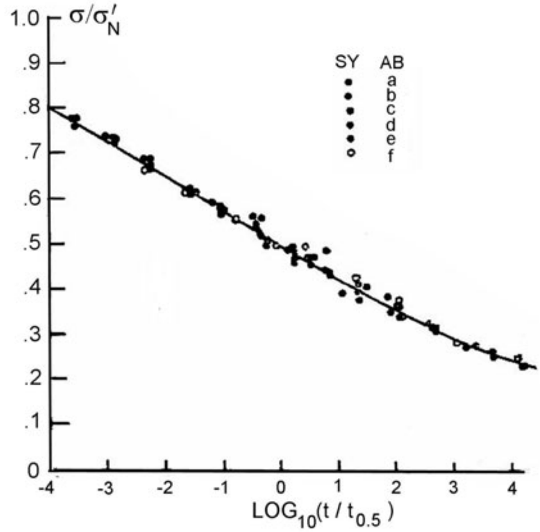


Fig. 5.77. *Universal static fatigue* for a traditional glass, with different types of abrasion.

stresses are not measured. Moreover, estensimetric recordings provide information on strain change during test and not the absolute strain values, depending on pretensioning.

Tab. 5.7 shows an example of stress peaks recorded on an inner windshield surface at a distance of 60 mm from border, both during windshield installation/bonding to body and during operation on the road.

It can be noticed that the recorded values, even if less than the glass strength, are in the same range of the average traction and bending strength.

Moreover, some stress conditions could apply simultaneously in vehicle use (for instance, traveling on heavy track and inserting windshield de-icing). Bearing in mind that the recorded values are only a random set of samples and that glass strength has a wide range of variation, these records highlight that the safety margin for glass is very narrow and the probabilistic approach represents the only reliability tool possible .

Discussed already is how glass stress can be measured in some typical use conditions. Another factor that needs to be clarified at this stage is the statistical range of glass strength.

As already seen, the statistical range of glass strength is influenced by many variables; to date, no universal test has been defined and agreed to measure glass strength which is capable of including all real glass operational conditions. Some car manufacturers have therefore preferred to define test methods aimed at investigating the natural strength range of a standard production glass component with fixed size, fixed material composition, and defined process. In detail,

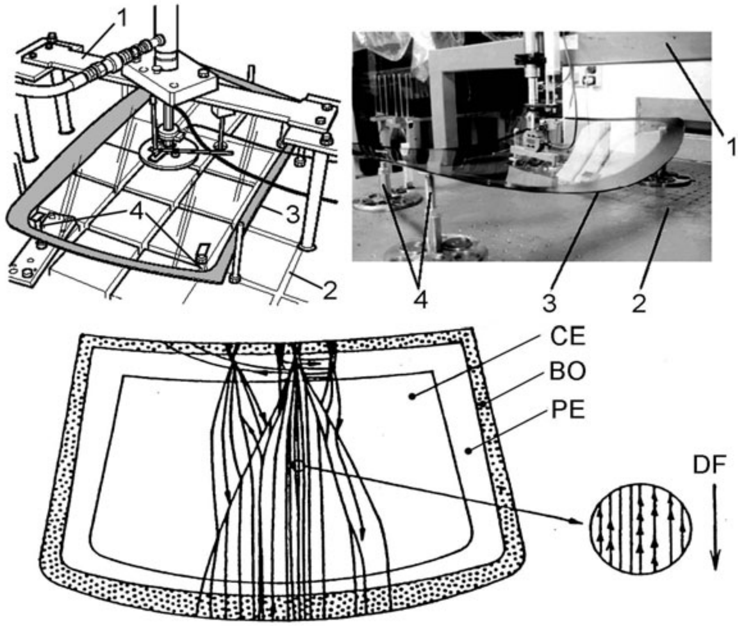


Fig. 5.78. Windshield break bending test. 1: loading support bridge; 2: work table; 3: glass to be tested; 4: spherical edge height adjustable supports; BO: boundary decoration; PE: perimeter area; CE: central area; DF: fracture direction.

these tests have addressed two typical resistance properties: bending resistance, relevant to the installation process and operation on roads; impact resistance, related to impact of hard and sharp objects such as stones.

As an example, it is appropriate to consider a break bending test agreed between a car manufacturer and several windshield glass suppliers for the statistical evaluation of supply lots. Fig. 5.78 shows loading system and the typical glass image after breakage.

Each windshield is laid down on 4 points defined on the pane diagonals at a distance related to the diagonal length. Load is applied at the cross point of the diagonals using disc loading through two spheres, acting in the direction orthogonal to the inner surface of the windshield and with a stated speed. To reduce the friction between the glass and the spherical actuators, *Teflon*® layers are used in between. Load increase is recorded with a load cell and deflection at the glass center by a displacement transducer, while temperature and humidity are monitored.

At breakage, the disc is stopped, and load and deflection are recorded; then, the glass is visually inspected to identify the fracture origin and the visible defects.

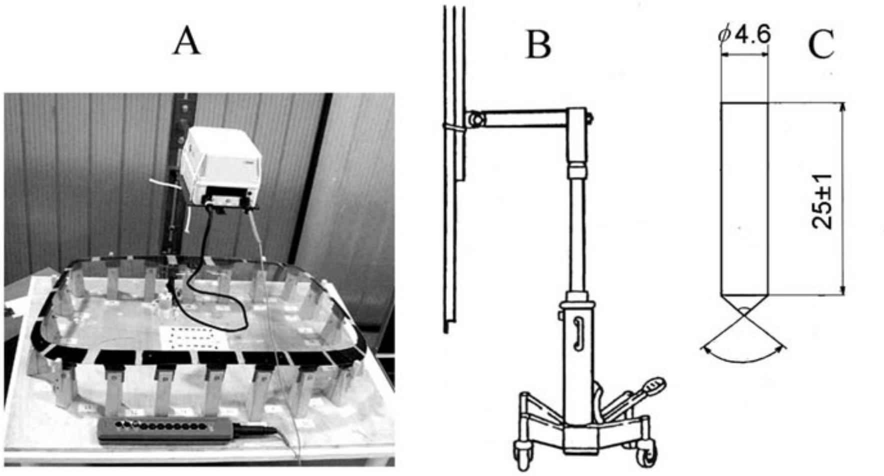


Fig. 5.79. A) Windshield dart throwing device; B) Dart gun detail; C) Dart detail (not to scale).

The test is repeated with at least 12 samples (the recommended number of samples is 20) and results are placed in increasing order according to the break load. The break probability ranking is defined by the estimator:

$$p_i = \frac{i - 0.5}{N} \tag{5.18}$$

p_i being the probability rank, i the sample sequence index and N the total number of samples.

The resulting cumulative breakage frequency is compared with probability curves presenting the same average value and the same standard deviation (for ease, double logarithmic table is applied) and used in the way that shall be explained later.

Another common test intended to simulate windscreen stone chipping is performed by throwing a diamond conic edge dart at rated energy (Fig. 5.79). The dart launch height is 1.5 m, while the speed is variable and hitting positions are chosen in two typical windshield zones, one where the glass pretension is close to zero and the other where the traction on outer glass is a maximum.

At least 10 samples of windshields are tested and results are collected in a cumulative break probability curve (Fig. 5.80). Using the same kind of test, it is possible to evaluate the break probability increase due to stone chipping as a function of traction pre-tension: the dart is launched with the same speed/energy against different windscreen points (Fig. 5.81). As explained more fully later, traction pre-tensioning level is a consequence of stresses applied

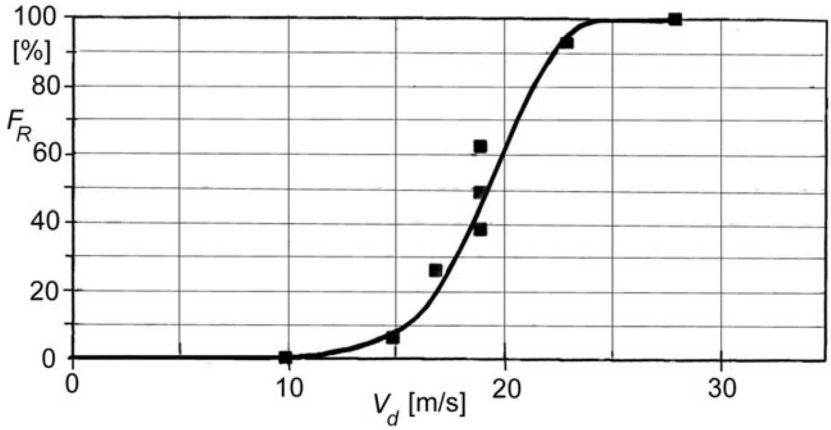


Fig. 5.80. Cumulative radial break probability F_R for a windscreen, according to Weibull function, from a set of 8 dart tests. V_d is dart impact speed. Weibull curve parameters are: m=8.5; V_0=20.2 m/s.

during windscreen production and installation, and depends also on the distance of a point from the windshield boundary (see Fig. 5.83).

Checking windscreen stone chipping resistance is a priority since this is the first cause (∼70%) of cars failure. Fissure morphology in this case can be: *radial* (mostly far from glass contour, with a central crater surrounded by radiant fissures), *Hertzian* (when the striking object is roundish and the fracture mark is developed toward pane core), *line fissure* (usually starting from glass contour and developing as a single filament). The type of test performed can indicate the most critical windscreen zones, also with respect to traction pre-tension and break morphology.

Measurement of glass pre-tension

As already stated, the border of a standard production annealed glass has a higher level of defects, mostly caused by working and handling. In order to contrast fissure propagation, pre-tensioning of the border region is used to increase glass resistance to defect growth: this purpose is commonly achieved by a border compression state, caused by a soft temper during annealing process. The resulting stress pattern in a glass section is visible in Fig. 5.82.

For stress balance, a glass strip close to the compressed border is consequently traction stressed: the glass pattern along a radial direction appears as in Fig. 5.83. Therefore the compression pre-tensioning cannot be as high as possible being conditioned by the maximum allowable traction stress in the inner strip. Pre-tension allowed levels are therefore specified by car manufacturers as, for example, shown in Fig. 5.83.

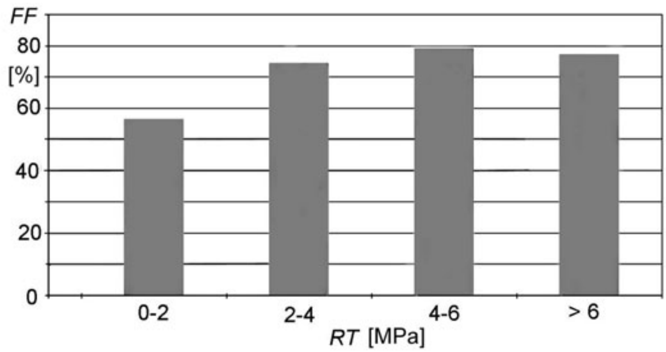


Fig. 5.81. Experimental line + radial break frequency *FF* in a windscreen tested with dart gun, at constant strike energy, as a function of residual traction stress *RT*.

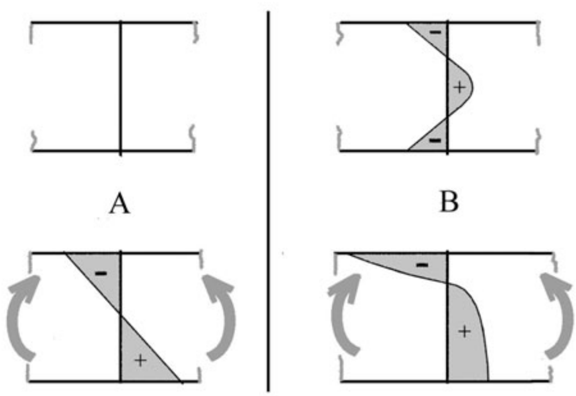


Fig. 5.82. Section stress pattern in an annealed (A) and tempered (B) glass pane. Above: without external load; below: with bending load.

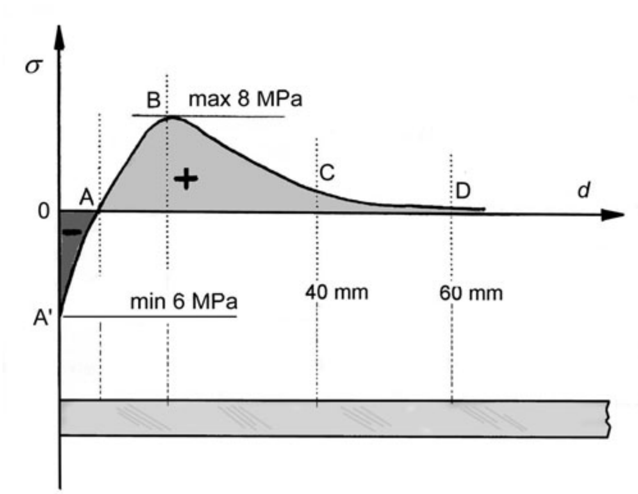


Fig. 5.83. Example of stress pattern for a pre-tensioned windshield, as a function of distance d from border, with specified pre-tension values agreed between car and glass manufacturer.

Measurement of glass stress distribution is usually made by a polarimeter, a device that enables the evaluation of stress values by the measurement of a phase angle between two polarizers, capable of blocking a light signal sent through the glass (Fig. 5.84).

This method takes advantage of the *photo-elastic properties* of transparent materials such as glass; these materials, when loaded by external forces, have a different refraction index in the principal strain directions. Light emission from a source is an electromagnetic wave radiation without preferential vibration direction. Some materials, for instance those known as *Polaroid*®, being made of *polar molecules* (*dipole*) all oriented in the same direction, perform a different filtering of light radiation when crossed by a normal light beam. The filtered light beam becomes *polarized*, that means it has a dominant vibration direction of the electro-magnetic waves. When the polarized light beam crosses an isotropic transparent body, it is divided into two polarized orthogonal components, each parallel to principal stress direction in the plane orthogonal to light propagation (Fig. 5.85–A). If the body stress field is uniform, both components cross it at the same speed and therefore their re-composition, when emerging, returns the original entering light beam.

If instead the body stress field is not uniform and is made by a *birefringent* material (glass, for instance), it causes a differential phase lag of light radiations. Therefore, the two components emerge from the body with a phase difference, referring to the entering condition. The phase difference between the transverse

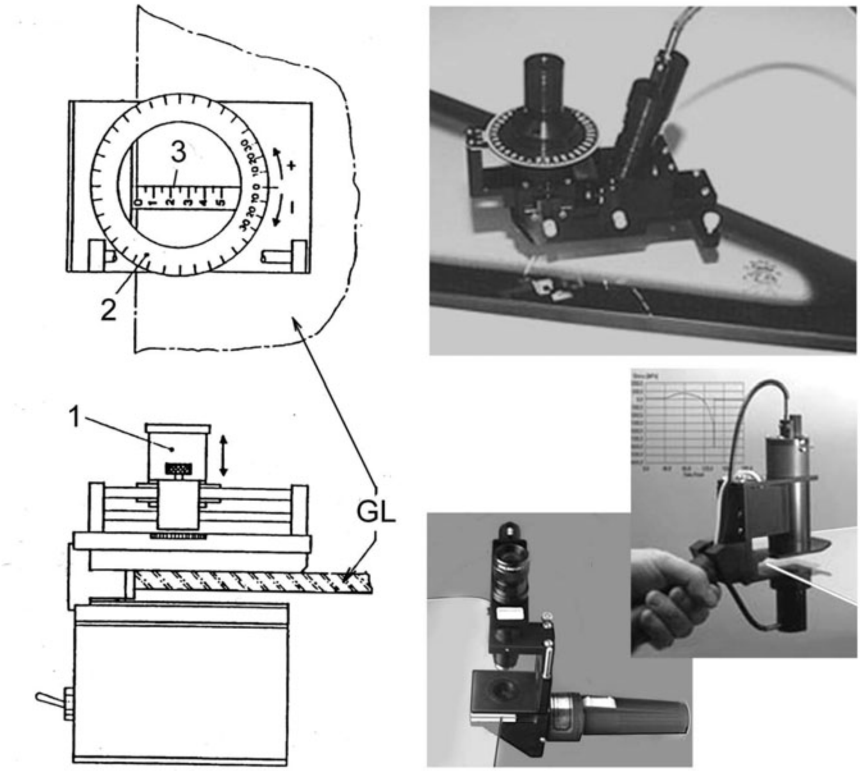


Fig. 5.84. Scheme and examples of polarimeters. GL: glass; 1: collimator; 2: goniometer for *optical rotation angle* measurement; 3: ruler for alignment.

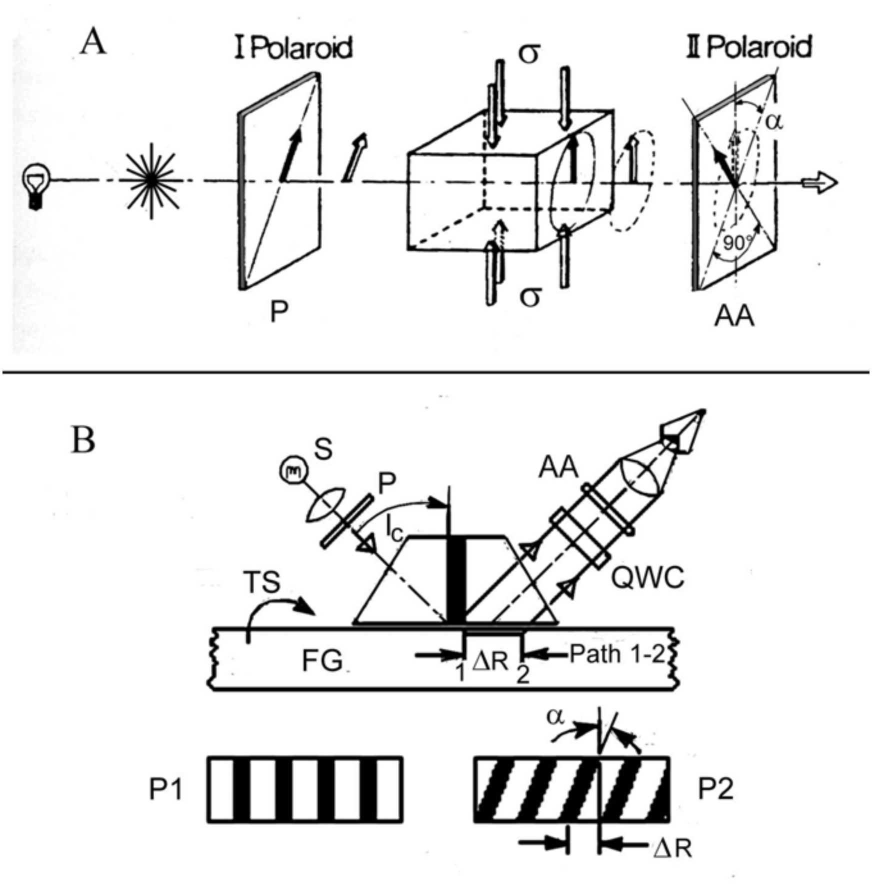


Fig. 5.85. Schematic function of polarimeter/polariscope (α= *rotation angle*). P: polarizator; AA: analyzer; QWC: quartz compensator; FG: float glass; TS: tin side; P1: image of a zero stress surface; P2: image of a stressed surface. Angle α is related to stress value.

waves is proportional to the difference between the principal stresses of crossed body.

If the coming out light is analyzed through a second *Polaroid*® (called *analyzer*), with transmission axis orthogonal to first *Polaroid*® orientation, it is possible to see only the wave transverse components that are parallel to this direction. In the case of a stress free body, the analyzer should absorb the light beam polarized by the first *Polaroid*®, unchanged by body crossing and therefore no light should be visible.

If the glass is stressed, in order to obtain the light beam extinction, the *Polaroid*® analyzer must be turned by an angle depending on stress of analyzed zone. This angle, called *optical rotation angle*, is read by a goniometer fixed to analyzer and enables to calculate local stress, by the *photoelastic* tested *material constant*.

Polarimeters can work on different principles, for instance by sending an inclined light beam to glass surface through a prism and evaluating rotation of fringes (due to delay among the glass reflected rays) on a quartz sheet crossed by the rebound beam (Fig. 5.85–B). The investigated stress is related to fringes rotation angle, through a material constant.

The methods explained are applied to a perimeter strip close to glass border, after laying down the glass on a relevant number of supports, to lower the effect of glass weight on stresses. The glass must be free of boundary decoration in analyzed points. It should be remembered that the stresses measured through polarimeter are average values in glass pane thickness: their approximation depends on local stress distribution inside pane thickness.

Fracture probability computing

Break probability F or reliability A=1-F can be calculated on a relevant sample set stressed in the same way, by making some assumptions regarding defect density:

- defect related to main fissure dimension;
- defect main axis oriented at 90° to applied stress;
- flaw density low enough to avoid defect interaction;
- flaw density distribution typical for tested material;
- pane break related to collapse conditions for the most critical defect.

Sometimes the proposed rules are not verified, but testing has shown that glass break probability can be approximately estimated by a mathematical expression, commonly used for probability distribution estimation, such as the Gaussian, Weibull or Log-normal.

Fig. 5.86 shows a comparison between cumulative Gaussian probability distribution and experimental breaks for a lot of same windshield, stressed in the same way.

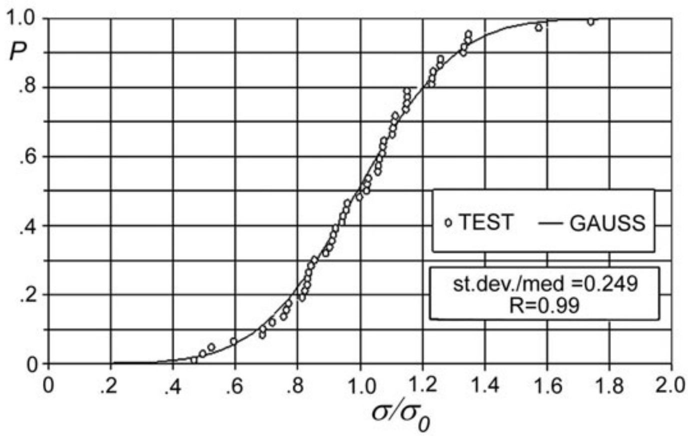


Fig. 5.86. Experimental frequency and cumulative break probability for static bending tested vehicle windshield. In abscissa, ratio between single and average break stress; in ordinate, cumulative frequency and gaussian probability.

Gaussian probability density is given by:

$$f(\sigma) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(\sigma-\sigma_0)^2}{2s^2}} \tag{5.19}$$

Where σ is break stress, σ_0 the average break stress applied to sample lot, s is the lot break stress standard deviation.

The calculated values are referred to a lot of 55 glasses and therefore are a sample, not the universal of production glasses, and therefore represent an estimation. To evaluate universal probability, the confidence range of the average and of standard deviation must be calculated. Confidence range for the estimated average s_0 is evaluated by the Student's t parameter:

$$\sigma_0 - t\frac{s}{\sqrt{n}} < \mu < \sigma_0 + t\frac{s}{\sqrt{n}} \tag{5.20}$$

Where μ is the *true* population average, s is the lot estimated standard deviation, t is Student's parameter for the range of values external to the chosen confidence range (for instance, choosing the 95% confidence, that means the range 2,5%–97,5%, $t_{0.025}$ is the Student's parameter to be used for n–1 freedom degrees). The expression is represented in Fig. 5.87:

The standard deviation s confidence range is evaluated through the parameter χ^2, by the expression:

$$\sqrt{\frac{(n-1)s^2}{\chi^2_{0.025}}} < s_{pop} < \sqrt{\frac{(n-1)s^2}{\chi^2_{0.975}}} \tag{5.21}$$

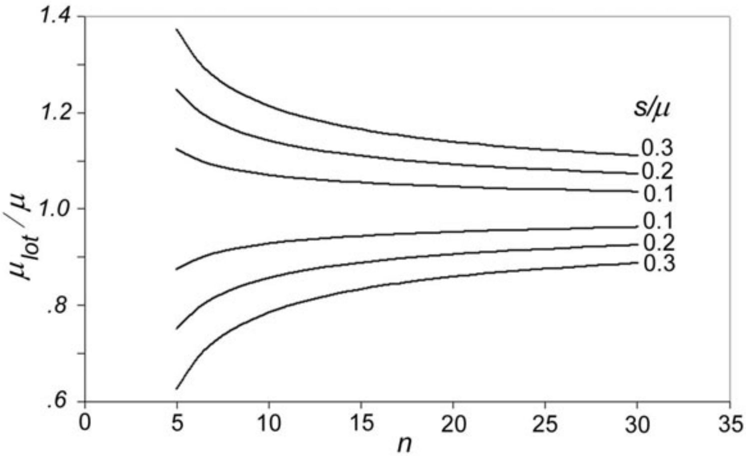


Fig. 5.87. 95% confidence range of average μ, estimated on a lot of n samples, for lot different standard deviations s.

Where s_{pop} is the true population standard deviation,$\chi^2_{0.025}$ and $\chi^2_{0.975}$ are the values of χ^2 for probability lower than 2.5% and higher than 97.5%, for a set of n samples. Usually, a 95% confidence range is considered adequate, meaning that 95% of cases fall in the calculated confidence range.

Fig. 5.88 illustrates the range of ratio between lot s_{lot} and universal s_{pop} standard deviation that has 95% probability of occurring, when changing the number of samples. In summary, if the glass shape, material composition or production process change, the explained statistical distribution of breaks can vary both in results average and range; however, by applying the explained statistical criteria, it is possible to define the variation allowable range.

These criteria have been used to establish the selection and delivery rules for supplied lots, as explained subsequently.

5.3.1 Windshield

Today, windshields are usually made of two annealed glass panes of same or two different thickness, with inserted thermoplastic layer (commonly *Polyvynil butyral PVB*, thick 0.76 mm). Until the 1980's, single pane tempered glass windshields were allowed with differential temper between center visibility area and close to border. Current solution can grant visibility and permanent glass surface, even in the case of breaking, because the plastic interlayer keeps the broken surfaces together. On the other hand, in case a head impact against the windshield during a crash, a tempered glass has a higher strength and, if broken, does not give rise to sharp splinters as happens with the annealed glass.

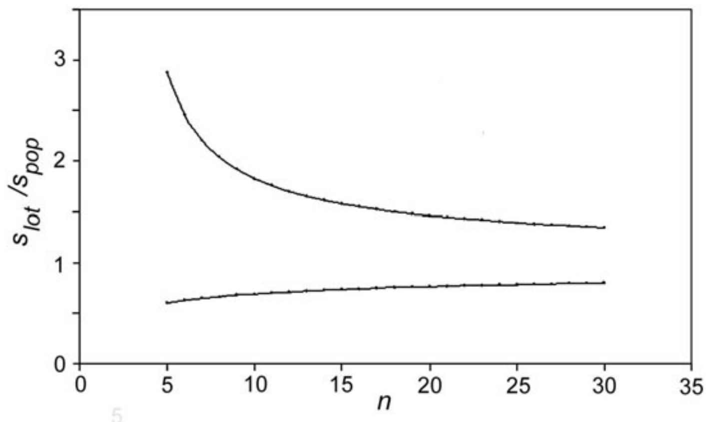


Fig. 5.88. 95% confidence range of standard deviation computed for a n sample lot.

While generally more effective than the single pane tempered windshield, due to its higher strength, the *laminated windshield* (two annealed panes, tempered close to border) requires that passengers always use seat belts, even at low speeds when airbags do not deploy during a crash.

PVB's physical and mechanical properties depend on temperature and humidity: below the *vitreous transition temperature* (16 °C), PVB is so stiff that the windshield behaves as a single monolitic pane of thickness equal to the sum of two laminated panes. Above that temperature, PVB behaves instead as a viscous elastomer and therefore the windshield stiffness in bending is the sum of individual stiffnesses. For its other properties, reference should be made to Tab. 5.8. In addition to laminates connecting function, PVB has acquired other tasks

Table 5.8. PVB's phisical and mechanical properties.

PROPERTY	UNIT	VALUE
Elastic shear modulus (G)	MPa	0,7
Poisson's coefficient		0,50
Density	kg/dm^3	1,06
Thermal elong. coeff. above 40°C	$°C^{-1}$	7,7x10^{-5}
Specific heat	J/kg$°C$	2100
Thermal conductivity	W/m$°C$	0,21
Elongation at break	%	210
Young's modulus at 100% elongation	MPa	5
Tear strength	MPa	3

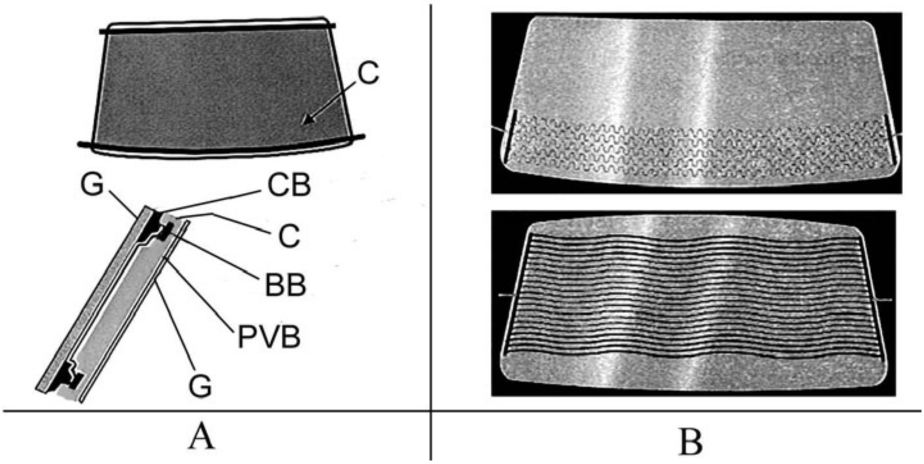


Fig. 5.89. Windshield heating systems by PVB: A) conductive heating at 42V; B) drovned copper $< 20\ \mu$m microfilaments; G: glass; C: coating; CB: ceramic band; BB: busbar.

over time, such as including or supporting electrical heating and demisting filaments, tinted antiglare band, solar control films to filter UV rays, accommodating antennas and different sensors (Fig. 5.89).

The PVB film can be damaged by humidity; for that reason, the windshield border is usually covered by a frame or an over-molded encapsulation (see weather strips chapter).

Windshield panes can have the same thickness (2.1÷2.3 mm) or the outer glass thicker (for instance, 2.6 coupled with 1.6 inner), in order to provide higher resistance to stone impact.

Manufacturing and installation

The panes are cut from flat glass sheets, floating over a tin melted bed, surrounded by an inert atmosphere (*Float process*) and grinded to remove border defects. Then the border is treated with a vitreous, usually black but even colored, silk-screen. This material is a glaze enamel, amorphous, isotropic and elastic, that changes the glass surface stress field and defectivity. In the following step, one pane is laid over the other, while inserting in the middle an inorganic layer that simulates the PVB layer, in a die the shape of which duplicates the required external surface contour. The assembly is put in oven at 650 °C where the panes become soft and adapt themselves under gravity to the die; then the assembly is cooled slowly (*annealing*) to make the product homogeneous, with the exception of a border strip, tempered by local air blow for quick cooling. Then the panes are coupled, with interposition of a PVB film, in a humidity and temperature controlled autoclave, where they are first pressed to extract the air trapped between the panes and the PVB. Finally, at 140 °C and 12÷15 bar,

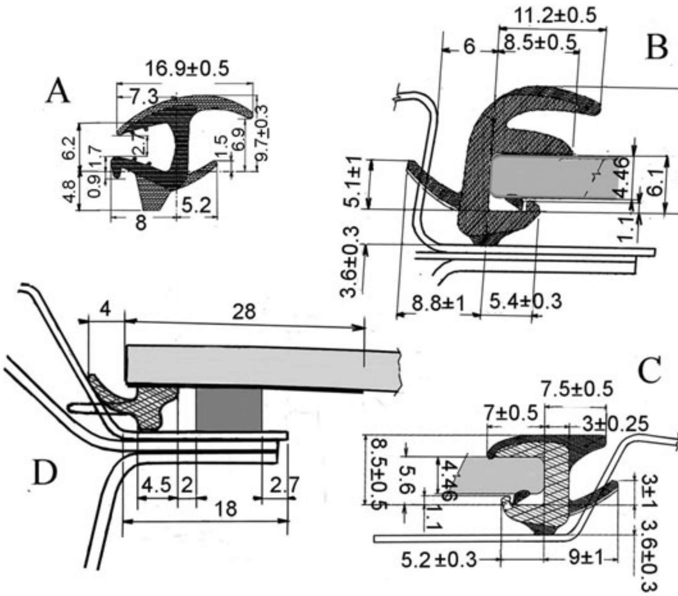


Fig. 5.90. Examples of different windshield encapsulations: A) wrap-over, co-molded; B) built-in, compact rubber; C) built-in, co-molded; D) extruded, frameless.

chemical bonding is performed between the panes and the PVB, the latter being transformed from being wrinkled and opaque into a perfectly transparent layer.

Today windshield installation on bodies is made using adhesive bonding of the already encapsulated glass assembly (with extruded or over-molded molding - Fig. 5.90). The windshield is degreased and the bonding surface primed, before being prepared with a manual or robot extruded adhesive rod (Fig. 5.91). Then the assembly is laid down on the windshield opening flanges, with interposition of spacers to establish the final adhesive thickness and glass to body centering. Finally, devices to maintain the windshield in place during adhesive curing are applied, while the body proceeds to the components mounting line.

The most commonly used adhesive is a *monocomponent polyurethane* (Tab 5.9), that is cured by air humidity, therefore starting from outer layers, adjacent to the body. This allows the operation of the movable parts after 40 minutes without risk of detachment, and enables the vehicle to be moved and even shaked in 3 hours. Full curing of the adhesive acceptable for vehicle fatigue and impact testing, requires approximately 7 days. Some *quick fix*® products are on the market that cure in less time, but require the immediate fitting of the windscreen following adhesive extrusion.

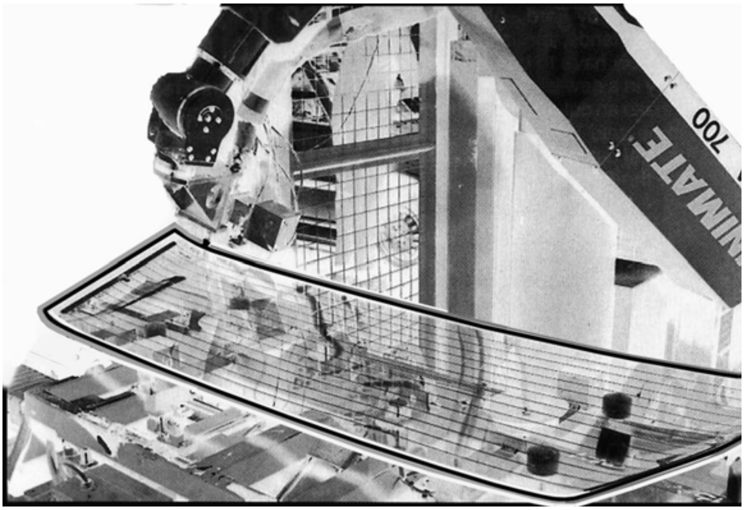


Fig. 5.91. Adhesive extrusion over a back window using a robot.

Table 5.9. Phisical and mechanical properties at 20 °C of a typical monocomponent polyurethane adhesive for glasses.

Young's elastic modulus (E)	MPa	3,68
Shear elastic modulus (G)	MPa	0,94
Poisson's coefficient		0,49
Density	kg/dm^3	1,25
Hardness Shore A - DIN 53505		60
Vitreous transition temperature	$°C$	-56
Elongation at break	%	> 500
Tear strength	N/mm	20
Shear strength	MPa	> 5
Traction strength	MPa	> 6

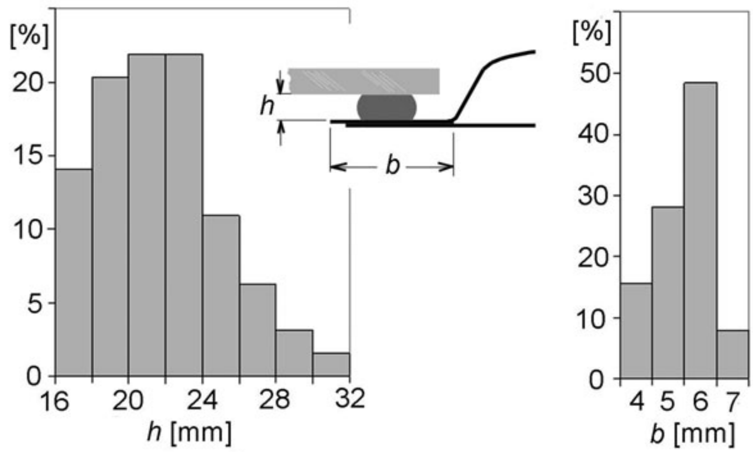


Fig. 5.92. Windshield opening flange size (b) and adhesive thickness (h) recorded on 32 European and Japanese cars.

Usually, a temperature increase causes traction, shear strength reduction and increase of elongation at break. A sample, polymerized at ambient temperature with G modulus of 1.10 MPa, has G=1.64 MPa at –30°C, and G=0.82 MPa at +80°C.

In any case, the introduction of these adhesives for windscreen sealing has created a number of advantages when compared to the previously used rubber gasket, primarily in terms of water and air proofing, but also improved glass retention in the case of crash, a relevant contribution to body torsional stiffness and cabin impact strength, and enhanced aesthetics mainly with flush windshield. The main disadvantage is the increase in labour for mounting and replacing operations.

Regarding body torsional stiffness, the contribution of the bonded windshield is as effectively higher as the body frame stiffness reduces; in some cases more than 30% increase has been achieved, without any danger due to the higher glass stress levels.

The main risk of bonded glass stress is caused by the uneven thickness of the polymerized adhesive, mainly due to waviness and discontinuities of the body flanges. The average adhesive design thickness is 4÷6 mm (Fig. 5.92): if local thickness reduces by half, a sharp increase of glass to body connection occurs with a local stress concentration consistent with hyperstatic fitting.

Dimensional windshield and body flanges tolerances are therefore priority windshield specifications.

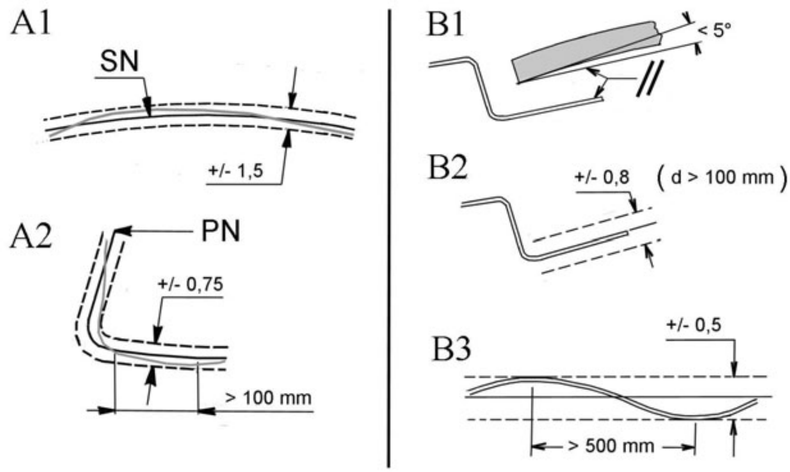


Fig. 5.93. Windshield shape tolerances (A1, A2) and positioning tolerances of body windshield opening flange (B1, B2, B3). SN is design surface, PN design perimeter.

Specifications and delivery tests

The specified geometrical parameters are windshield tolerances on main curvature, perimeter, thickness; body tolerances on length, position, waviness and inclination of metal flanges (Fig. 5.93). Values shown in this figure represent the lowest tolerances, consistent with normal windshield and body manufacturing.

In addition to dimensional control, a sample measurement of border pretensioning is performed, and checked to fall within assigned specifications (Fig. 5.94).

It is important to investigate the distance from the border where pretensioning inversion takes place and where the traction stress is a maximum (Fig. 5.95), because this is effectively the weakest glass region. Most often breakages from stone impacts start from that region: as can be noticed in the figure, the critical area is between 10 and 20 mm from border, where also fitting and silk-screen stresses are applied.

This measurement is made using samples of pre-production supply lots, usually manufactured in order to tune the production process of a new windshield. In order to measure the pre-tensioning with a polariscope, border treatment must be removed by a smooth grinding process. After that, the windshield is no longer acceptable for production and therefore tested samples are used for final bending break test, the results of which indicate whether accept or reject the supply lot.

The bending break test can be performed using the previously described tools and method. The delivery criteria are related to average break loading, standard deviation to average break load ratio and therefore cumulative break probability:a lot is accepted if its results comply with qualified pre-production lots.

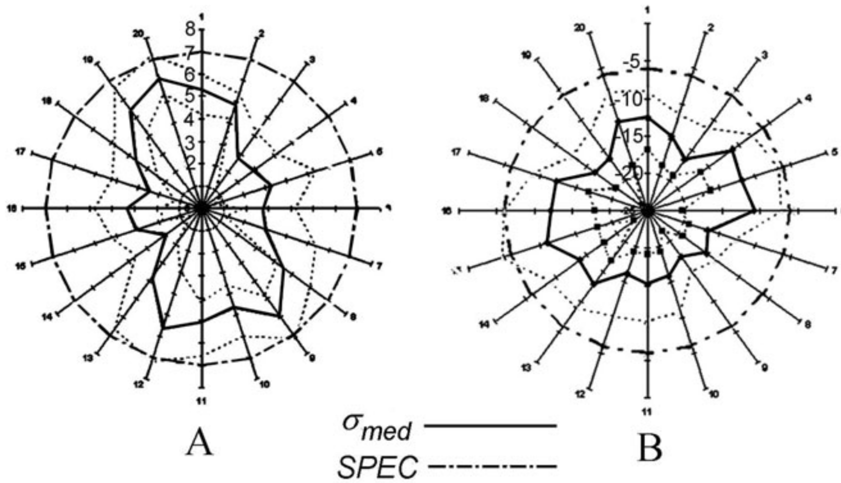


Fig. 5.94. Maximum, minimum and average traction (A) and compression (B) pretensioning (MPa), recorded on all windshield border zones, numbered 1 to 20. *SPEC* is the specified pretension level.

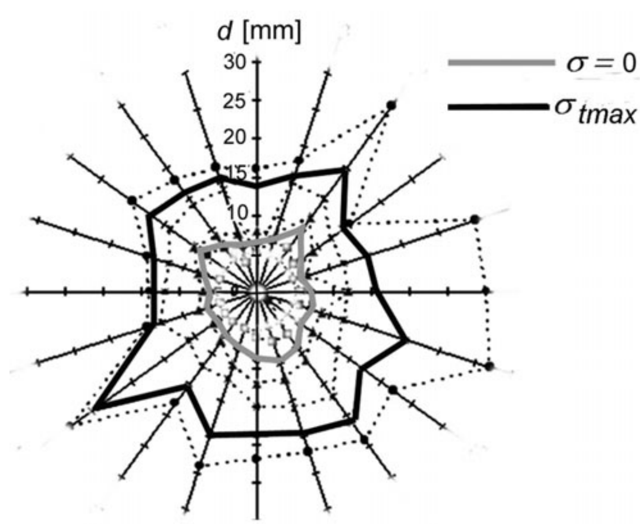


Fig. 5.95. Example of polariscope analysis of pretensioning inversion ($\sigma = 0$) and maximum traction pretensioning ($\sigma_{t\,\max}$). Every radial line refers to a windshield perimeter position; d is distance from border.

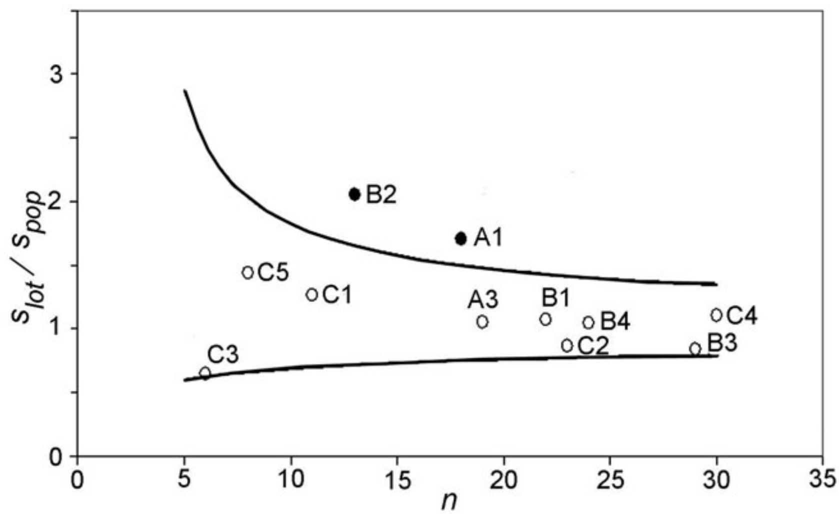


Fig. 5.96. Examples of lot standard deviation to universal standard deviation ratio, for break load of the same windshield, related to sample number n. Lots A1 and B2 have been rejected, resulting external to 95% confidence range.

Comparison of the standard deviation with historical results is made using the graph in Fig. 5.88, that in practice becomes as in Fig. 5.96.

Cumulative break probability is evaluated using a specific bilogarithmic plot for the tested windshield, where values related to the lowest cumulative probability range (between 0.1 and 10%) are compared (Fig. 5.97). The abscissa corresponds to the bending break load, the ordinate to the cumulative probability.

On the plot, the estimated confidence range for the tested lot and the theoretical probability generated by computer analysis are shown, together with a more favourable probability obtained by displacement of the theoretical one and considered *acceptance threshold*. If the tested lot confidence range is to the left of threshold (meaning loads lower than threshold, as in the case of figure), the lot is rejected.

Furthermore the windshield is subject to specifications regarding visibility, both in the fully clean condition and in wiped zones, following conditioning in a climatic cool chamber (–20°C). A windshield must never cause *double* or *distorted images*; these optical defects can be caused by design inadequacy or by an uneven manufacturing process. Regarding design, inclination, curvature and mostly their variation close to the body front pillars must be verified.

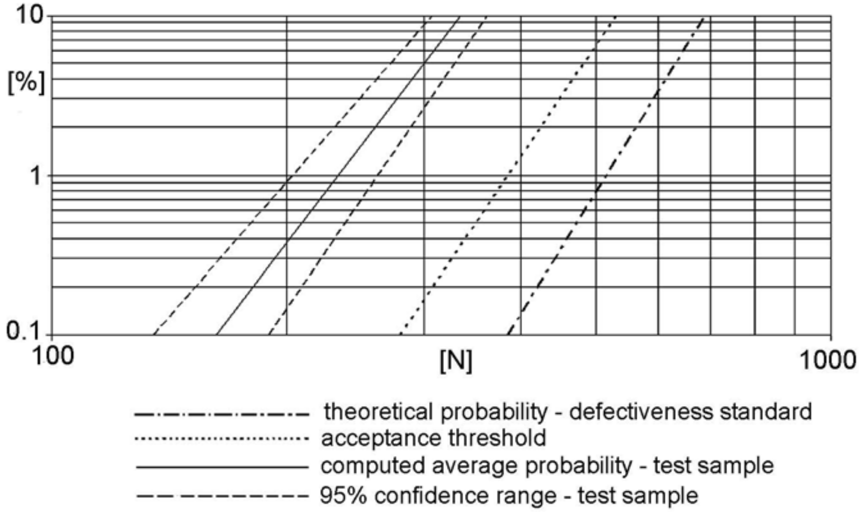


Fig. 5.97. Nomogram used to deliver or reject a windshield lot, verified in bending break test.

These values are generally considered critical:

- inclination, referred to horizon, when $< 30°$;
- curvature radius, when < 500 mm in horizontal plane and < 700 mm in vertical plane;
- curvature variation when $> 40\%$ over 100 mm;
- primary curvature camber, when > 100 mm;
- secondary curvature camber, when > 10 mm.

Image distortion is related to windshield inclination, as explained by the distortion amplification factor (Fig. 5.98).

Glasses can be white (transparent) or tinted: 4 classes have been defined, corresponding to four overall energetic transmission level (Tab. 5.10).

International regulations require that the windshield transmission of visible rays be not lower than 75%. Therefore no dark coloured glass can be homologated for windshields; only acceptable are white windshields or those belonging to the *solar control*family , special tinted glasses with anti-glare and heat transmission properties without penalising the visible rays wavelength.

These glasses are mainly designed to reduce *infrared rays* with wavelength $>$ 780 nm, by radiation absorption and/or reflection. This result is obtained using films or coatings coupled with traditional PVB, capable of absorbing 25÷30 %

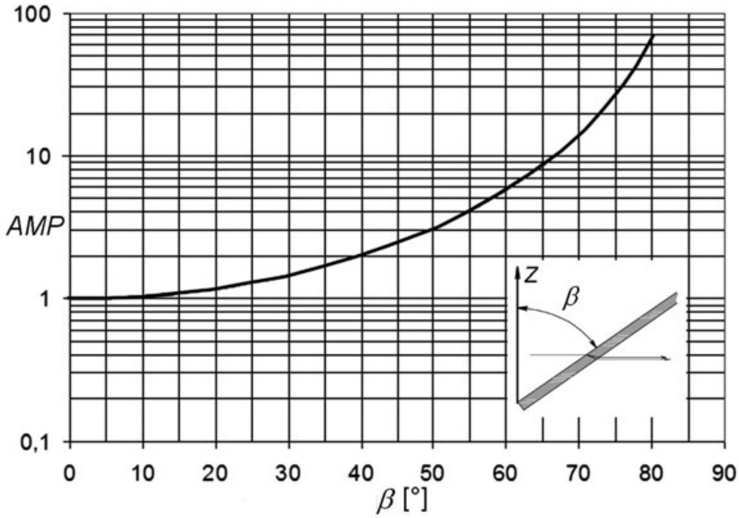


Fig. 5.98. Distortion amplification factor AMP of a glass, referred to inclination angle β.

Table 5.10. Overall energetic transmission for the four glass market classes.

CLASS	GLASS COLOR	TRANSMITTED ENERGY
0	white	$\simeq$100%
1	light coloured	$<$ 67%
2	medium coloured	$<$ 55%
3	dark coloured	$<$ 50%

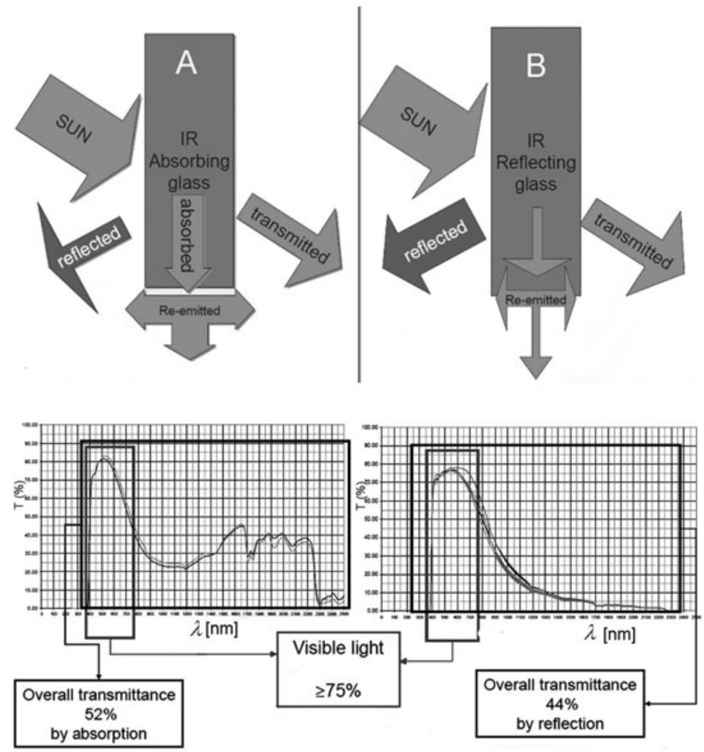


Fig. 5.99. Solar rays transmission spectra through an absorbing (A) and a reflecting (B) glass.

of radiant heat and transfer to passenger compartment no more than 44÷52 % of energy entering the glass (Fig. 5.99).

To comply with windshield de-icing test, a number of solutions have been introduced to heat the glass, especially in the lower region, where wipers are usually located (see Fig. 5.89). In practice, PVB is filled with micro-filaments or invisible conductive particles or covered with a conductive coating.

Innovations

In the case of rain, even today windshield cleaning is still not completely satisfactory, despite the improvement of wipers over the years. The problems still to be completely solved include water mass adhesion to windshield between two following wipers brushing, and drops *diffraction* that causes night glare.

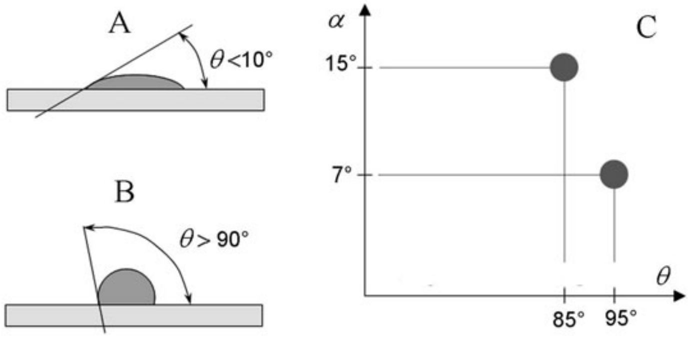


Fig. 5.100. Schematic behavior of glasses with water-repellent coating. A: uncoated glass; B: water-repellent coated glass; C: glass slope α, referred to horizon, needed to glass self cleaning, as a function of drop contact angle θ.

Significant research has shown that water drop inclination to adhesion is related to the *contact angle* between drop and glass: the higher the contact angle, the lower the glass slope needed to make the drop slide (Fig. 5.100).

Some inorganic coatings, based on silicium and titanium oxides have been tested, resulting in an increase in contact angle and, at the same time, abrasion resistance; the issue remaining is the need to repeat the treatment periodically.

Plastic-glass windshield

Instead of three layers laminated glass, *bi-layer* windshields have been tested, made using an external glass pane of about 3 mm (2÷4) and a transparent polyurethane 1 mm thick sheet incorporating two layers: one for the absorption task and the other for scratch resistance. This windscreen offers a number of advantages when compared to laminated windshield including lower weight for the same stiffness, a better glass retention in the case of a crash, no misting, and feasibility with more complex shapes without optical defects: however still required is an anti-scratch treatment which is reliable.

5.3.2 Door Windows

Today the door windows are usually curved cylindrical (one curvature) or cask (two curvature) glasses, sliding inside sealing channels fitted to door rails and operated with window regulators, connected to the glass by bonded brackets or pressed with rubber in between or hinged by pivoting clips snapped into the glass holes.

For economy and mid class cars, door windows use a single tempered pane of glass, the thickness of which over the years progressively decreased, from 4÷4.5 to

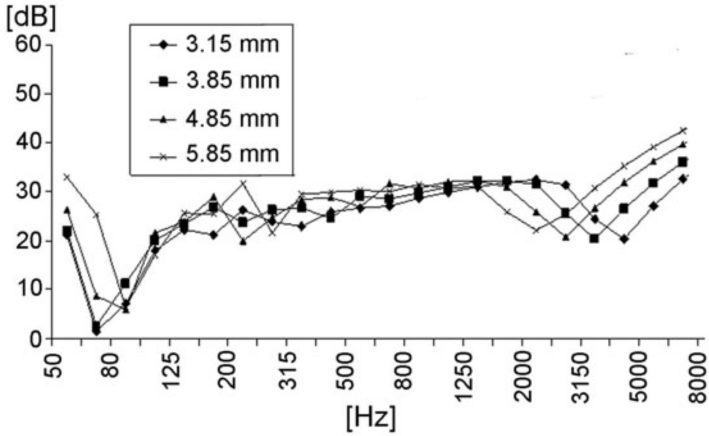


Fig. 5.101. External noise reduction, through tempered glass of different thicknesses: it is interesting to observe how the behaviour difference depends on frequency.

2.5÷3 mm (for weight reduction purposes: 2.5 kg/m^2 per 1 mm thickness), before over recent years rising again to 3.15÷4.05 mm, mainly to improve acoustical insulation (Fig. 5.101.

Today, in order to obtain significant acoustical improvement, cars (mostly high comfort class) are on the market with side laminated windows (2 glass panes of 1.8÷2.1 mm with a PVB layer in between or better a special PVB with improved sound-proofing properties (Fig. 5.102).

Noise comparisons, recorded in road traffic, between side tempered and laminated glasses are shown in Fig. 5.103, illustrating the different external noise transmission to cabin interior in a car with high acoustical comfort level (from 3 to 6 dB for average traffic noise, from 1 to 3 dB for wind noise).

To improve effraction resistance, laminated glass against breakthrough have been tested, made of two glass panes of 1.8÷2.1 mm, with an interposed Polycarbonate layer of 1.5÷2 mm.

Even for doors, bi-layer glasses have been proposed, the aim being to contrast effraction and reduce weight.

In the case of side impact, these multi-layer solutions are beneficial with respect to a single tempered glass window being more effective in terms of passenger's retention (head) without breakage.

Even single layer plastic side windows have been tested, the purpose being weight reduction and side crash protection; however, their relative flexibility for the same thickness (elastic modulus being 1/30 than the glass') results in unacceptable levels of deformation, due to aerodynamic de-pressurization, while traveling.

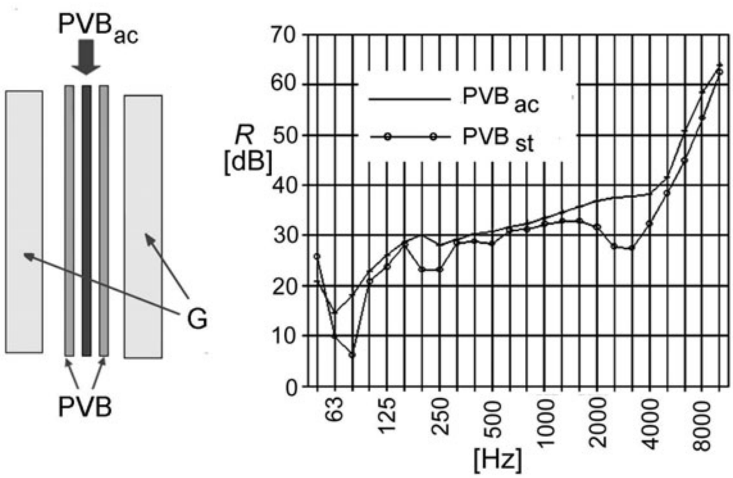


Fig. 5.102. Noise level attenuation R, through a side window laminated glass with different PVB types. PVB_{ac}: acoustical PVB; PVB_{st} : standard PVB; G: glass.

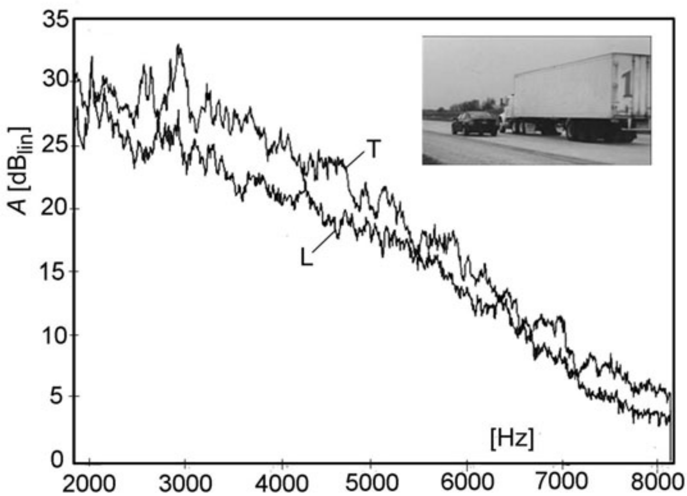


Fig. 5.103. External lorry noise transmission through side windows, while drawing up alongside, at 100 km/h. T: 5 mm tempered glass; L: laminated glass, total thickness 5 mm.

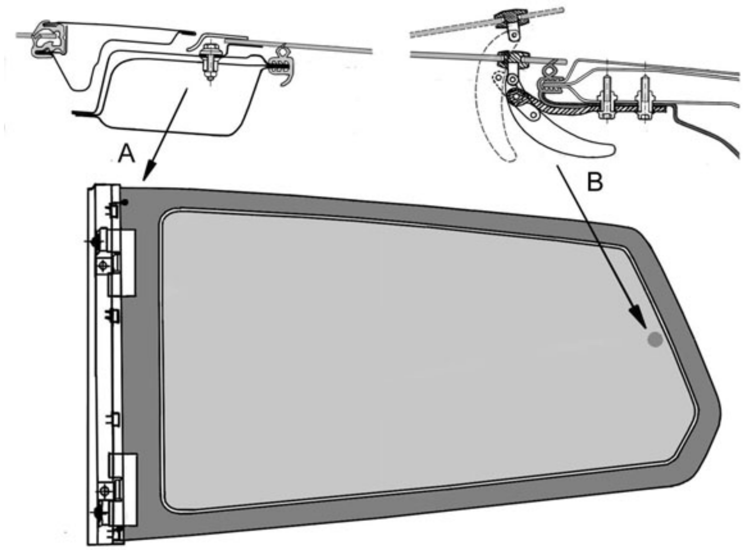


Fig. 5.104. Example of pivoting quarter glass: detail of hinges (A) and handle (B) with limited opening angle. The border silk-screen band shields the weather strips and metal frame underneath.

Specifications and delivery test

Door windows functions cannot be separated from the components involved in window operation, and are a consequence of the design and production process of the door itself, the window regulator and the *carrier* (a frame that usually carries the glass operating system).

Within this system, dimensional glass conformity and its resistance to durability door testing are verified.

Usually, no specific test on glass resistance and pretension field is performed.

Production quality regards mainly dimensional tolerances, contour grinding quality and regulator pivoting holes quality.

5.3.3 Quarter Glass

The quarter galss is sometimes bonded or snapped onto rear doors; always present on 3 doors cars, fixed or pivoting around a vertical axis (Fig. 5.104), they are usually made of single tempered glass of thickness similar to the side window (3.15÷3.85 mm) and silk-screen decorated on the border, mainly to shield the body frame underneath.

Delivery testing of the quarter glass focus on the waterproofing and fatigue verification of hinges and handles.

Fig. 5.105. Back window styling to improve rearward visibility.

5.3.4 Back Window

Usually back windows are made from single tempered glass with thickness 3.15 ÷ 3.85 mm, although they are also made of laminated glass 2.1+2.1 mm thick with PVB 0.76 mm in between.

The back window indirect visibility is achieved via the internal mirror, and optical defects are less critical: as a consequence, back windows can feature relevant curvature both in horizontal and vertical plane. To facilitate visibility towards all rearward areas, back windows are sometimes extended to the sides and lower part of the rear body (Fig. 5.105).

Back windows are usually bonded using adhesives to the body with process, materials and design similar to the windshield; in common, as they also share a structural task, mainly in terms of body stiffness, particularly important in the case of missing rear bulkhead. On some cars, the contribution of bonded back window and windscreen to overall torsional stiffness reaches 70%.

Regarding encapsulation and tinting, the same data as for windshield are available.

Specific functions of the back window include heating, demisting and de-icing, while sometimes accommodating antenna on the internal surface, using silk-screens and copper electric conductors. These devices must be designed to provide sufficient heat to de-ice or de-mist the back window within few minutes, while not subjecting the glass to overheating and not obstructing rear visibility.

Referring to rheophores, the mainly horizontal conductors that are applied to back windows with silk-screen, the typical control parameters to obtain de-icing which avoiding these risks are:

- pitch (usually 20÷30 mm), that establishes the total number of filaments;
- electric current absorption, that defines the average thermal power per window surface unit;
- heating timing.

According to regulations, de-icing quality and effectiveness is measured in two back window regions, denoted A and B (Fig. 5.106). Region A includes the

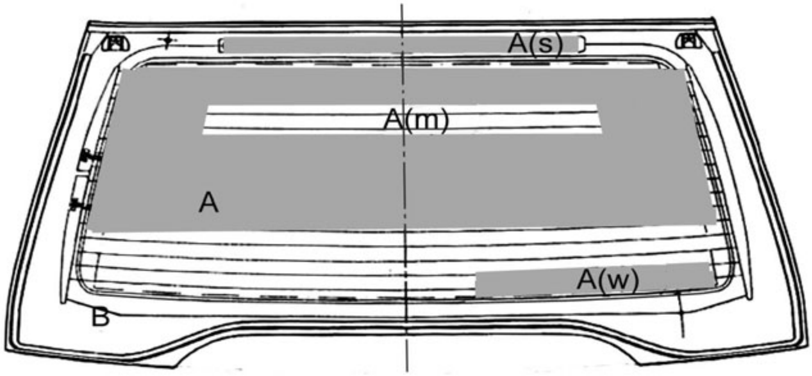


Fig. 5.106. De-icing back window zones; grey coloured zone A, white all remaining B zone.

heated A(s) surface that covers the third back light, the wiper standing area A(w), the internal mirror back visibility area A(m); B is the remaining area.

Maximum de-icing time allowed by most car manufacturers specification is:

a) $<$ 5 min for wiper standing area A(w);

b) $<$ 15 min for areas A, A(m), A(s);

c) $<$ 30 min for B area.

Fig. 5.107 shows the recorded de-icing time of a sample of European cars, as a function of applied power; all, except one, remain within the allowed limits.

The electric power required for de-icing is related nominally to the volume of glass, or in practice to the back window surface due to the relatively small variation of thicknesses used (Fig. 5.108).

It can be observed on the same car sample that specific power decreases as the surface increases. At the same time, local measured temperatures are similar and therefore no apparent risk due to overheating arises for stress or PVB damage in laminated glass (Fig 5.109).

Rheophores pitch is also conditioned by optical constraints as they can cause image distortion, the disturbance increasing with slope with respect to the vertical plane; it is therefore recommended to increase the pitch of rheophores as the slope of the back window increases. In practice, 20 mm pitch can be tolerated by glass inclined less than 50° to the vertical plane, 25 mm for glasses inclined 50° to 60°, and 30 mm for slopes exceeding 60°.

The timing of back window heating can be on/off, or timer controlled, to obtain the highest de-icing effectiveness with the lowest possible energy

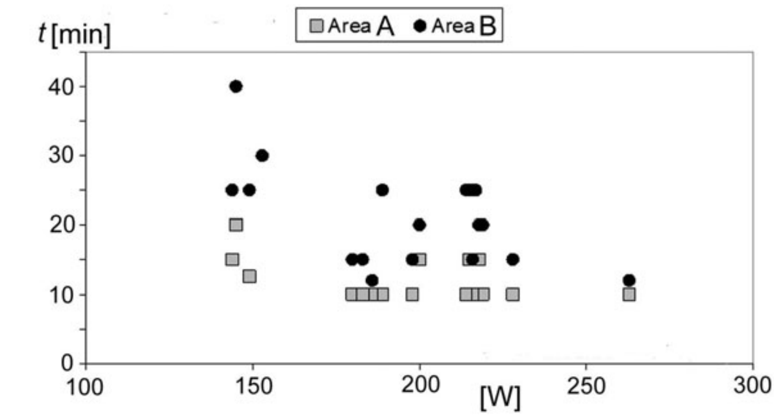


Fig. 5.107. Back window de-icing time in selected zones A and B, recorded on European cars, related to applied electrical power.

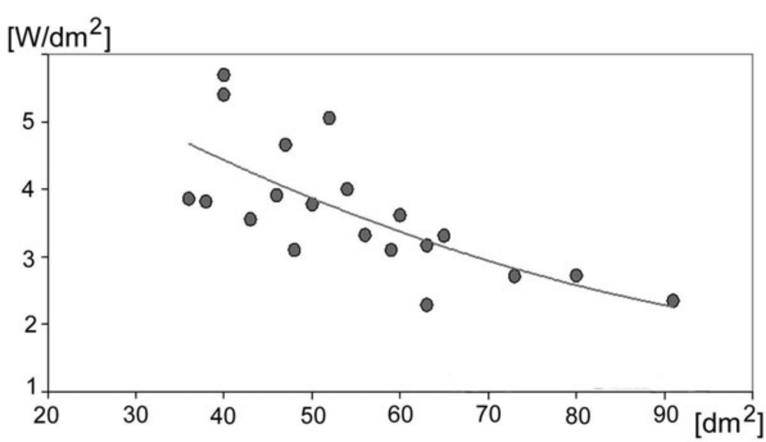


Fig. 5.108. Back window heating specific power, measured on a sample of European cars.

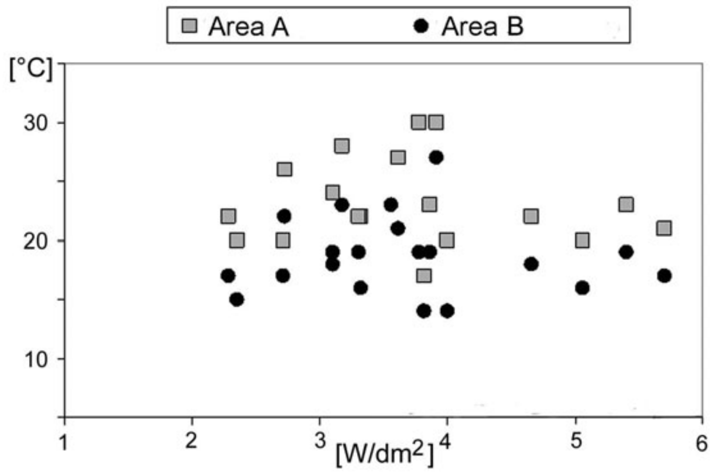


Fig. 5.109. Local overheating recorded on back window zone A and B during de-icing test, referred to specific applied power.

consumption: a full timing cycle requires at least 30 minutes, while the best compromise requires about 60 minutes. According to commonly used timing cycles, heating rate is between 30 and 40 % for the centre-south European region, while is 45 to 55% for the north Europe cycle.

Phantom reflection

As concerns the verification of back window optical quality, particularly worthy of attention is the risk of anomalous reflections or *optical phantom reflections* which are visible images (for instance, crossing vehicle lights) that cross the windshield and are reflected by the back window towards the inside mirror (Fig. 5.110), and appear as images coming from behind the vehicle. The problem depends on the back window slope, and is common on vehicles with a vertical or pseudo-vertical glass, mostly curved (as pick-up or work vehicles). The solution is geometrical and can be verified on the drawing table.

Open back window

Some markets require the availability of back window that open, mainly vehicles that feature a liftgate with stiff hat shelf that can be loaded separately from the trunk underneath. In this case, the hinge, support and lock devices can be fitted to the glass or to frames (fig. 5.111 and 5.112).

In any case, design specifications mainly concern the glass sealing, obtained by a contour weather strip (snapped on liftgate frame) and individual gaskets around each hole (for wiper and gas springs).

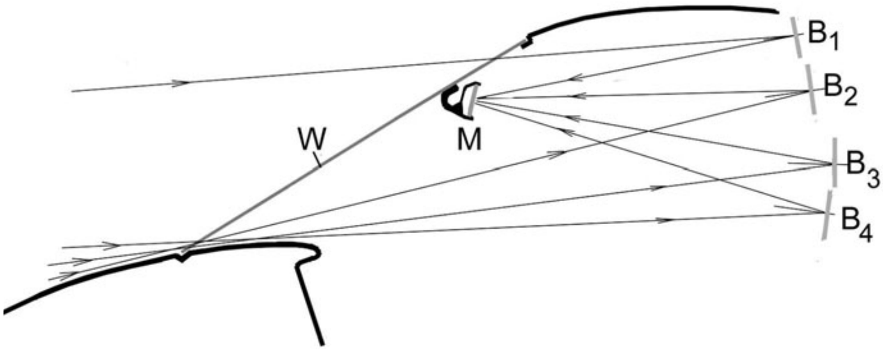


Fig. 5.110. The images that cross the windshield W and hit the back window at positions B_1, B_2 , B_3 , B_4 , are reflected towards inside mirror M as images from behind.

5.3.5 External Mirrors

External mirrors are usually supported by a bracket, body fitted with the interposition of a molding and a seal. The bracket carries a movable reflecting device, covered by an aesthetic casing (Fig. 5.113), that houses the electric harness.

The usual installation body zone for external mirrors is the door window front end, offering advantages with respect to the driver's eye position, visibility, smaller obstruction, and the ease of installation, bearing in mind that the door is commonly trimmed off-line and needs electric connection.

The main inconveniences, as already mentioned, relate to the protrusion from body side (exposing the mirror to small impacts both in parking and on road), aerodynamic vortex and rustle, and the difficulty in terms of sealing of door holes bearing in mind its position in a noisy region.

The door outer panel is drawn with a triangle between belt line and front pillar frame, where the mirror bracket (usually in cast aluminum) is fitted, featuring a large hole for the electric harness and three small holes for screws (Fig. 5.114).

In another solution, clamping is obtained using a single large threaded ring nut (Fig. 5.115), to which a mechanical hand control (e.g. by bowden cables) is connected.

In each case, a stamped seal is interposed between the mirror bracket and the body door panel.

Rearward visibility is determined with reference to international regulations, regarding both the field and image transmission ratio. Moreover an external mirror should comply with a wide set of performance criteria including:

- small size, while achieving visibility goals, to enable reduced side obstruction and lower aerodynamic drag;

Fig. 5.111. Example of open back window fitted to liftgate, with gas spring fittings on glass.

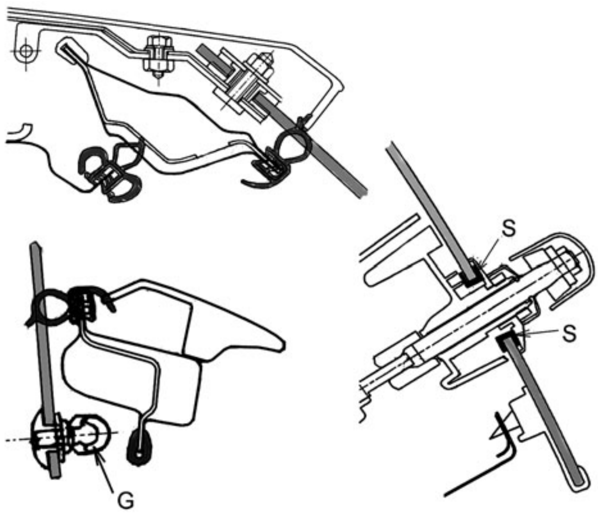


Fig. 5.112. Examples of open back window sections: above, hinge area; G: gas spring fitting; S: gaskets between wiper and glass.

- adequate visibility even out of field, eg. towards overtaking vehicles, ie. absence of *dead angle*;
- correct evaluation of the speed and distance (image transmission ratio) of vehicles overtaking from behind;
- no rustle;
- reflecting surface protected from ice, water and dust;
- ease of folding towards the body side, without breakage of the casing or bracket, in the case of contact with other vehicles or obstacles such as walls, etc.;
- no night glare;
- mechanical or electric operation from inside the vehicle ;
- provide housing for light signal device (for instance, side repeaters);
- aesthetics (in terms of shape, materials and painting).

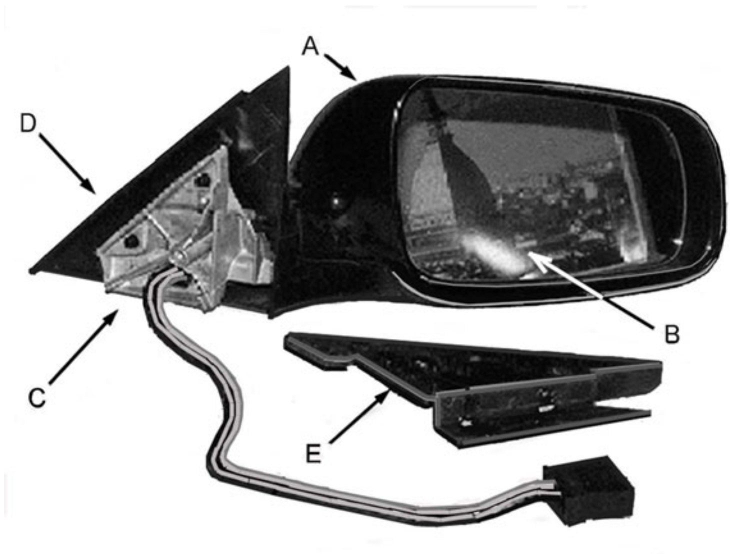


Fig. 5.113. Basic components of an external mirror: A) casing; B) reflecting device; C) bracket; D) molding; E) seal.

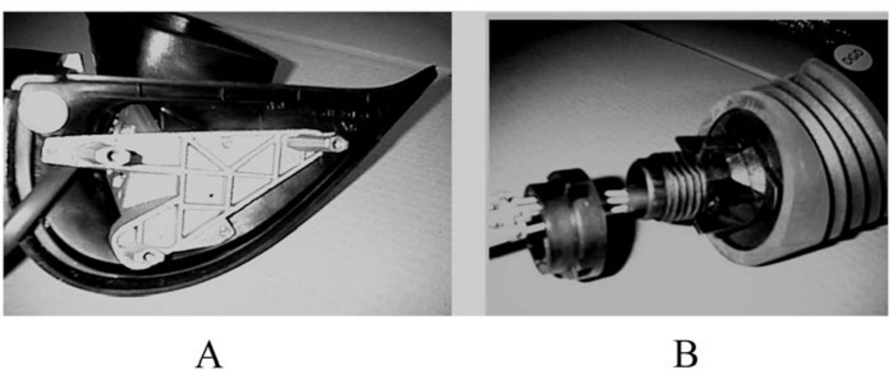


Fig. 5.114. A) cast aluminum bracket with 3 screws seats; B) threaded ring nut fitting.

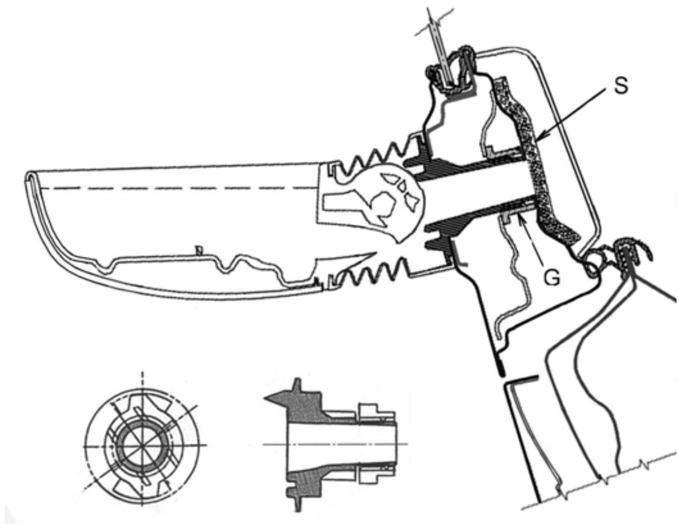


Fig. 5.115. Example of mirror section, with G clamp ring nut detail; S is a noise insulating cloth.

Design solutions and innovation

In order to comply with visibility regulations, either flat or spherical mirrors can be used, but the latter reduce the perceived image with respect to the real image size; apart form being smaller, the image appears farther than its real position.

In order to understand why and by how much, it is appropriate to consider the optical scheme of Fig. 5.116 with a mirror of radius R, an object B at distance D from mirror, the observer's eye at a distance from mirror and D_R from the object, and the object reflected image B'.

According to classical optics theory (Gauss), image B' of an object B is defined, by the expression:

$$B' = B\frac{0.5R + c}{R + D} \cong \frac{2Bc}{R} \tag{5.22}$$

therefore the ratio between the apparent distance D_A and the absolute distance D, between the object and mirror, is:

$$\frac{D_A}{D} = \frac{B}{B'} \cong 1 + \frac{2D}{R} \tag{5.23}$$

It can be noticed that in this expression the observer's distance a from mirror does not appear.

But, taking into account the human vision process, apparent distance D_{appar} from observer's eye to object is related to absolute distance D_R by the expression:

$$D_{appar} = D_R + \frac{2aD}{R} = D_R + \frac{2a(D_R + a)}{R} = D_R(1 + \frac{2a}{R} + \frac{2a^2}{RD_R}) \tag{5.24}$$

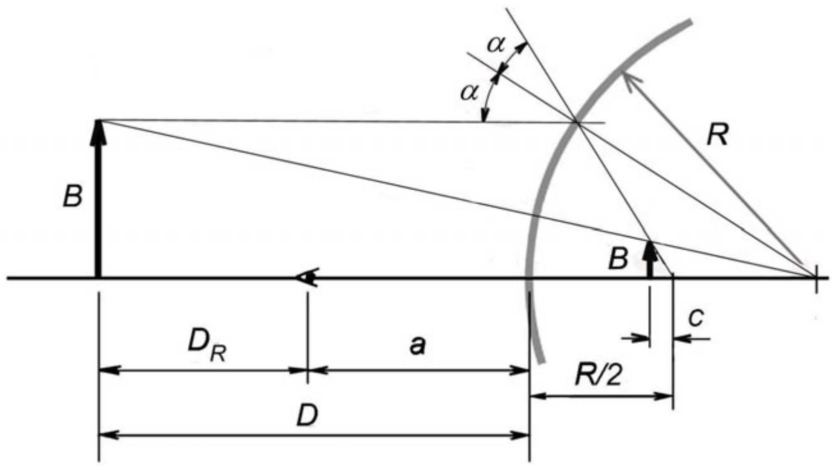


Fig. 5.116. Optical transmission of an image B at distance D, by a spherical mirror of radius R, positioned at distance a from observer's eye.

Usually $a^2 << RD_R$, therefore as a first approximation we obtain:

$$D_{appar} = D_R(1 + \frac{2a}{R}) \tag{5.25}$$

The first consequence is that if $R = \infty$ (flat mirror) the apparent and absolute distances are identical . Moreover, the equation shows that apparent to absolute distance ratio becomes greater as the observer's distance a from the mirror increases. As a consequence, if external mirrors have different curvatures (and the inside mirror probably has another one), the images of the same object can be perceived by the driver with different sizes, therefore causing some confusion. Since this event is rather common, flat mirrors are compulsory in the U.S. according to regulations, while a curvature limit is imposed elsewhere .

To minimize the problem, in the case of three different curvature for the three mirrors, each of their radii should be proportional to the driver's eye distance from each mirror respectively.

Fig. 5.117 quantifies the distance perception error, computed using the equations above.

To address the problem of *dead angle*, a number of solutions have been investigated and tested, focusing on both the reflecting device and additional electronic devices.

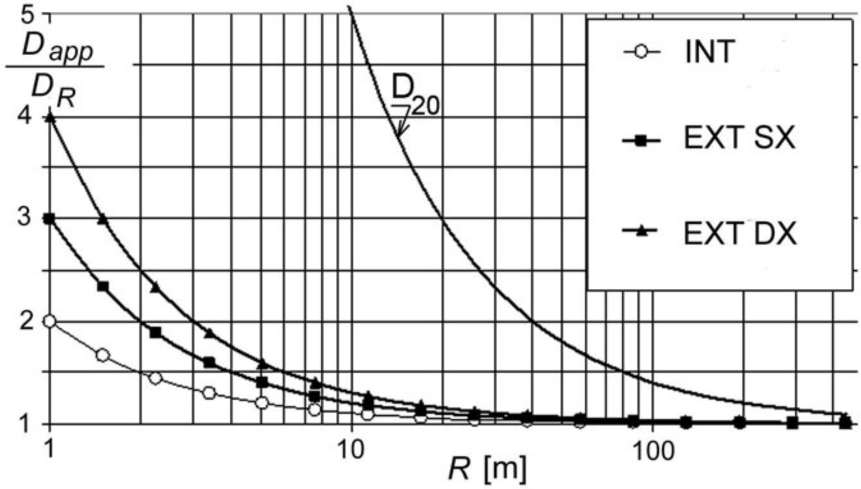


Fig. 5.117. Influence of inside (INT), external right end (EXT DX) and external left hand (EXT SX) mirror radius R on distance estimation error of an object from driver's position. D_{app} is the perveived distance, D_R is the real distance, D_{20} is the computed error, if mirror were at 20 m from driver.

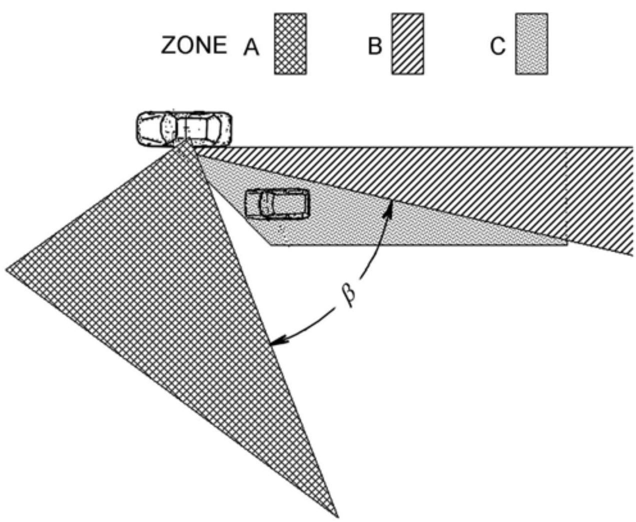


Fig. 5.118. β) dead angle; A) direct visibility area (overall about 150°); B) compulsory area for external left hand mirror, right-lane driving; C) detected area by dead angle sensor.

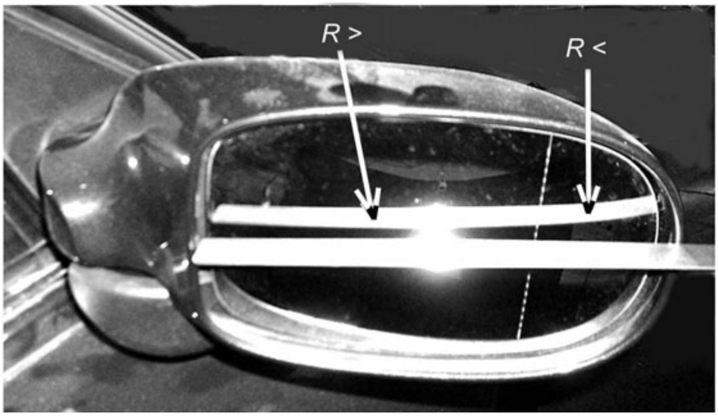


Fig. 5.119. Example of a mirror made by two side by side reflecting surfaces of different radius (bigger $R>$; smaller $R<$)

Fig. 5.118 shows the angles of direct and indirect (by a regular mirror) visibility and the angle explored by a camera used as input sensor for an electronic system to detect overtaking vehicles.

Solutions involving the mirror reflector use mainly double curvature mirrors, one for rear vision according to regulations and the other, located close to the outer end of the mirror, to detect objects in the blind side region (*aspherical mirrors*- Fig. 5.119).

The main inconvenience of such solutions concerns the image distortion and the sudden speed variation perceived when the reflected object is crossing the border between main curvatures. In fact, as already seen in the reflected image equation, as the radius decreases, the apparent size of the vehicle behind also decreases and it appears further.

But overtaking time is determined by real vehicle speeds: as distances appears longer, apparent speed also appears greater and is inversely proportional to mirror radius.

To avoid such inconvenience of spherical mirrors another solution has been tested, consisting in a plastic moulded single piece mirror, one side being a flat transparent surface and the other a hyperbolic reflecting surface [4]. Mirror thickness can be, for instance, variable from 2 to 9 mm (Fig. 5.120). Such a mirror is based on double refraction and reflection of light rays over an hyperbolic surface, so that the emerging rays are perceived parallel and without distorsion by the driver even when arriving from different directions.

That solution not only removes the typical inconvenience related to spherical and aspherical mirrors, but helps maintain mirror size and cost at a reasonable

[4] G. Manfrè, *New technologies on the back visibility in automotive mirrors*, Proceedings of Glass Processing Days, Tampere 2001.

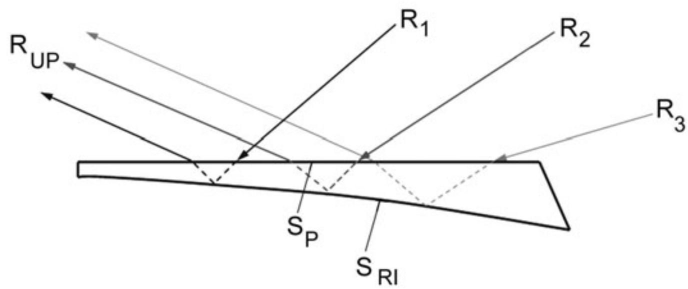


Fig. 5.120. Schematic section of a variable reflecting thickness mirror. S_P: flat surface; S_{RI}: reflecting hyperbolic surface; R_1, R_2, R_3: entering rays; R_{UP}: parallel coming out rays.

level thanks to plastic molding technology that complies with any coating required for heating, cleaning and glare cutting. The only intrinsic inconvenience is the apparent longer distance run by the overtaking vehicle in the mirror, and the fact that, as a consequence, overtaking speed appears greater (although this anyway tends to promote better safety behaviour of the driver).

To reduce protrusion and aerodynamic perturbance, camera featuring solutions have been developed as has a special optical system patented by Milner. This system uses a reflecting surface and two prisms, located in the front door window angle, in order to split mirror obstruction between inside and out, the main mirror extension being in the X instead of Y direction (Fig. 5.121).

Regarding reflecting surface cleaning, there are in practice two improving ways in case of rain or ice: heating and water-repellent coating, usually combined.

Heating can be performed by resistive filaments bonded over mirror back surface, therefore in an uneven way and subject to aging, or by a titanium oxide resistive layer, feeded by two busbar and controlled, if needed, by a temperature sensor that stops heating when temperature reaches 80 °C. A number of different alloy exist, with overall resistance between 5 and 9 *ohm* (Fig. 5.122), that perform heating speed higher than traditional filaments with lower energy consumption.

The combined effect of heating and *water-repellent coating* is visible in Fig. 5.123. Coating influences water drop contact angle, as explained in *glass chapter*: materials and processes are quickly evolving and therefore patent granted.

Light reflexion and night glare also can be reduced by coatings or electrochromic filtering, the reflectance of which can be tuned.

Delivery tests

In addition to the tests for visibility and geometrical compliance already explained, external mirrors must usually comply with the following:

- bench, wind tunnel and road rustle measurements;

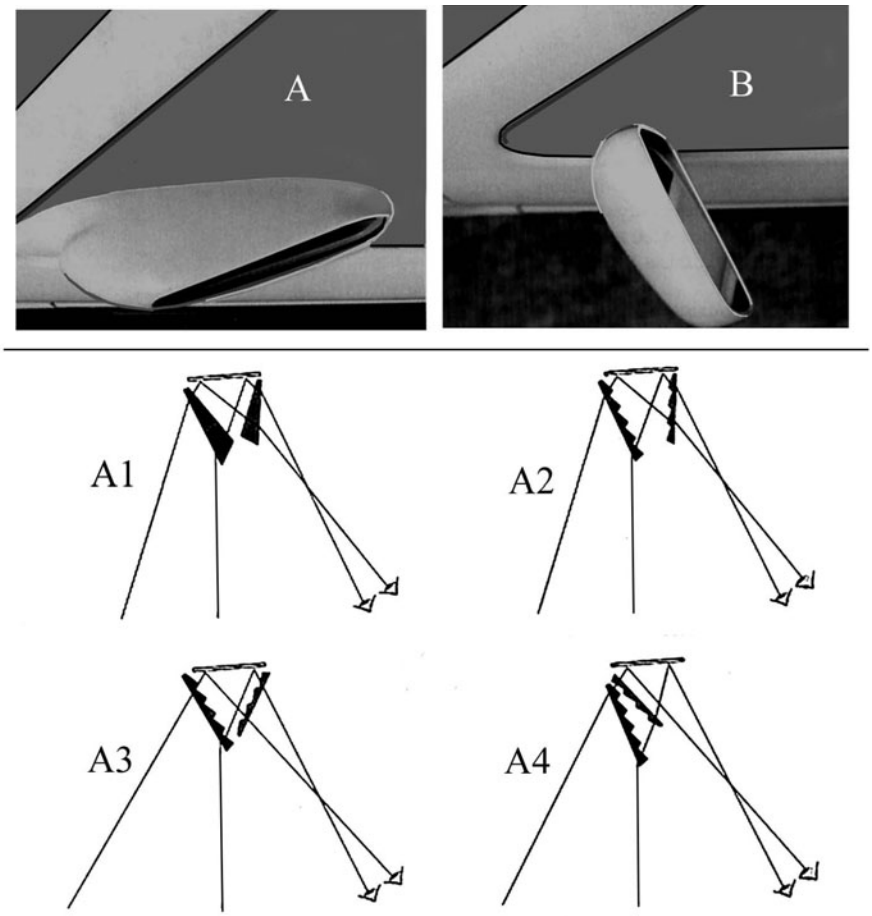


Fig. 5.121. Example of Milner (A), compared with traditional mirror (B), applied to a car. Milner mirror has been proposed and made by different optical systems. A1: solution wiyh two solid prisms; A2: with Fresnel prisms; A3: with prism lens; A4: double lens; prisms of different material.

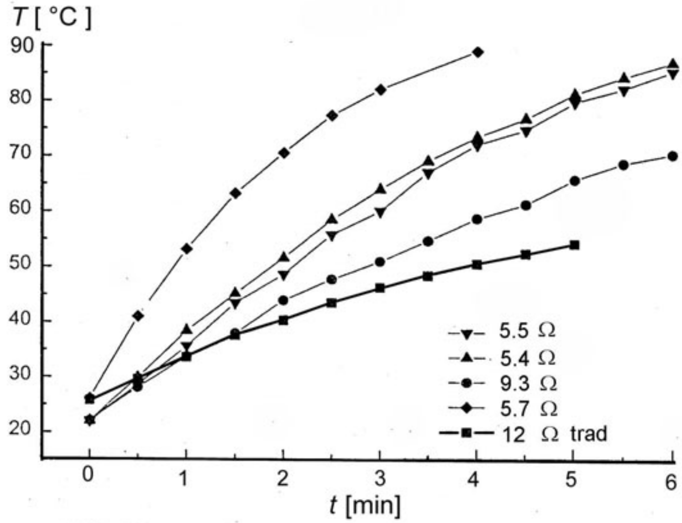


Fig. 5.122. Heating speed of different suppliers' mirrors, coated with titanium based alloys and silver busbar, feeded at 12 V, compared with a traditional mirror (trad), featuring higher resistance.

- resistance and climatic durability;
- road and bench vibrations;
- powder infiltration;
- water proofing;
- door slamming;
- crash test;
- heating and de-icing;
- accelerated reliability test in climatic chamber.

5.3.6 Inside Mirrors

The main components of an inside mirror of recent production are shown in Fig. 5.124.

The mirror shown includes a movable plate that rotates in anti-glare position, operated by an electronic control unit; also hand operated mirrors are in production, where rotation is possible via a trigger, hinged on the mirror housing.

Glare prevention is one of the main targets of the inside mirror: traditionally, the reflecting surface was rotated of about 5°; instead, more recent solutions are,

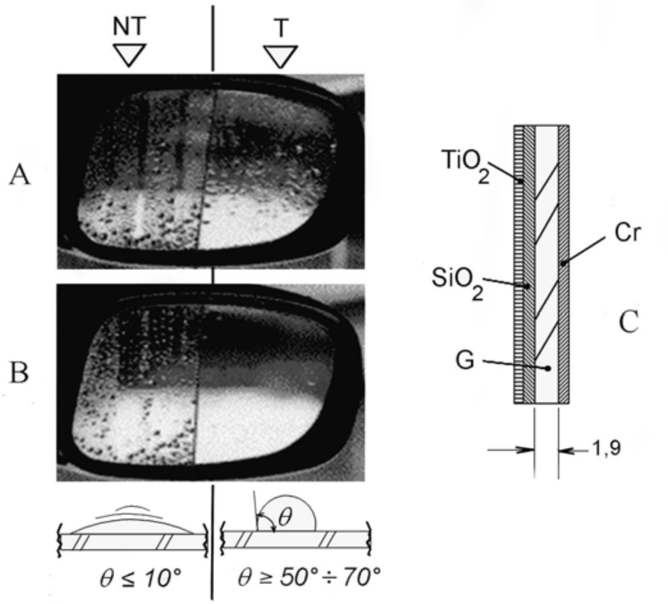


Fig. 5.123. Mirror surface treated (T) with water-repellent coating shown in Fig. C and additional heating (B) is compared with solution without heating (A) and without coating (NT). θ: drop contact angle; TiO_2: titaniumoxide layer; SiO_2: silicium oxide layer; CR: reflecting layer (chrome); G: glass.

for instance, electrochromic reflectors, that darken when the measured intensity of the light that hits the mirror exceeds a specified level (Fig. 5.125).

Other primary goals for inside mirrors are rear visibility field size, together with limited obstruction of frontward visibility and release without passengers injury in the case of impact with the mirror casing.

Regarding the rear visibility field, from the driver's position full rearward visibility allowed by the back window should be available as the remaining fields are usually covered by the external mirrors. Often, inside mirrors are smaller to reduce forward obstruction: the mirror width is usually in the range 190÷260 mm corresponding to an ambinocular vision angle between 22° and 30° for a distance of 500 mm from the driver's eye center and the mirror center.

In order to enable mirror removal in case of crash, the casing of the inside mirror is usually supported by a bracket via a spherical device that allows detachment (Fig. 5.126): the bracket can be screwed to the roof cross member or (as is the common solution today), adhesively bonded over a silk screen decorated windshield surface. The surface of the adhesive is specified by the car manufacturer depending on the adhesive used with an average value of approx. 600 mm^2.

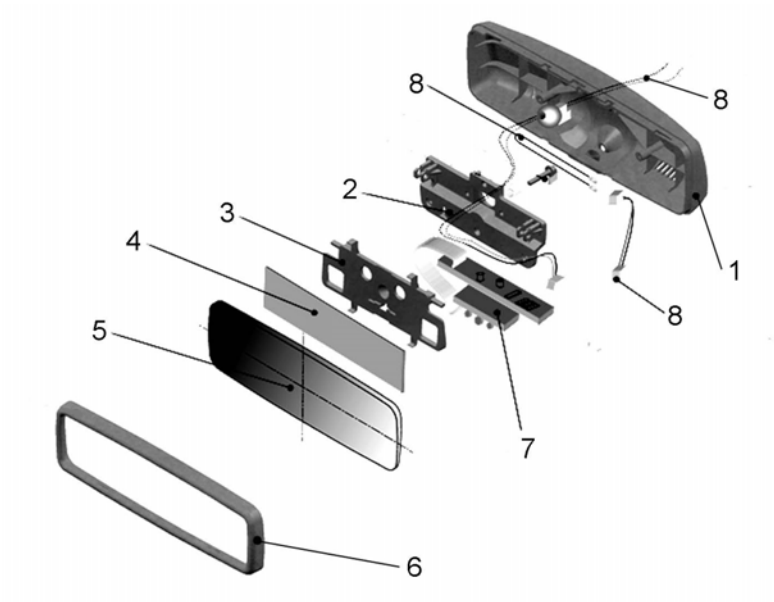


Fig. 5.124. Inside mirror main components: 1) casing; 2) support housing; 3) movable plate; 4) biadhesive strip; 5) prismatic reflector; 6) frame; 7) electronics; 8) harness.

The local adhesive-borne stresses are additional to the silk-screen, mirror handling and impact stresses: usually, as part of the delivery testing of inside mirrors, an adhesive peeling test and a windshield break test are included.

5.4 Movable Parts

The term *movable parts* refers to body macro-components which have the task of opening and closing the body compartments, ie. doors (passenger compartment), hood (engine compartment), deck-lid (luggage compartment), liftgate (passenger and luggage compartments) and sun roof.

These components are affected by the same relevant problems of the body and by additional frequent operations that should be performed without any trouble and with absolute warranty against any infiltration.

The standard specifications of movable parts are:

- Static and fatigue strength.
- Stiffness.
- Insulation and fluid infiltration prevention.
- No travelling resonance on whatever track.

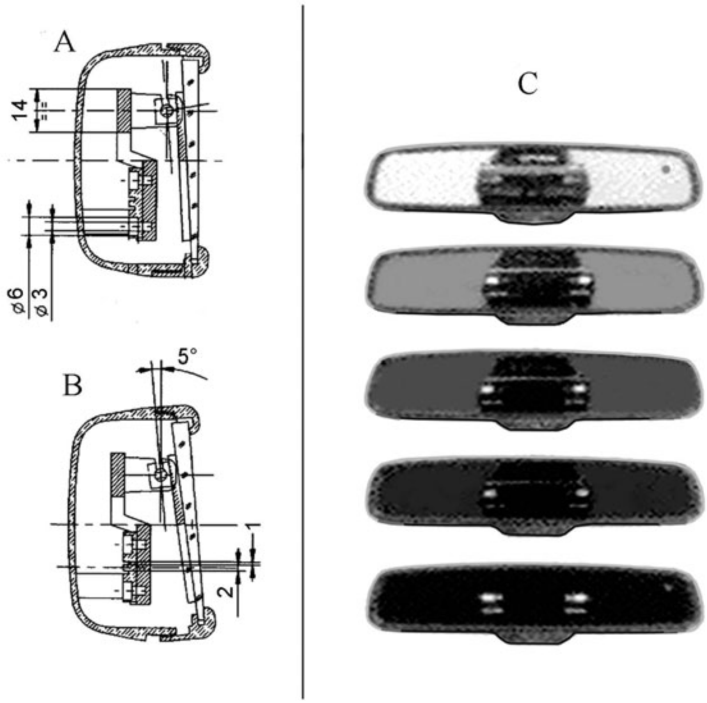


Fig. 5.125. On left side, sections of traditional mirror in day (A) and night (B) position: the last is obtained by rotation of the movable plate that carries reflecting surface. On right side (C), darkening sequence of an electrochromic mirror, hit by glaring lights of a vehicle.

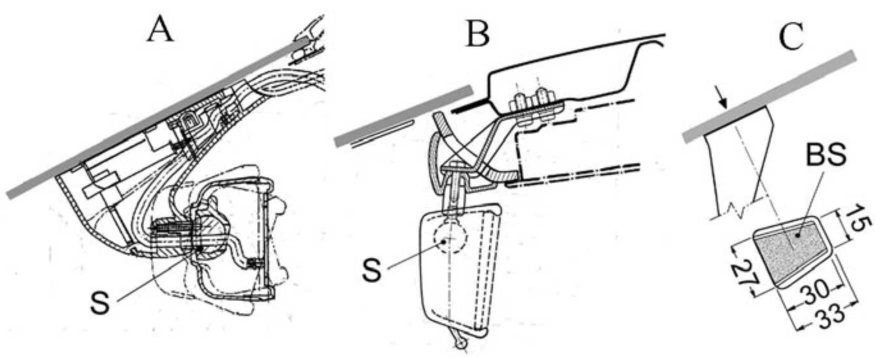


Fig. 5.126. Example of inside mirror fitting to windshield (A) and to roof front cross member (B). C: details of mirror bracket bonding to windshield. S: safety detachable mirror articulation. BS: adhesive surface.

- Lock keeping during a crash.
- No sticking after impact.
- Smooth operation.
- Resistance to misuse.
- Crushing strength in the case of crash.
- Easy replacement in case of damage.
- Breach resistance.

Specific characteristics of the different movable parts shall be specified in the corresponding chapter.

5.4.1 Side Doors

On average, car doors are operated between 10,000 and 50,000 times during its lifetime. In this operation, the customer applies a load, registering either a pleasant or unpleasant sensation associated with a perceived noise timbre (soft, smooth or hard, metallic closing, silent or squeaking opening and so on) depending on the interaction between the different constituent components, namely: the door frame, the weather strips, the locking devices, the handles, all door fitted components featuring specific function (glasses, window regulators, electric actuators, rear mirrors, loudspeakers, inner trim) and interface components, as the body pillars where door hinges and latch are fitted.

Door delivery testing, which is performed on simple assembled frames as well as on completely trimmed doors, can be summarized as follows:

- door torsional and window frame stiffness;
- vertical and horizontal yield of the door, both fitted to a stiff pillar and to body;
- matching precision with door opening and weather strips housing;
- noise, water and powder seal effectiveness (with weather strips);
- lock fittings strength, resistance to breach;
- water drain between glass and weather strips;
- precise drop windows and quarter glass operation;
- fatigue, cyclic operating and slam resistance;
- vibration, squeak and rattle, while travelling;

Fig. 5.127. Examples of side doors with different hinge axis slopes.

- strength in side impact against posts or other vehicles;
- ergonomic operation.

Door mass is directly or indirectly involved in every test; it is effectively a design tool and can be adapted to different goals. For energy saving, ecology and ergonomics, reduced weight is beneficial. Regarding impact protection, noise, strength and perceived quality, the best results can be achieved if low weight is not strictly targeted. Seeking a compromise, the trend has been towards lighter doors for economical cars (although a extreme weight reduction, when achieved with light materials such as aluminum, magnesium, plastics, is expensive) but heavier doors for medium and high class cars.

Door families

Doors can be classified with reference to their opening kinematics or their structure.

Referring to opening kinematics, different types include:

- Rotating doors, with vertical, transverse horizontal, longitudinal, sloped axis or additionally with fixed or variable rotation axis (Fig. 5.127). Cars with two side doors usually have a vertical axis, with either both at the front door, or one at the front and one at the rear.
- Sliding doors, featuring longitudinal rails (Fig 5.128).

Fig. 5.128. Examples of sliding side doors.

The most common rotating doors use a nominally vertical hinge axis, usually applied in case of two side doors; when the door is opened, no supporting device is needed, which is different from horizontal or sloped axis.

Also open door obstruction in parking areas is reduced. In the case of two pillarless side doors, which is generally met with appreciation at car shows, exiting from rear seats becomes critical in narrower parking areas; moreover, for safety reasons, the rear door can be opened only following front door opening .

Rotating doors with front vertical axis can be slightly uncomfortable when getting out of the vehicle, due to the need to articulate the feet in order to get around the pillar obstruction; moreover, their trajectory with respect to the body side can contrast the desired behavior of the weather strips. On the other hand, horizontal or sloped hinge axis doors require a special border design to enable acceptable matching of roof and side weather strips.

Sliding kinematics increase weight, complexity, cost and require straight rails: although very comfortable when getting out in narrower parking areas, today this solution is much less diffused on cars but is common on vans, particularly for side goods loading. In the case of side impact, should the door rails become bent, opening may become impossible (unless the door is demolished).

Referring to their structures, four main door families can be considered (Fig. 5.129):

1) *unitized stamped doors* (Fig. 5.130).

Such doors are made of two large stamped sheets, the outer and the inner panel, both carrying a part of the window frame. The panels are usually assembled by hemming, the outer panel being downflanged and then hemmed over the inner, following a structural adhesive extrusion on the panel border and with a limited number of spot welds. The assembly also includes a number of

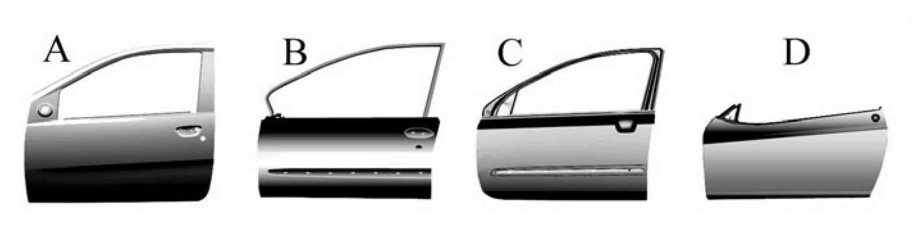


Fig. 5.129. ain door families: A) unitized stamped door; B) sash door; C) hybrid door; D) frameless window door.

reinforcements including the window frame channel which is spot welded to both panels or to one panel, hemmed over the other or hemmed over both panels. This channel performs two main functions: the first is structural, featuring a window frame section boxing to increase the frame stiffness, mainly torsional; the second is to provide a window channel weather strip housing.

2) *Sash doors* (Fig. 5.131)

The sash door assembly is made up of two stamped panels (inner and outer) below the belt line and a sash assembly made of roll-formed, bent and welded profiles making up the window frame. The sash is welded to the inner panel before the hemming of inner and outer panels; in case of heterogeneous panels, screwing or riveting and adhesive bonding can be adopted, instead of hemming.

3) *Hybrid doors* (Fig. 5.132).

The hybrid door is a mixture of the above solutions, as the stamped inner panel includes the window frame, while the outer panel is extended just up to belt line. Before hemming the main panels, a roll-formed or stamped channel is usually welded to the inner panel to obtain a boxed window frame in order to be adequately stiff in torsion. These doors have the aesthetic appearance of sash doors, while geometrical quality and belt seal performance are more similar to unitized stamped doors.

4) *Frameless window doors* (Fig. 5.133).

In this solution, the window frame is completely missing, with glass sealing being provided by body side and roof weather strips. It is typically used for spiders and convertibles.

Unitized stamped doors represent the cheapest solution, considering all the components of the doors, weather strips included, and the most precise and strong; usually, they are not the preferred choice of designers, due to the size of the window frame.

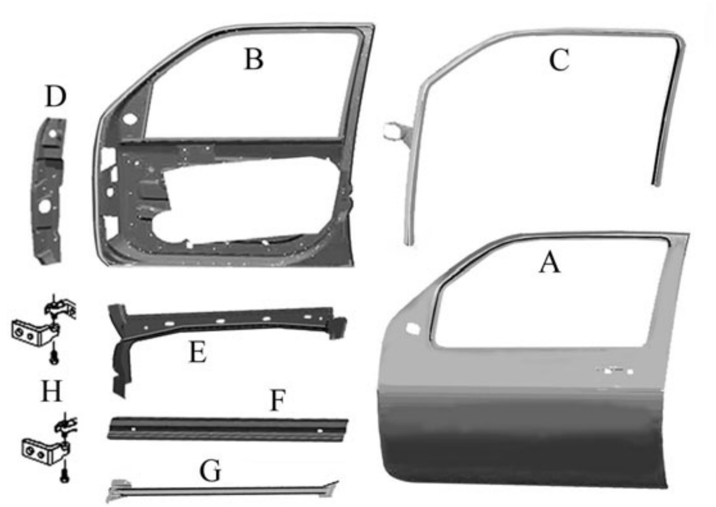


Fig. 5.130. Main components of a stamped unitized door: A) outer panel; B) inner panel; C) glass channel; D) hinges reinforcement; E) inner belt reinforcement; F) outer belt reinforcement; G) intrusion bar; H) hinges.

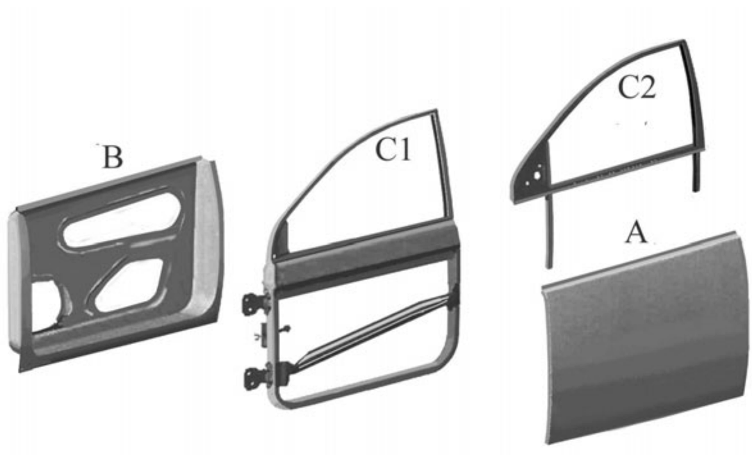


Fig. 5.131. Typical components of a sash door: A) outer panel; B) inner panel; C1) frame assembly - modular door; C2) window frame (sash).

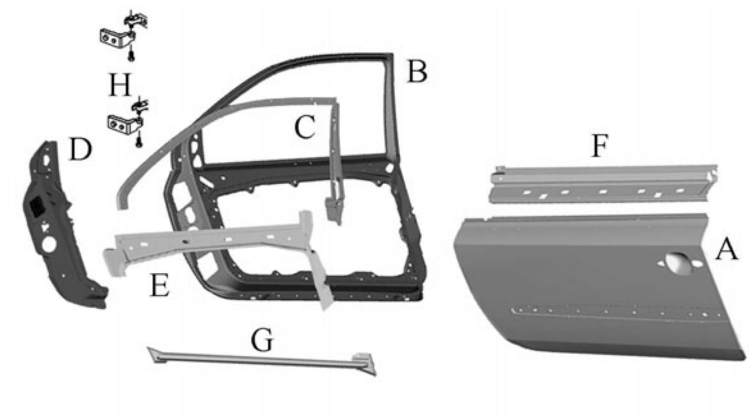


Fig. 5.132. Typical components of a hybrid door: A) outer panel; B) inner panel; C) window frame reinforcement; D) hinges reinforcement; E) inner belt reinforcement; F) outer belt reinforcement; G) intrusion bar; H) hinges.

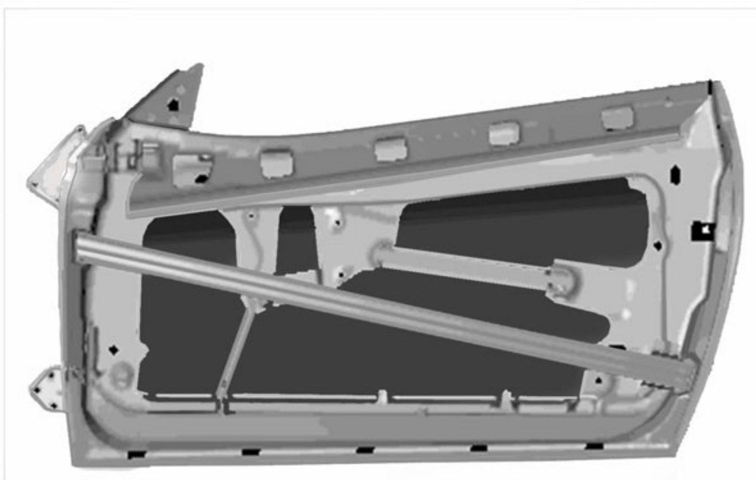


Fig. 5.133. Example of a spider door frameless window frame. Additional straight braces with reinforcement purpose can be noticed.

In terms of dimensional quality and performance, next is the hybrid door design, preferred by designers because the window frame is narrower and can be completely covered by an aesthetical weather strip; therefore, the result ha s better aesthetics than the unitized stamped door. On the other hand, it is more expensive due to the aesthetical weather strips, their complex design and the need to be coated.

The sash door uses a strong, narrow cross-section window frame; the cost is less than the hybrid solution, but inconveniences include embedding of the sash in the inner panel, below the belt line, due to the lack of stiffness and the need to braze the sash to the inner panel in the belt line. This can cause a lack of weather strip sealing due to the presence of a braze ribbon on belt line joint, close to a metal step caused by the superposition of panel and sash, that the rubber seal cannot adequately match.

The frameless window doors, commonly used on spiders and convertibles, are sometimes present on sedans or coupes. The amount of sheet metal for these doors is the lowest, but waterproofing relies entirely on the glass-weather strip matching on the body side, mainly on the belt line node transition. In fact, for convertibles, weatherstrip contact in this area moves from window glass to door inner panel in a very short space, with high curvature and section discontinuity, as explained previously.

Regarding the typical door sections, it is interesting to analyze the window frame design for these reasons and the front door pillar design where the hinges and the door brake device are fitted.

Fig. 5.134 shows some examples of window frame to roof sections for the most common door structures; it is clearly noticeable that the widest sections can be achieved with wrap-over doors, while the smallest sections correspond to hybrid doors. Usually the latter are reinforced by an increase of frame channel thickness. Window frame stiffness is related to the effectiveness of the weather strips, mainly when a higher vehicle speed causes a higher de-pressure on side window, additional to the effects of road vibration. Later it will be seen that this parameter can be specified, computed and experimentally tested.

Regarding the door front pillar, due to the stress superposition of the hinge load, door brake and bending-torsion, caused by door opening over-run (for instance, due to wind or to a sloped attitude of the car), the most common design includes boxed sections. These are obtained by welding the pillar reinforcement to the door inner panel, while the reinforcement and panel are assembled together with hinges and brake plates (Fig. 5.135). The reinforcement thickness is usually between 1.2 and 1.5 mm.

Door design criteria

The fixed points of door design are: setting of hinge axis and door perimeter, tolerances chain, stiffness and strength, frame pre-bending, window and window rails kinematics, acoustic holes sealing, side crash resistance.

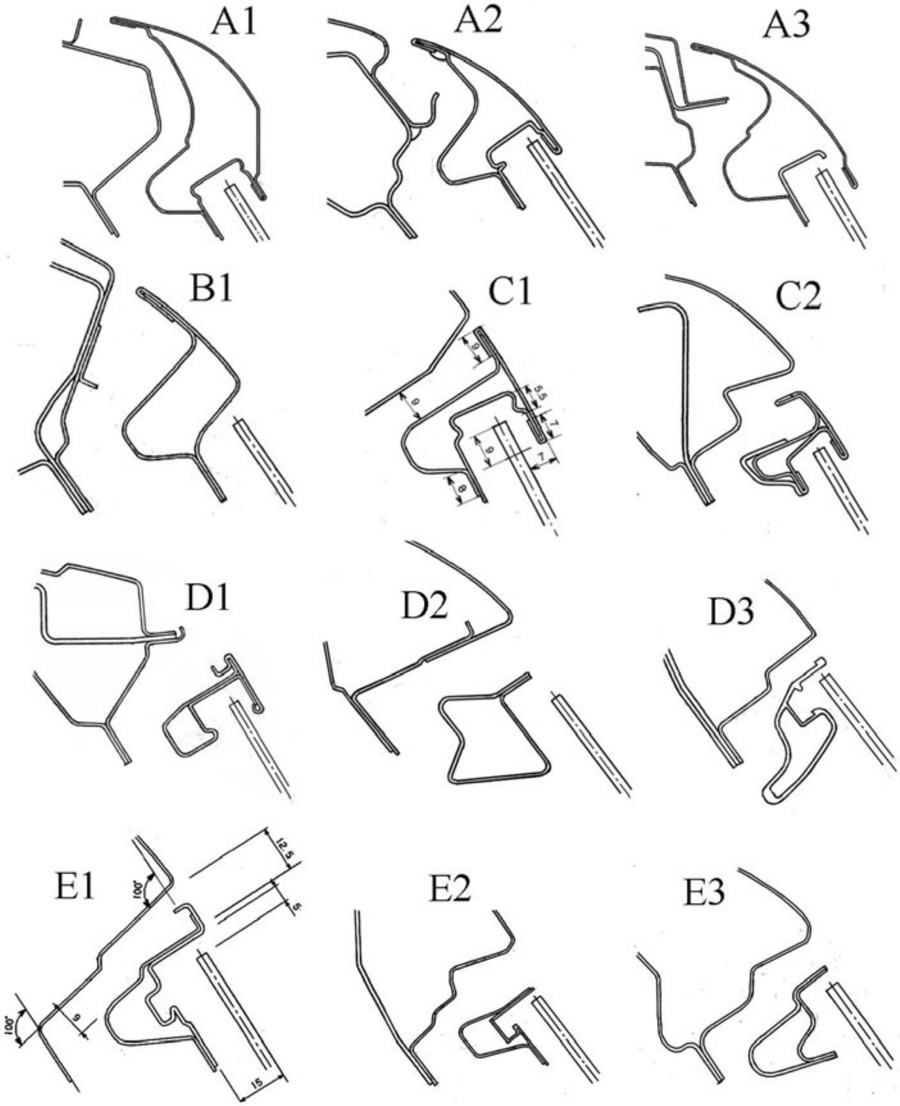


Fig. 5.134. Typical window frame sections. A1, A2, A3: wrap-over unitized doors; B1: semi wrap-over unitized door; C1, C2: built-in unitized doors; D1, D2, D3: sash doors; E1, E2, E3: hybrid doors.

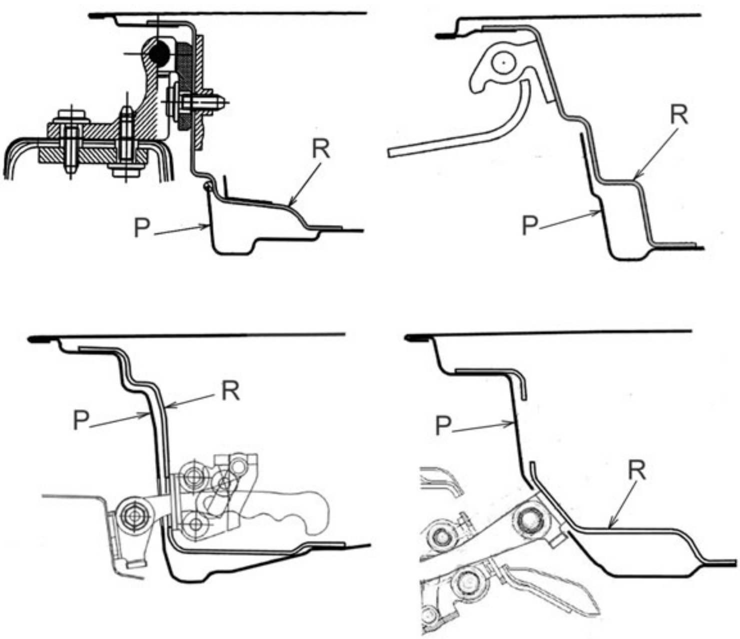


Fig. 5.135. Door pillar section on hinges and door brake fittings. P: door inner panel; R: pillar reinforcement. It can be noticed that hinges are usually welded or screwed to reinforcement only, while door brakes, in case of reinforcement deflection, can also load the inner panel.

The setting of the hinge axis is a consequence of hinge positioning (close to outer door surface) and of door perimeter cutting (so as to allow complete door rotation without any interference with adjacent components, e.g. front fenders). Given the body side shape, frequently styled with deep channels and complex volumes, the said settings must be co-designed during body style modeling in order to introduce the changes needed for feasibility immediately. The main constraints affecting that setting, in addition to style model, are the allowable span between hinges (as shown in the following vertical yield evaluation) and the self closing criterion selected.

Self closing criterion: if the hinge axis is perfectly vertical, when opening the door of a climbing car, the door tends to close whilst, in a descending car, it tends to complete opening. Instead, if the hinge axis is sloped, a self closing effect can be increased or reduced, of course with an opposite effect on self opening.

A calculation can be performed according to the expressions and scheme shown in Fig. 5.136, where also a computed example of a real hinge axis angle is displayed.

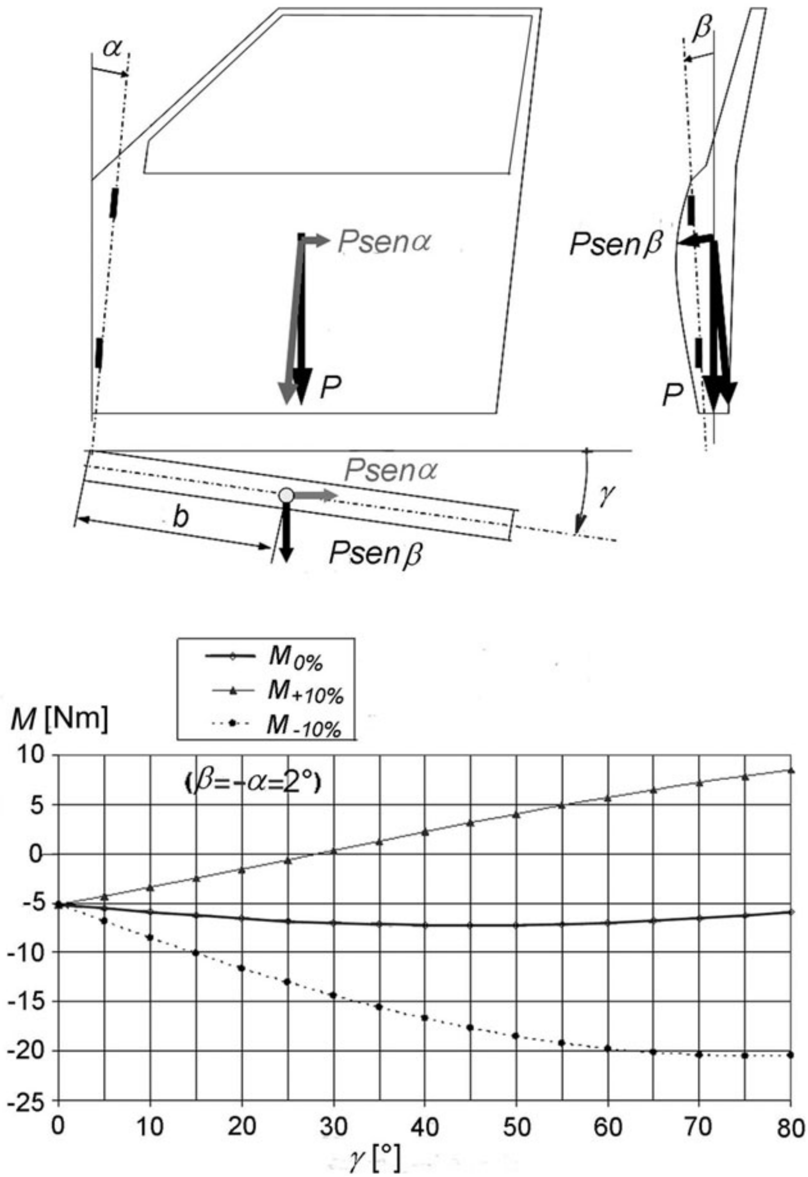


Fig. 5.136. Calculation model of door self closing moment, as a function of α and β hinge axis angle, γ door angle. For positive moment values, the door tends to close. $M_{0\%}$ is the self closing moment on horizontal road; $M_{+10\%}$ is the moment on a climbing road whose slope is 10%; $M_{-10\%}$ is the moment on a descending road 10% sloped.

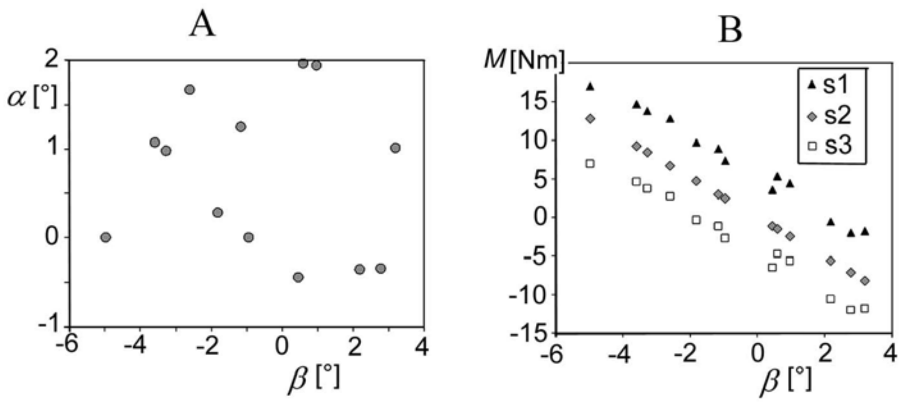


Fig. 5.137. A) α and β angles measured on some European and Japanese cars. B) computed influence of β angle on self closing moment M for a 25 kg door, angles α, β given by Fig. A, different vehicle attitude and γ angle. s1: climbing 10%, $\gamma = 20°$; s2: horizontal, $\gamma = 0°$; s3: descending 10%, $\gamma = 20°$.

The self closing moment M_{ac} is given by the approximate expression:

$$M_{ac} = Pb(\alpha \text{sen}\gamma - \beta \cos\gamma) \tag{5.26}$$

Therefore, for small door opening angles (γ), the behavior depends mainly on β angle; when the door is completely open, its behavior is driven by α angle.

From the above expression and scheme, it can be easily understood that, for instance, with a β angle of 2° and a α angle of $-2°$ (that means hinge axis forward and sideward sloped), the moment should always help door opening on horizontal road and also on a climbing road, at least for small opening angles. Of course, no universal rule exists to choose hinge axis angle: every car manufacturer has its own practice and the choice is driven by factors of customer satisfaction.

The Fig. 5.137 illustrates the measured angles α and β of some production cars and related self closing moments, computed through the above expression. The door mass is 25 kg, the distance from gravity center to hinge axis is 600 mm and the angles α, β correspond to the cars under study.

It can be noticed that a relevant change of moment can be achieved by changing the β angle.

Static and dynamic stiffness

From the structural point of view, the window frame is the most critical system due both to the aesthetics and visibility requirements which influence the frame section, and to the relevant stresses on the whole frame caused by loads on the weather strips and glass, aerodynamic pressure and vibrations.

Insulation from fluids and noise is related to the contact of door and weather strips; tolerance range of weather strips is $<\pm 2$ mm, and the total tolerance

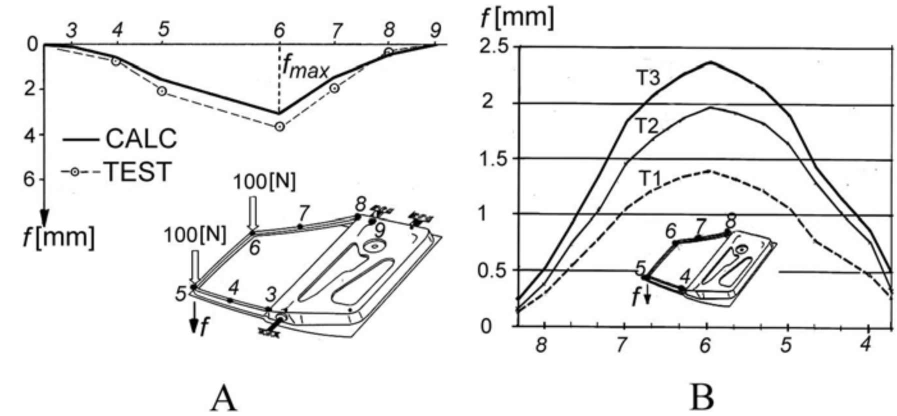


Fig. 5.138. Door frame deformations of a mid class European sedan, in a static bench test (A) and measuread on road (B). T1 and T2 are caused by weather strips only, at border tolerance value of the gap between door and body side; T3 is the total deformation on the road at 150 km/h, if the door is fitted with the design specified gap.

between door and body side is usually in the same range. Therefore, it is easy to understand that, in practice, window frame deformation caused by such stresses cannot be absorbed. After verifying that door frame stiffness is inadequate, the short cut usually applied consists of a *pre-bending* operation on door frame. This means that the door fitted to the body side has a pre bent frame so as to establish variable gaps between the door frame and body side, which is nevertheless lower than the specified gaps, while no stress is applied. After mounting the weather strips, and in the presence of dynamic loads, the frame flexibility will tend to establish the designed gaps automatically. In any case, the maximum value of pre-bending is limited by the free window glass drop in the case of the open door: from experience, a pre-bending of 2.5 mm at the frame edge may be judged to be acceptable. This means that frame stiffness must deform less than ~2 mm, under weather strips, glass, aerodynamic loads and vibrations.

Fig. 5.138-A shows, an example of the static measured and computed deformations on a door of a mid class European sedan, in the standard static test, consisting in the application of two loads (100 N each) over the upper edges of door frame, while the door is clamped by hinges and latch on a stiff bench.

Fig. 5.138-B displays dynamic deformations recorded on the same door mounted on the car when being driven at 150 km/h, in different tolerance conditions between door and dy side.

The applied pre-bending in the shown example was 1.5 mm at edge 5 and 2.0 mm at edge 6, 0.0 mm at the belt line, with a linear change in between.

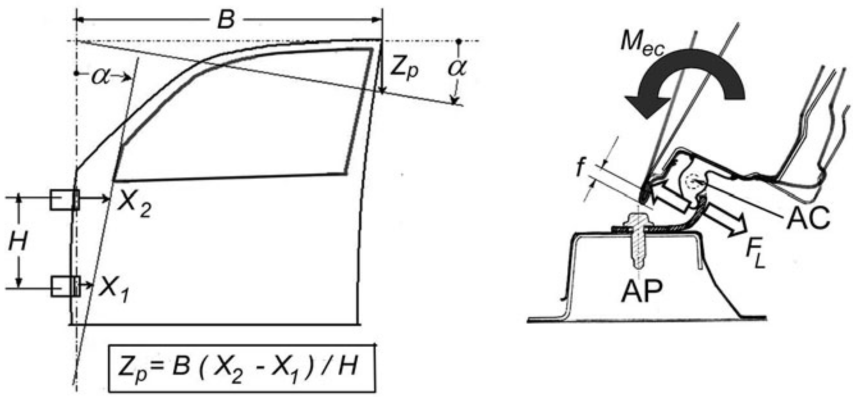


Fig. 5.139. Vertical door yield, as a consequence of horizontal deformations in hinge areas. AC: hinge axis; AP: body pillar; M_{ec}: over-run moment; F_L: action and reaction of door brake; f: door panel slide.

For the same door, clamped by hinges and latch, but without glass and trimming components, the first vibration modes have been computed in order to verify their separation from typical chassis, suspension and body resonances. The computed values for a steel door have also been compared with the values of the same door made of aluminum.

1° vibration mode:	steel door 40 Hz	aluminum door 41 Hz
2° mode	62 Hz	71 Hz
3° mode	66 Hz	74 Hz
4° mode	85 Hz	89 Hz
5° mode	87 Hz	93 Hz

Resistance to yield

In real use, the most stressed areas of the door are those subjected to concentrated loads: hinges, locks, window glass regulator fittings.

Especially the hinge fittings are subject to relevant vertical as well as horizontal loads during door operation. Vertical loads are, for instance, a consequence of using the door as support when seating in a car or getting out from a seat. Horizontal loads are, for instance, inertial loads due to complete door opening or a gust of wind.

When hinge attachments undergo different horizontal permanent deformations (yield), as shown in the left side of Fig. 5.139, the door assembly rotates around a transverse horizontal axis. From the figure, it can be understood that parameters influencing the door rotation are the yield difference ($X2$–$X1$) and hinge distance H. The only geometric design parameter that can be managed is therefore H: it must be as high as possible (usually > 300 mm), consistently

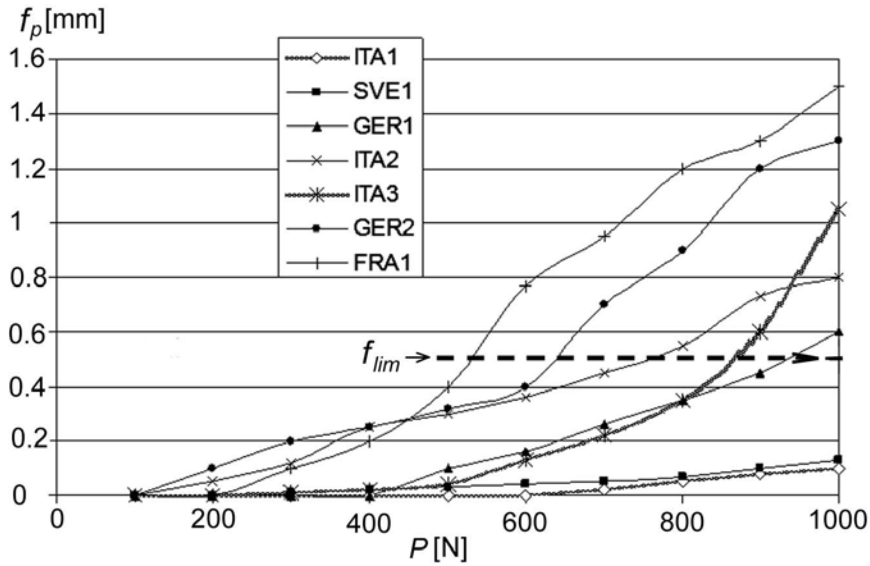


Fig. 5.140. Door vertical permanent yield f_p, measured on a number of european cars. P: applied load at door rear end; f_{lim}: recommended maximum yield.

with body side curvature. If yield in the upper hinge zone overcomes yield in the lower hinge, as in the figure, the door rotation causes a permanent vertical deflection of the rear door side.

The horizontal hinge yield can be caused by the hinge itself and/or by the event shown in the right side of Fig. 5.139: the door over-run, limited by hinges equipped of stop devices, can cause the outer panel sliding forward over the inner panel, in hem zone, often lacking of structural adhesive.

In order to avoid this problem, the over-run stress should be shared among different devices, the intervention of which is designed as a sequence. First is the *door brake*, designed to absorb energy in progression, along an allowed deformation space; then the upper hinge stop and finally the lower hinge stop. In this way, the most frequent cases of hinge yield should occur at the upper hinge level and therefore, according to the principle explained, the door rear side should rise instead of fall.

Regarding the vertical load effect only, the door resistance to permanent yield is measured through a door bending test on body, by loading the rear end of door with a rising load at different opening positions and then recording the residual deformation (Fig. 5.140). Each car manufacturer has its own specified target for such a test, for example less than 0.5 mm of permanent vertical deformation under 1000 N load. Moreover, the absolute yield value is not as critical as the yielding curve progression which is an index of the available safe margin.

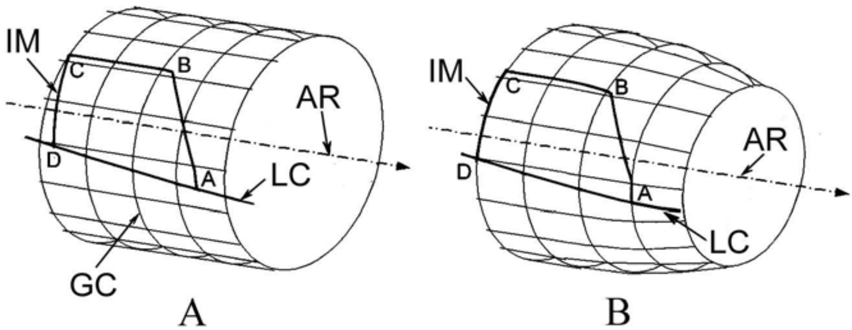


Fig. 5.141. Geometrical examples of possible cuttings for a cylindrical glass (A) and barrel glass (B). IM: pillar interface; AR: rotation axis; LC: belt line; GC: glass cylinder.

Geometrical aspects of the door surface

The most important geometrical properties of the door are related to the *door window drop,* ie. the kinematic behavior of glass points distributed on the mean surface of side glass (along window rails, while the glass is dropping), and also the influence of the door tolerance on the main glass functions.

During body style modeling, the complexity level of the window glass surface must be chosen. In fact, the model body side surface is made up of different connected variable radius patches that can, for instance, be mathematically expressed by polynomial functions. The obtained surface must comply with a rotational surface, needed to allow window operation control by fixed boundaries (as belt weather strip or window rails). In addition to plane glasses, which are unusual nowadays, cylindrical (one radius) side glasses or *barrel glasses* (two orthogonal radiuses) are available, the schemes of which are shown in Fig. 5.141.

Today cylindrical glasses are the most used; the usual radius is > 1200 mm (in order to preserve optical quality and cost); in practice the rotation axis is horizontal. During its up and down operation, a cylindrical glass, can move forward or rearward by a defined pitch.

Barrel glasses are needed when body side curvature cannot comply with cylindrical glasses, even with sloped axis (as in Fig. 5.142, where the cusp or curvature discontinuity effect on central pillar is visible). In such cases, forward or rearward glass motion during glass drop is not achievable, due to the change in generator radius: glass rails in this case must be set orthogonal to the barrel axis.

After the glass type choice, body side modeling and glass curvature definition should be set interactively, in order to minimize the error between body side mathematical surface and real glass surface: that error should remain in any glass point within a range of some tenths of mm, ie. a lower order of magnitude than glass and stamped door tolerance.

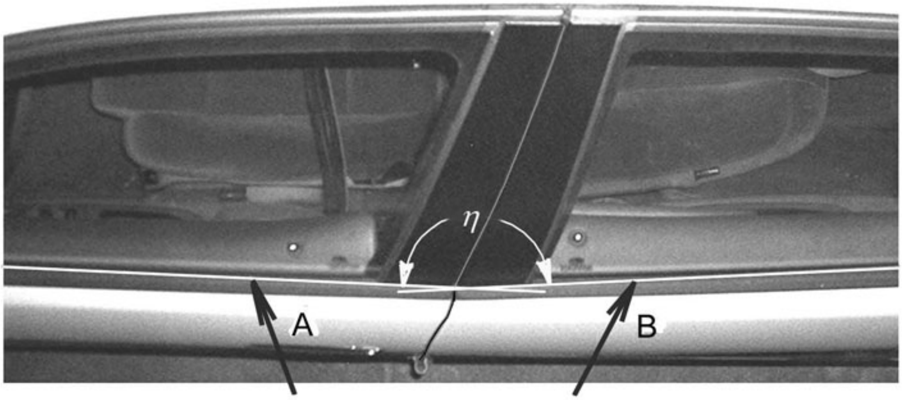


Fig. 5.142. Example of a body side with front and rear side cylindrical glasses, whose axis have a relative angle η, as shown by intersection of glasses with belt line.

Regarding the influence of tolerance, it must be noted that door constraints are located in hinges and lock area and therefore their three tolerances result in the overall tolerance of a plane, compared to the theoretical plane passing through the three reference points. This means that, for instance, in the furthest door frame edge, in addition to local stamping and assembling tolerance, the error due to hinges plane location must be computed: that contribution is relevant, because the distance between door edge and hinges can be more than 1000 mm, while the distance between hinges can be about 300 mm.

In practice, the tolerance of hinges fitting planes, both on door and body side, must stay in a range of tenths of mm, in order to result in less than 1 mm of error between the door end and the body side. If this target cannot be achieved, a boundary manual matching of door mounted to the body is required, meaning individual door permanent deformation in order to obtain an acceptable matching.

Impact strength

In both front and side crash, doors can contribute to cabin integrity. In case of front impact, the rearward deformation of front pillar, mainly at belt line level, can be contrasted by inner and outer belt reinforcement, acting as axially stressed columns. Section and end design of such reinforcements must provide stability under axial loads; materials should provide high yield properties.

In side impacts, it is necessary to distinguish between large and narrow surface contacts. In the first case (e.g. against walls or big vehicles) the door contribution is very low, because impact stresses are mainly addressed to the body side frame (pillars and rocker panels), the strength of which is not influenced by the doors.

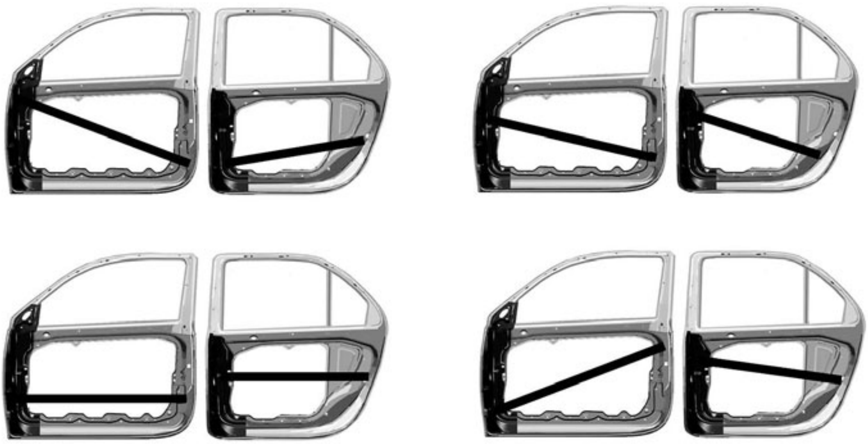


Fig. 5.143. Examples of door safety beams positioning in the space between outer and inner panel.

In the second case (e.g. against poles or trees), the door is directly involved in impact energy absorption and resistance to impact loads: therefore its design is relevant. In the first step of crash, the door is pushed against its housing, that is against body side flanges; the door outer panel starts bending. As a critical deformation level is achieved, door panel and border frame start deforming body side flanges as well as hinges and lock fittings, sliding towards the inside of the cabin. As the door starts sliding, it is no longer held by the body opening flange, but only by hinges and the lock; therefore it deforms as a membrane under traction and its strength rapidly drops. To avoid such behavior, first the bending strength of the door must be increased and the door border sliding must be avoided by embedding the door in the body side.

The first goal is usually achieved by insertiing one or more cross members in the space between the inner and outer door panels: depending on the door configuration as well as hinges and locks positions, different beam lay-out are available (Fig. 5.143). Depending on their position, these beams can also contribute to the second goal: for instance, a side bar close to the sill can enable the door to avoid sill overriding. If door bars are not sufficient, other devices (e.g. metal hooks or pins in body side frame) must be added.

Safety door beams can be manufactured using a range of process (e.g. drawing, extrusion, pultrusion, rolling), with different materials (steel, aluminum, composites) and various shapes (Fig. 5.144). The material selected should have high yield and break strength; moreover, bar ends, fitted between outer panel and door frame, must provide enough contact surface to meet the body side during crash.

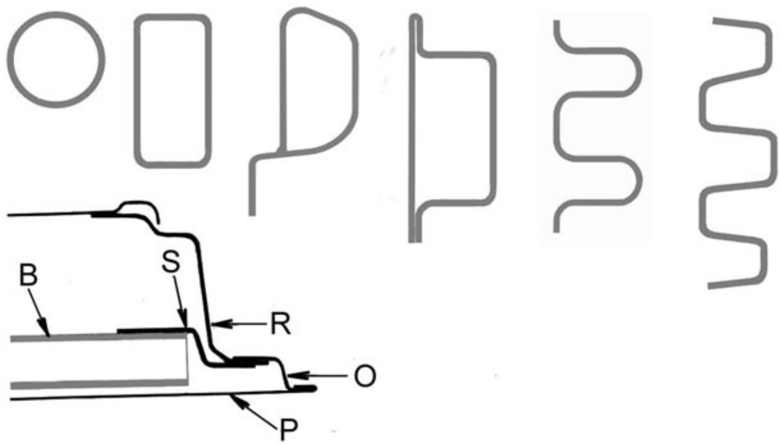


Fig. 5.144. Examples of boxed and open sections used in door safety beams; detail of link between a tubular beam and door pillar reinforcement. B: tubular beam; S: bracket; O: door inner panel; R: door pillar reinforcement; P: outer panel.

Materials and technology

Doors are usually made of sheet steel stamped elements, but even aluminum and hybrid doors have been manufactured. Hybrid doors have, for example, a steel or cast magnesium or aluminum or thermoset resin inner panel, covered by a drawn steel or aluminum sheet outer panel or by a thermoset or thermoplastic injected outer panel.

Steel sheet doors are assembled by spot or continuous welding, by brazing or clinching of the stamped inner and outer panel. Typically used for doors is the hemming process, consisting first in the insertion of inner panel (including prewelded reinforcements) in the outer panel, previously downflanged in the mating die; then, outer panel 180° hemming is performed, after structural adhesive extrusion in between (Fig. 5.145).

Hemming is aesthetically pleasing and recommended for a smooth border, but has two main problems. The first regards the inner panel centering inside the outer panel, as the last one cannot usually feature reference holes. In practice, matching precision is supplied by perimeter contact between the hemming die and the outer panel, while the inner panel is positioned in the die through reference holes. The second problem is the unreliable link between the inner and outer panel, that leaves a sliding risk just after hemming. For that reason, a structural adhesive is laid on the outer panel hem flange, before inner panel fitting. The structural adhesive is usually thermoset and therefore needs time and heat to be cured. For that reason, the hem assembly is usually locally spot

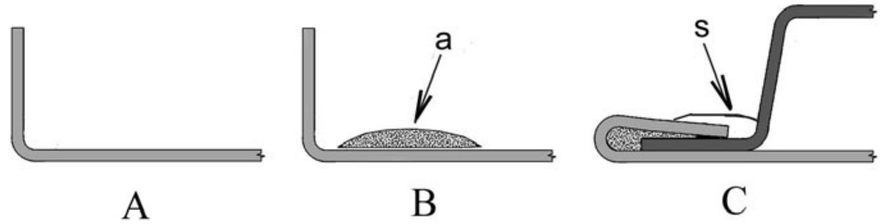


Fig. 5.145. Door hemming process. A) door outer panel is downflanged and laid in the die; B) the structural thermoset adhesive (a) is laid on the outer panel; C) after inner panel insertion, outer panel 180° hemming is completed by the die. It is now possible to extrude a sealant (s).

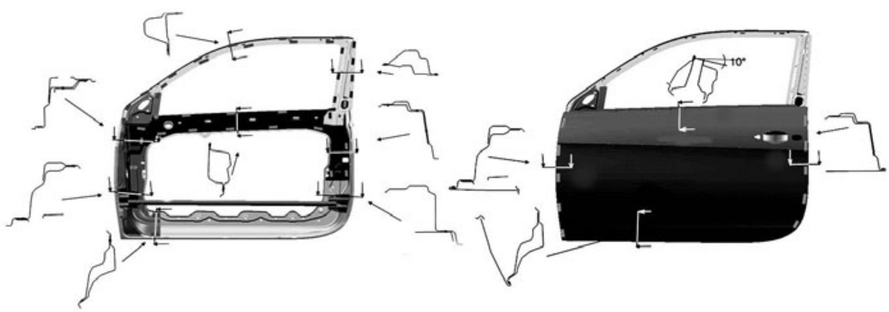


Fig. 5.146. Example of laser weld design on door hem and window frame contour: weld seams position in different sections are shown.

welded and immediately put in a baking module where a local heat hardening of the hem joint is performed. Only after such a process can the door be handled safely.

Laser welding

In order to replace the structural adhesive, the continuity of which is critical due to spray, even in robot operated processes, a number of laser weld seams on the hem contour have been adopted (Fig. 5.146). The lower thermal energy of laser welding means that this process leaves the hem zone undeformed.

As it can be noticed in the figure, some further traditional spot welds around the window frame have been replaced by laser weld seams.

The development of laser seam welding has allowed the use of tailored blanks even on doors (Fig. 5.147). Sheets number reduction and thickness tuning, therefore weight reduction, have driven this process. In particular, the involved parts are the hinge pillar reinforcement and lock reinforcement, whose needs are usually higher thickness, boxed section and high yield materials. Some choice of

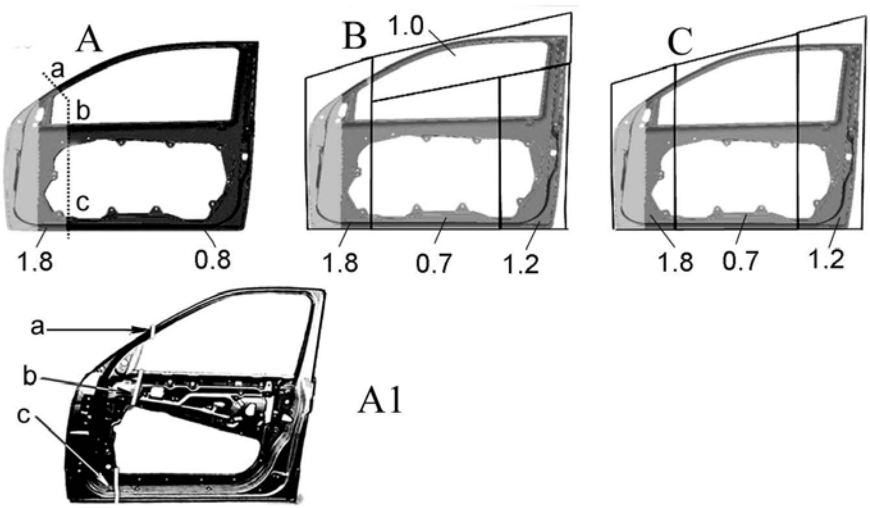


Fig. 5.147. A, B, C are usual composition schemes of different thickness tailored blanks in a door frame, according to reinforcement needs. a, b, c are blanks joints. A1 is an axample of door made according to scheme A.

cutting of different thickness blanks are available, such to replace section boxing, without stiffness loss. Still some aesthetic problem remains, as the blanks weld seam on inner panel is visible, when opening the door.

Magnesium door frame

In order to reduce door weight, doors with cast magnesium inner panel and aluminum outer panel have been tested. However, a second goal to achieve is to reduce the door module cost, by integrating in the cast panel some components such as hinges, usually split on traditional steel doors.

An example is the frame of a spider door, shown in Fig. 5.148, the mass of which is 3.7 kg. The overall door mass, with aluminum outer panel, was 8.6 kg, saving 48% of the original steel door. The estimated total cost, referred to traditional doors, can be lower for a production rate of 100 vehicles/day.

Hinges and door brakes

This chapter examines the properties of the most common hinges for vertical axis side doors usually made up of two half hinges, articulated using a cylindrical pin. The movable half hinge is screwed or welded to the door whereas the fixed half hinge is usually screwed or welded to a body side pillar. The cylindrical pin connecting both half hinges and leaving one freedom degree only (the rotation around pin axis), is kept in its seat by a removable screw.

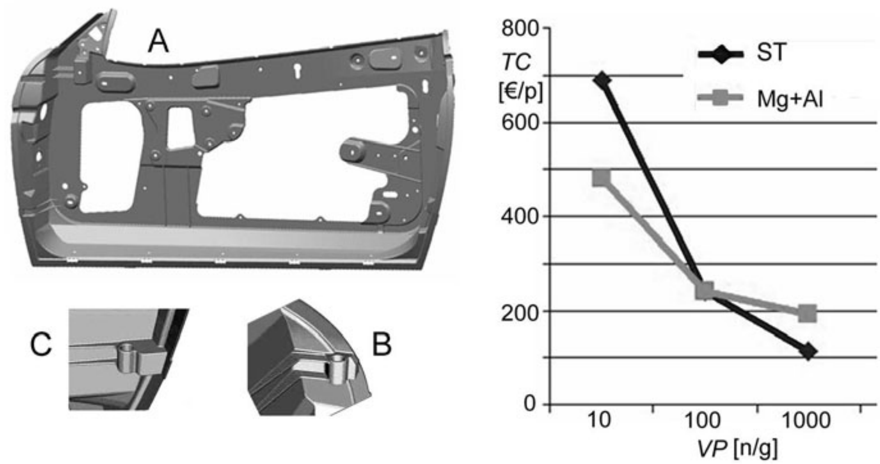


Fig. 5.148. Example of cast magnesium door inner panel (A) of a spider and details of the upper (B) and lower (C) hinge, integrated in the cast piece. On the right, a comparison between overall cost *TC* of a traditional steel door (ST) and a hybrid door (magnesium inner and aluminum outer panel), with reference to daily production rate *VP*.

In Fig. 5.149 the archetypes of three typical hinge families are shown. Type A includes two steel forged half hinges: blade 1 is inserted in a slot inside the body side pillar, until the rectangular flange stays close to the body surface. After the controlled hinge positioning, following the door centering and alignment to the body side, one seam weld of the hinge flange to the body side outer, and another of the hinge end to the body side inner, are performed.

The outer half hinge 2 can be screwed or welded to the door pillar reinforcement. As can be observed, the end 4 of half hinge 2 has a tooth shape in order to provide a stop to the complete door rotation.

Type B is always drawn from steel sheet; it is welded to the door and screwed to the body side outer, to which it is matched. Door to body alignment is performed, in this case, by a chosen number of selected spacers positioned between half hinge 1 and the body side before screwing.

Type C is made of extruded aluminum or steel profile, screwed to door and to body side; even in this case, alignment between door and body side is fixed by insertion of spacers between the fixed hinge and body side.

In the body assembling process, the movable half hinges are installed first, on a bench where a mechanical fixture simulates the hinge axis, i.e. the axis that connects both hinges. With reference to this axis, each hinge should have a maximum angle error of 1°. Otherwise, after the hinges are fitted to body side also, hinge pins could be overstressed during door operation, and could break as a consequence. If this specification cannot be respected, the pin stress could be

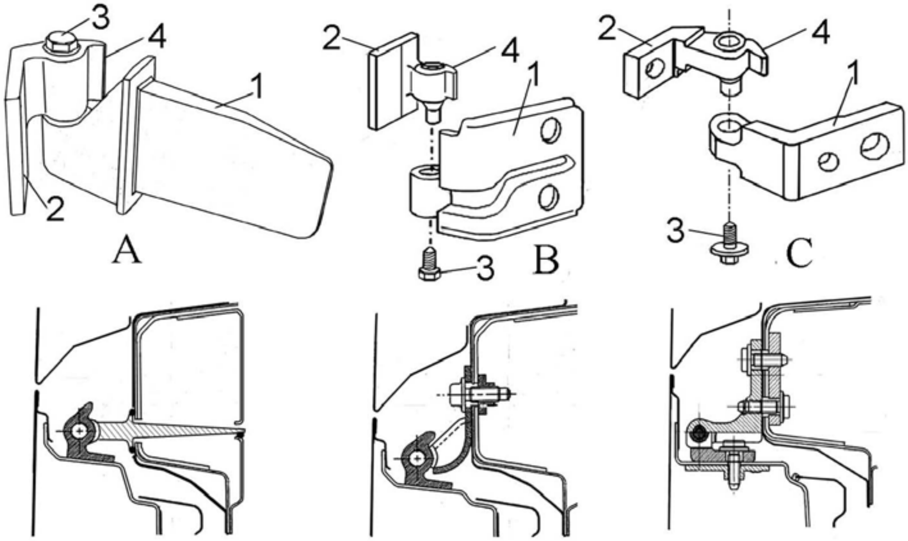


Fig. 5.149. Usual hinge families and fitting sections: 1) movable half hinge; 2) fixed half hinge; 3) pin retaining screw; 4) end stop tooth.

reduced by using barrel instead of cylindrical pins, causing an increase in cost as a result.

After alignment, the movable hinges are welded or screwed to the door. Usually, welding is preferred when the purpose is to fix the movable hinges axis once and for all; however many cars use screwed movable hinges to enable further adaptation.

After door matching with the body side, the fixed half hinges are fitted to the body side pillars: this process is usually performed with closed doors and therefore the screwing or welding operation should be made from the outside; otherwise robots should be used. The usual process specifies first the rear door hinges fitting on the central body side pillar, then the front door hinges to the front pillar before the fenders are in place.

The choice between screwing or welding the fixed hinges to the body side is influenced by many factors: type of plant, process automation, manpower costs, manual operation quality, availability of reset stations, after market repair after crash, manufacturer technological tradition. Statistically, screwed hinges represent the most common solution.

In addition to the examples shown, other hinge configurations are on the market with similar technology and behavior, although the shapes can be different (Fig. 5.150).

A hinge family, that is distinguished by its specific features, is that which includes an *elastic door brake device* (Fig. 5.151). As previously indicated in

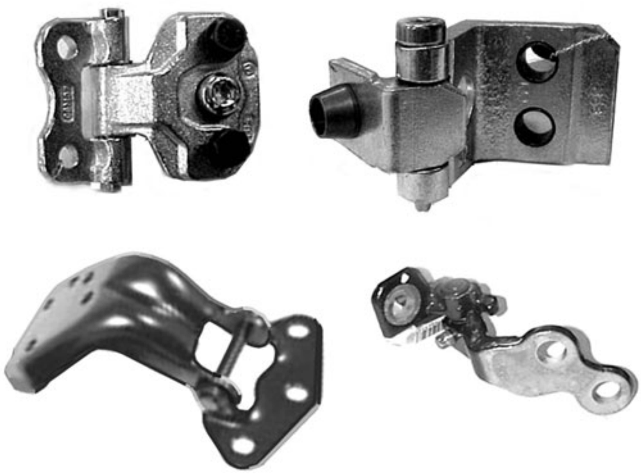


Fig. 5.150. Examples of screwed door hinges made of forged steel and drawn sheet.

Fig. 5.149, hinges usually include a stop tooth, to contrast the rotation of the door, when the opening angle is larger than specified (usually between 60° and 70°) .

But, if the door is opened with a strong pulse, as in case of a gust of wind or misuse, it may reach the final opening position with still a relevant amount of kinetic energy, the absorption of which results in higher loads that depend on the stiffness of the stop. If the stop consists in a hinge tooth, its stiffness can cause either the door, the hinges or the body side to yield, and sometimes the door can even hit the body pillars or fenders.

To avoid this happening, an elastic absorber (brake) must be added, designed to intervene some degrees before the door stop to provide braking and result in lower loads.

The stop teeth on hinges can then be considered to be a back-up device, acting if necessary, when most of the kinetic door energy has alreday been absorbed. For this task, the brakes could be simple springs or bumpers, positioned at a specified door opening angle.

In practice, the various brake configurations which have been invented provide a more articulated use: they are furtherly adopted as door operation control, by providing one or more stopping aids, from which it is possible to move the door only by voluntary action.

Usually, the first intermediate stop is positioned in such a way as to allow the exit of the passengers from the cabin, whereas the last one is close to the opening end angle. The presence of one or more intermediate stops depend on the strategy of the manufacturer.

Apart from brakes integrated into the door hinges, independent brakes are also in production, usually located between the hinges. The main advantage of

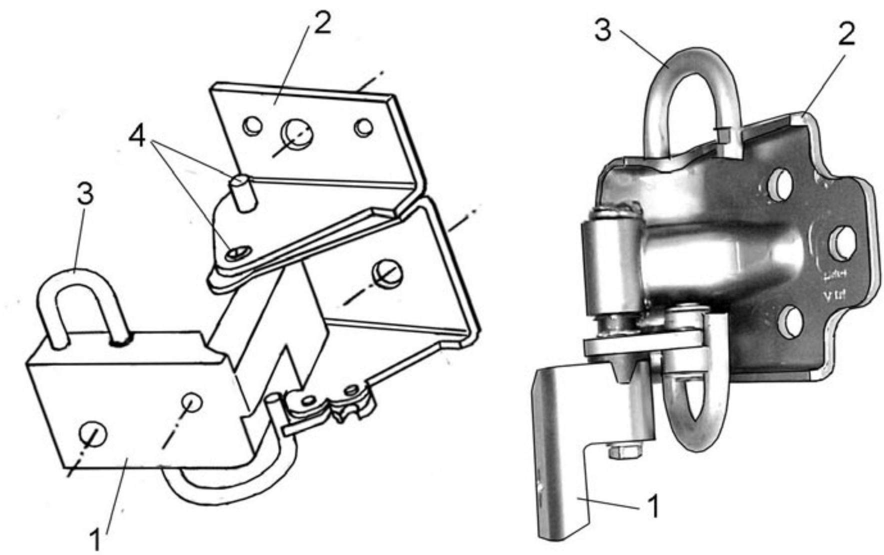


Fig. 5.151. Examples of door hinges with incorporated brake: 1) fixed hinge; 2) movable hinge; 3) brake spring; 4) reference and centering pins.

such independent brakes is a better sharing of stop stresses between the different devices connecting the door and the body side. Of course the disadvantage is a higher overall cost.

The most common types of such devices are shown in Fig. 5.152.

Type A uses a shaped plate rod sliding between two plastic rollers, one of them being pushed by a spring pivoted on a cage screwed to the door while the other slides over an uneven profile. The latter will tend to stop in the valleys and the door must be pushed to overcome that stop.

In type B, the link has a shaped thickness and slides between two plastic rollers, pressed against the link by two elastomeric devices, inserted in a cage screwed to the door.

In type A, the end position is determined by the contact of the roller with the hook shaped link, whereas in type B by the end bumper contact with the cage.

Brake specifications focus on stop locations, on door stop stability without vibration and on door operating loads. Also specified are the roller and sliders friction properties (even obtained by surface lubricant coatings) and lubricant grease and components corrosion resistance.

Delivery tests must verify reliability and therefore resistance, operating loads, stability, absence of permanent deformation due to over-run, absence of

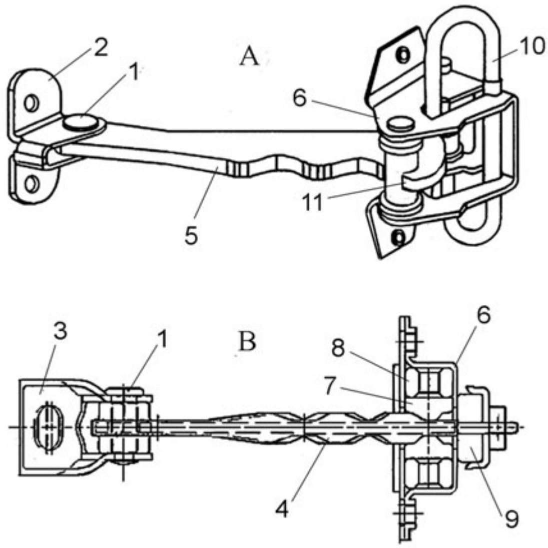


Fig. 5.152. A) door brake of shaped rod plate; B) three dimensional rod brake. 1) hammer pin; 2) two fittings clevis; 3) one fitting clevis; 4) thickness shaped rod; 5) shaped rod plate; 6) cage; 7) plastic sliders; 8) elastomeric springs; 9) end bumper; 10) torsion spring; 11) end hook.

squeaks during repeated door operation, and include climate chamber cycles due to the presence of plastic and elastomeric components.

Door locks

A door lock includes a mechanical module with movable parts usually fitted to the door and a striker, usually fitted to body side, the mechanical opening device being a handle in the door. It is anyway possible to exchange both components position (that is to fit the latch module on body side and the striker on the door) by other opening devices that in any case must allow the door to open after a crash.

Fig. 5.153 shows the main operating scheme of a traditional side door lock. Two pins that carry two rotating shaped plates are riveted to a boxed, usually metal, housing. The upper rotating device is called the fork, and the lower is called the retention lever. A torsion spring acts on the fork, to move it clockwise, while another tends to move the retention lever counter-clockwise.

The housing usually includes a slot positioned between the fork edges; a striker pin, mounted on the body side, engages the slot. A detailed view of the slot, together with the visible part of the fork, is shown in Fig. 5.154: a tapered opening at the slot entrance can be seen. Its purpose is to facilitate the capture

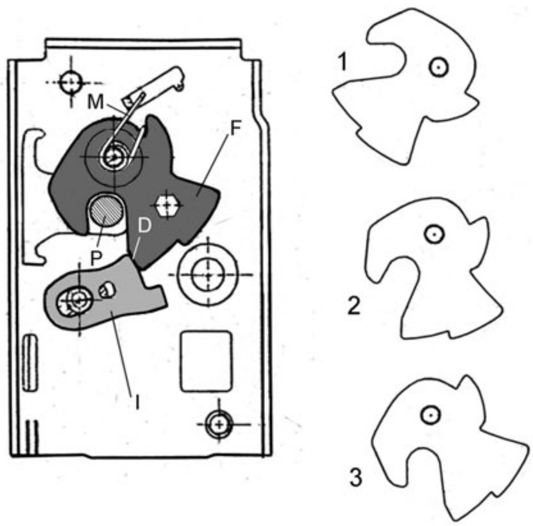


Fig. 5.153. Schematic view of an open door lock: the fork F has the three work positions visible on the right. I: retention lever; P: striker pin; M: torsion spring; D: primary fork tooth.

of the striker pin, even in case of small door yield or rise. For this reason, a similar slot is cut on the door inner panel where the lock is screwed.

The same figure shows an example of the section of a striker (A), selected from hundreds used by different companies.

Fig. 5.155 shows a section of door, body side, latch and striker assembly, on an XY plane across a cylindrical striker pin S, in the door end closing position.

The different door positions, open (1), closed at first click (2) and completely closed (3), refer to different latch angular positions, as can be seen in Fig. 5.153.

When the door is slammed, it must not only press the weather strips, but also overcome the friction of the internal lock mechanism. The energy needed to complete the maneuver is supplied by the kinetic energy, transferred to the door by the slam action. If door speed is not sufficient for complete closing, the first click position can however provide a safe lock, meaning opening is not possible without mechanical action on the door handle.

Referring again to Fig. 5.153, it can be seen that the latch, under spring action, has three stable positions:

1. open, when the fork is completely clockwise turned, stopping at its end click: in this condition, the cavity is open and able to mate the striker pin;
2. closed at first click, meaning a partial counter-clockwise fork rotation, corresponding to retention lever stop by tooth 2 , cut on its perimeter. Such a position is obtained by hitting the striker pin with the latch, causing

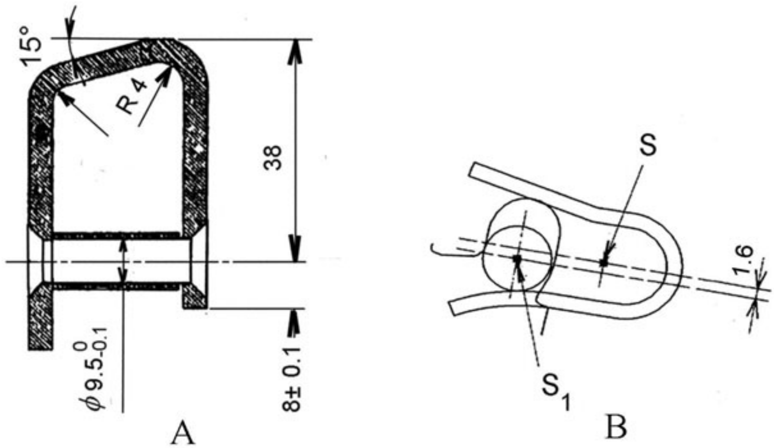


Fig. 5.154. A: section of a striker; B: latch and door sheets cutting, in order to catch the striker pin; S_1: pin position at first click; S: pin position at closing end.

rotation and the concurrent retention lever click. The position is chosen in such a way that the weather strips begin contacting the door surface. In this way, the door is locked even if the door slam energy was insufficient;

3. completely closed, following a similar procedure to point 2, but with adequate closing energy ensuring engagement of the retention lever with fork tooth D.

In order to achieve the lock opening, only required is clockwise rotation of the retention lever until the latch fork becomes free to open due to the action of the torsion spring and elastic rebound of the door weather strip.

The lock plate includes other components as shown in Fig. 5.156-A. In addition to fork F and related retention lever I, two more levers are marked 1 and 2, the task of which is to control the lock opening and its safe clamp (with retention lever stuck) respectively. Lever 1 has a protruding end that can move the retention lever; when it is pulled forwards (with respect to the page), it forces the retention lever to rotate clockwise and free the fork. When the latch is open, the lever cannot engage the retention lever and therefore latch opening control, through internal or external handle, is missing.

The retention lever can be engaged by the end of lever 2 (the lever pin is positioned close to mid lever), if the latter is rotated clockwise; in that case, the retention lever rotation is contrasted and the latch is securely closed.

The end of lever 2 can be moved either by the external key or by internal control. The same operation can be performed through sector 3, moved by an electric motor 4: therefore closure and opening can be performed by manual operation (internal lever or key unit) and by electric motor.

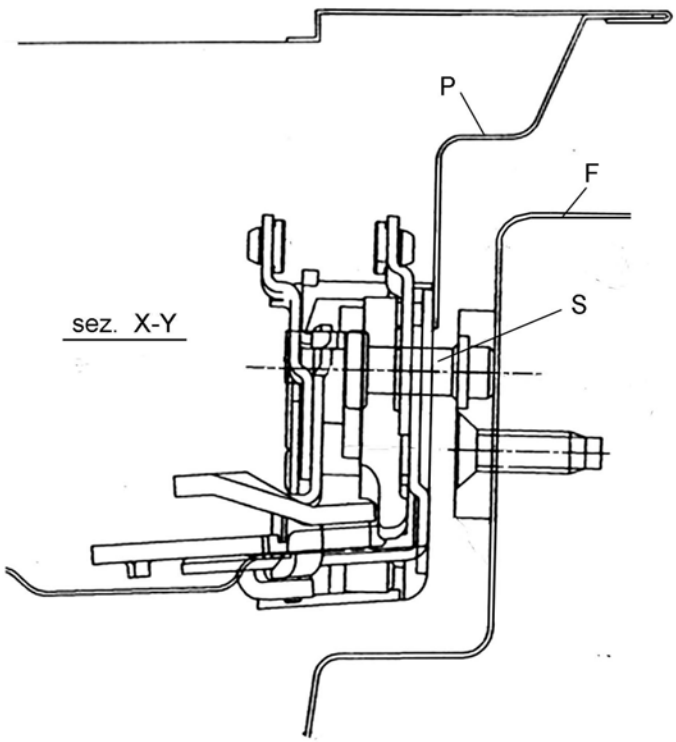


Fig. 5.155. *XY* section of a door (P) mounted lock, with the closing end position of the striker S, mounted on body pillar F.

Such electrical control can be defined to be semi-automatic, as its function is limited to the security device operation, while the energy for latch in and off operation must be provided manually.

Other types of completely automatic control are available, in which the latch operating energy is provided by an electric system. In that case, the striker pin is part of an eccentric device, free to rotate and controlled by a motor M, as can be seen in Fig. 5.156-B. It is only necessary to push the door until it touches the latch to start closure. Striker S shall engage the fork, without pressing the door weather strips. The fork rotation shall be performed by the rotation of the eccentric striker, that shall enable the compression of door weather strips and the retention lever clamp. The reverse operation of the same steps enables door opening to the first latch contact position.

The following figures illustrate some examples of door latch connections to its internal and external controls. Fig. 5.157 shows an example of handles connection, security control and latch layout, and a section of inner handle. In

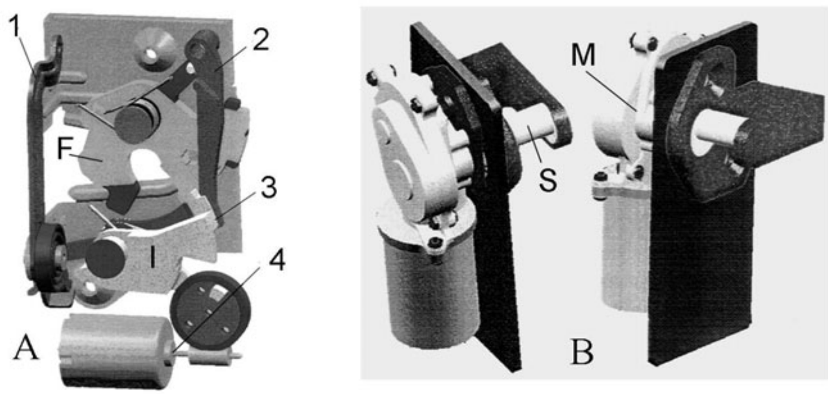


Fig. 5.156. A) mechanical lock with security lever 2, motor operated; B) completely electrical lock, in which closing, security lock and opening are operated by the motor M that rotates the striker S.

Fig. 5.158, the lock connections with the external key cylinder, with inner handle and with the security inner device, are displayed.

All connections visible in the figures comprise rods and shaped levers, and can all use Bowden wires in flexible housings.

The main problem of these types of connection is lock vulnerability from the outside, especially through blades inserted between the door and window glass which can be used to deform the connection levers or flexible housings, reducing their length. The usual solution consists in additional sheet metal covers, welded to door panel, to protect the connections where contact from the outside could be possible. It is also good practice to avoid any possible engagement of inner handles and security controls by hooks or knots.

Door lock specifications

International legal requirements relate first to lock strength and lock performance in event of a crash. During a specified front or side impact against barrier, the doors must be kept closed, while after the crash it should be possible to open any door from inside or outside without using tools.

According to the individual experience, car manufacturers specify the corrosion protection treatment for lock metal components and the surface coatings against friction for any sliding mechanism; even the grease selection can be specified.

Regarding lock fastening, it must be remembered that a stiff installation is required featuring a three dimensional adjustment in order to allow the best matching of latch and striker.

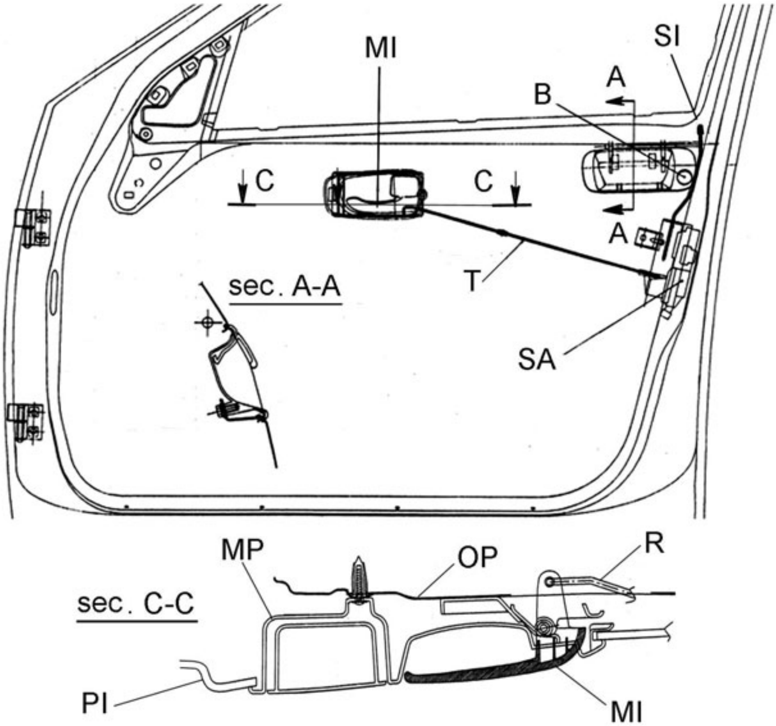


Fig. 5.157. Typical lay-out of door lock controls. MI: inner handle; T: inner handle rod; B: key cylinder; SI: inner security rod; SA: latch with actuator; OP: door inner panel; R: rod; PI: door trim panel; MP: handle bezel.

The main lock performance criterion perceived by the customer is the handle operation load, and more generally that associated with the lock controls. The handle load should be as low as possible and without variation along the lever run, due to stick and slip phenomena for instance. It is recommended that not only some average reference value with their tolerance range be specified, but also the load limits related to the lever position.

It should be borne in mind that the lock load is influenced not only by the locking system but also by the compression of the weather strips. A full set of door weather strips can require a load of 200 N (at door handle position) for a single bulb and up to 400 N for a triple weather strip layout.

A useful way to specify the door handle opening load, related to weather strips overall load, is shown in Fig. 5.159.

Usually the security lock and unlock loads are also specified: these loads should feature a clearly bi-stable behavior, i.e. the lever should stop in only one of the two end positions.

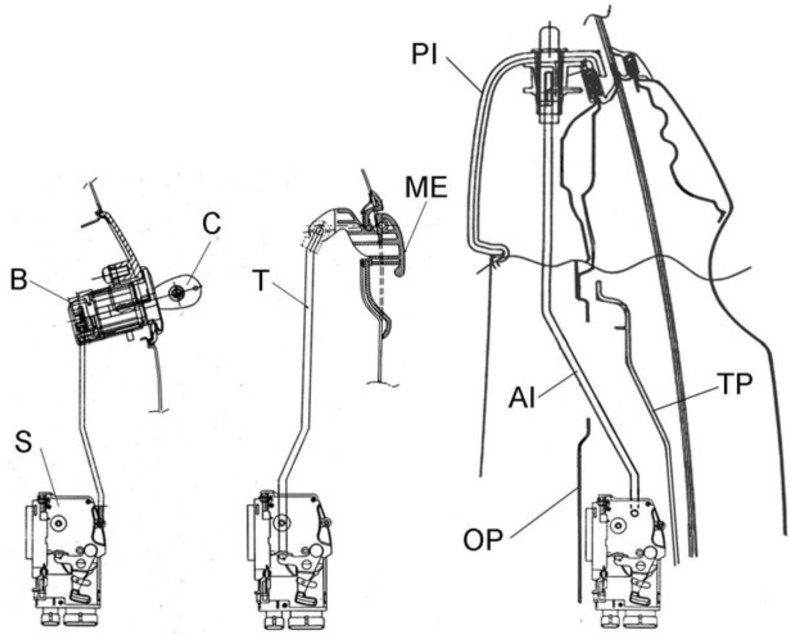


Fig. 5.158. Examples of lock S control connections: from key C, through cylinder B; from outer handle ME, through rod T; from internal security pin, sliding inside trim panel PI, through shaped rod AI. OP: door inner panel; TP: protection cover.

It is also recommended to establish the reference temperature for the load range specifications; in fact, the dimensional changes of plastic and metal components can cause relevant effects in the use of the car in practice.

The door opening and closing noise is perceived by the customer to be an indicator of quality. The closing noise is caused by the door residual kinetic energy (after closure completion) and the impact between the internal system components (latch against striker; retention lever against fork). The opening noise is mainly caused by the mechanical system; in this case noise quality rather than level is the main issue: e.g. long lasting metallic noise and rebound noise of door metal panels are to be avoided. These effects are related to door panels that can be improved in terms of dynamic stiffness and added damping if necessary.

To reduce the metallic noise, many parts of striker, fork and retention lever are over-molded with a plastic material offering anti-friction properties.

A recommended practice specifies an acoustical reference spectrum for the noise emission with respect to a specific door slamming speed.

Moreover, a water proof test in the rain chamber and an oxidation test in a wet chamber are specified. The purpose of these tests is to verify the insulation of internal components from water contact following raining or car washing, and the absence of any kind of change in the operation loads due to corrosion.

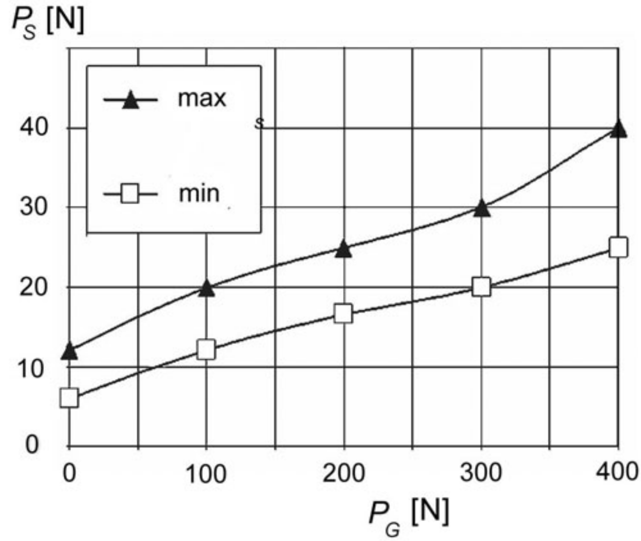


Fig. 5.159. Range of door handle load P_S, specified in relation to door weather strip load P_G.

Regarding the effraction test, even the best designed lock has a strength limit; for that reason, its security is rated according to some reference procedure, which measures the time requested to unlock the door with common professional theft devices. In some European countries, the insurance fee for theft is related to such a measurement.

Door modules

In the traditional body assembling process, doors were fitted to body in white through hinges screwing or welding and never again dismounted. The main reason was that each door had been individually adapted to its housing by manual adjustment, often deforming the door in such a way that it would not match any other body.

Nevertheless defects in the painting process and damages in the final mounting process were frequent, resulting in door dismounting and causing a series of organizational problems that are easy to imagine. In order to avoid damage to the door during the mounting process and to facilitate the car trimming operations, doors were therefore dismounted after painting, trimmed off-line but close to the main line, and finally refitted at the end of the line.

The off-line process facilitates door trimming with modular sub-assemblies, such as the window glass regulator together with the glass, pre-assembled on a

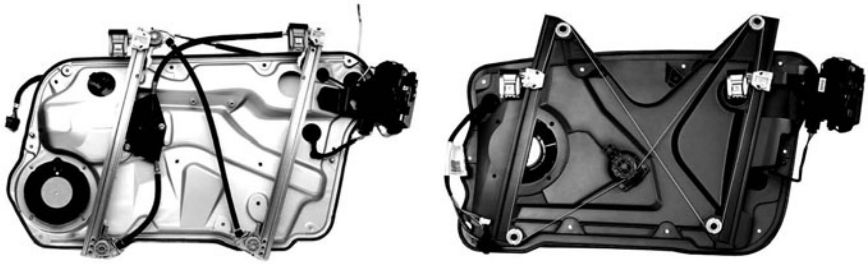


Fig. 5.160. Examples of door carrier with window regulators, lock system and loudspeakers.

carrier to be screwed to the door inner panel with the insertion of a weather strip inbetween (Fig. 5.160).

On the other hand, the use of re-painted doors has confirmed that doors painted individually can be aesthetically consistent with an independently painted body. Last but not least, the use of robotized fixtures to fit the doors to body in white and the improved quality of both subassemblies, has resulted in the complete interchangeability among different bodies and different doors.

This evolution has paved the way to doors designed as modules, i.e. assemblies including all constituent components, manufactured in specific plants, even located away from the body mounting line, at the end of which they should arrive *just in time*.

This kind of door module concept can facilitate the car manufacturer in the choice between make and buy, and the selection of materials and even the door architecture, and therefore can also create cost benefits. In practice, door design concerns an assembly of a robust three dimensional frame with an inner module including window glass, window regulator, rails, interior trim, harness, controls and an outer panel, already painted (Fig. 5.161).

Delivery testing

The main recommended delivery tests for a side door in white are:

- Side deformation of window frame < 6 mm; permanent yield < 0.35 mm, under a load of 200 N.
- Side deformation of belt line inner/outer < 1.2 mm; permanent yield < 0.2 mm, under a load of 100 N.
- Door slamming: 50,000 cycles without any break or yield.
- Fatigue under repeated vertical loads: 50,000 cycles without any break or yield.
- Permanent yield under vertical load of 1,000 N < 0.5 mm.

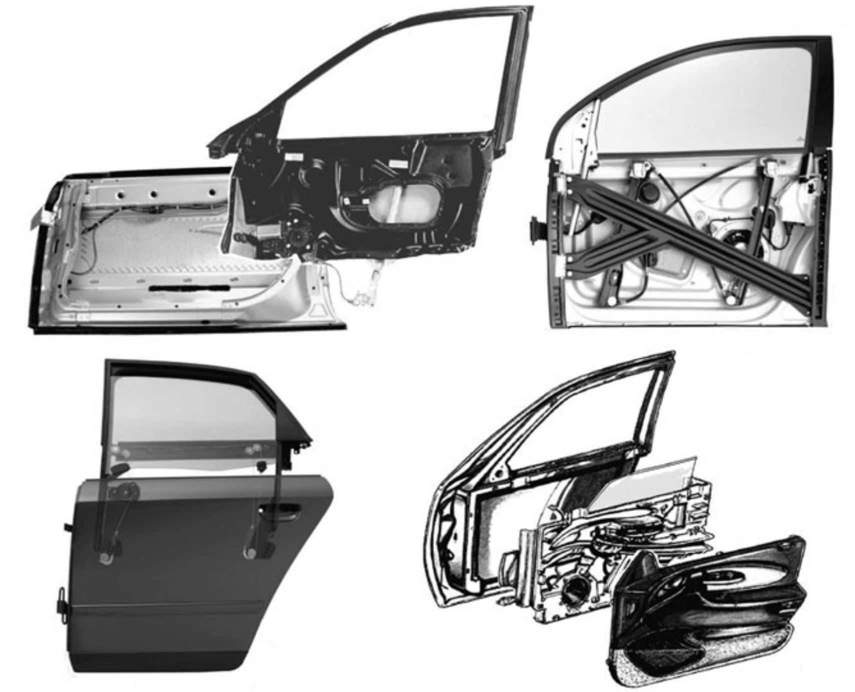


Fig. 5.161. Examples of modular door concept.

- Over-run: no interference with body parts; yield < 0.5 mm, under a load of 300 N.
- Stiffness of window glass regulator attachments > 100 N/mm.
- Stiffness of door brake attachment $> 3{,}000$ N/mm.
- Stiffness of external door handle attachments > 100 N/mm.
- Stiffness of internal main handle > 100 N/mm.
- Stiffness of latch attachments > 400 N/mm.
- Stiffness of glass rail attachments > 100 N/mm.
- Stiffness of loud speakers attachments > 100 N/mm.

5.4.2 Sliding Doors

Sliding doors have nearly rectilinear rails, in which trolleys with one or more rollers (depending on the specified constraints) slide.

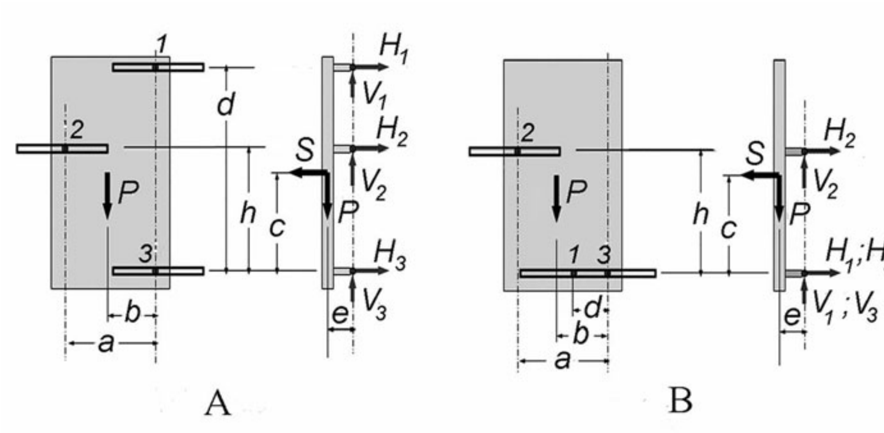


Fig. 5.162. Static schemes of trolleys reactions on 3 rails (A) and 2 rails (B) sliding doors.

The rails can be on the roof or sills or on the body side (in which case the trolleys are fitted to the door) or on the door (in which case the trolleys are hinged to the body).

In order to establish a statically determined overall constraint condition, three connecting, non-aligned devices should be designed which can be located on three or two independent rails (each of them leaving only one freedom degree, along the principal axis).

Doors of this type are usually adopted on commercial and industrial vehicles body side with straight side surfaces which enable three rails at different heights to be located: low (sills), middle (belt line) and up (roof), see Fig. 5.162-A).

Usually a car body side, on the contrary, has very different curvatures at different heights: for that reason only two rails are frequently used, one at the belt line level and one at the sill level. The third trolley is located inside one of the two rails, in such a position so as to avoid door rotation around the axis determined by the other two trolleys (Fig. 5.162-B).

Examining the trolleys reactions in each case, with three rails:

$$H_2 = \frac{Sb}{a} \tag{5.27}$$

$$H_1 = \frac{S(c - bh/a) + Pe}{d} \tag{5.28}$$

$$H_3 = S - H_2 - H_1 \tag{5.29}$$

$$V_2 = \frac{Pb}{a} \tag{5.30}$$

$$V_1 + V_3 = P(1 - \frac{b}{a}) \tag{5.31}$$

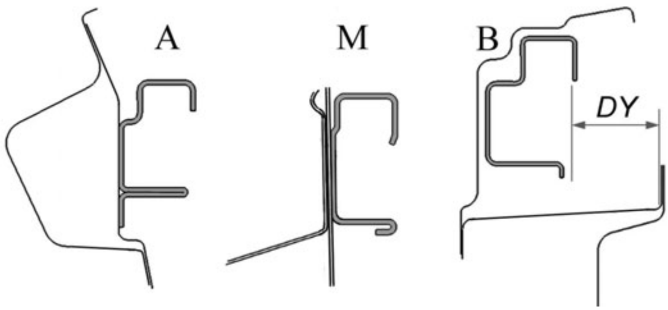


Fig. 5.163. Dimensional comparison among the typical rail layout for vertical reaction; A: upper rail; M: belt rail; B: lower rail.

whereas in the case of two rails:

$$H_2 = \frac{Sc + Pe}{h} \tag{5.32}$$

$$H_1 = \frac{Sb - H_2 a}{d} = \frac{S(b - \frac{ca}{h}) - \frac{Pea}{h}}{d} \tag{5.33}$$

$$H_3 = S - H_1 - H_2 \tag{5.34}$$

$$V_2 = \frac{Pb - V_1 d}{a} \tag{5.35}$$

$$V_3 + V_1(1 - \frac{d}{a}) = P(1 - \frac{b}{a}) \tag{5.36}$$

As can be seen, only two trolleys can provide vertical reaction without redundancy: therefore one of the reactions V_1, V_3 must be eliminated.

For instance, referring to three rails, the choice between vertical reaction on lower rail and upper rail can be examined on two vehicles, RVB (featuring the vertical reaction on the low rail) and RVA (vertical reaction on the upper rail).

The reaction, calculated according to the scheme shown above, does not provide any useful selection criterion, since trolleys 1 and 3 are aligned to the same X position and therefore V_1 in vehicle RVA is equal to V_3 in vehicle RVB.

Therefore, the choice must be driven by other factors, which are considered relevant with respect to vehicle properties.

Some factors in favor of the upper rail vertical reaction are:

a) lower mud risk;

b) easier alignment of the door with upper body side;

c) lower distance (DY in Fig. 5.163) between the upper trolley and the door, therefore lower stress on body and door frames;

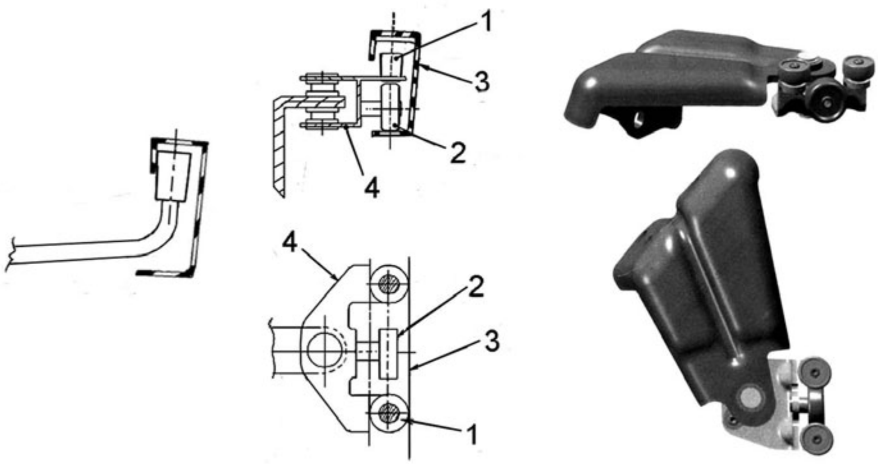


Fig. 5.164. On the left, section of a upper trolley that carries horizontal loads only; on the right, upper trolleys that carry horizontal and vertical loads as well.

d) lower crush risk in the case of side impact;

e) lower risk of trolley wedging.

The main advantage of vertical reaction on the lower rail relates to the higher strength and stiffness of rocker panel, compared with the roof frame.

Regarding two rails comparison with three rails, it can be seen that the horizontal reactions are much higher in the case of two rails, due to the lower lever distance. For instance, in the case of two rails, the horizontal reaction H_2 is inversely proportional to the distance h between the rails.

Figs. 5.164, 5.165 and 5.166 illustrate some sections and three dimensional views of trolleys. It can be seen that trolleys have one horizontal roller when they provide a horizontal constraint, while two horizontal rollers are required to control the direction of the vertical reaction roller.

Fig. 5.167 shows a schematic example of the location of door attitude control devices which are used to drive a precise latch matching at closing run end and support the door on the road, while reducing the load on the trolleys. In the transverse direction, some rubber pads are located for vibration damping.

It is important to note that side sliding doors never feature self closing while the vehicle is stationary on up to a 20° slope: this legal requirement can cause a closing startup force between 120 and 180 N, depending on the door mass and device type.

Even the door slam testing speed on a horizontal road is specified: the maximum allowed value is < 1 m/s, while the recommended value is about 0.5 m/s.

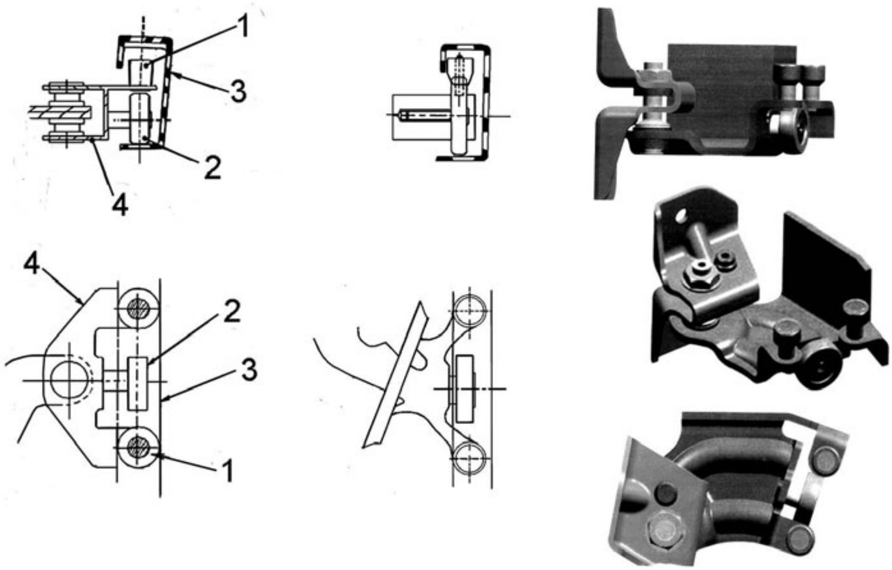


Fig. 5.165. Belt line trolleys, with rollers supporting both vertical and horizontal loads.

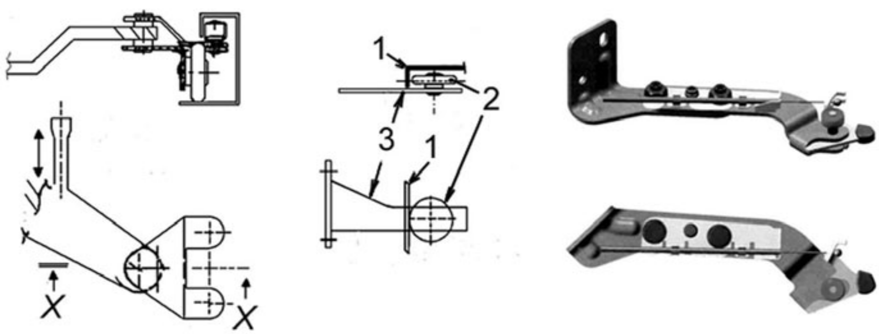


Fig. 5.166. On the left, lower trolley carrying horizontal and vertical loads as well. On the right, a trolley designed for horizontal loads only.

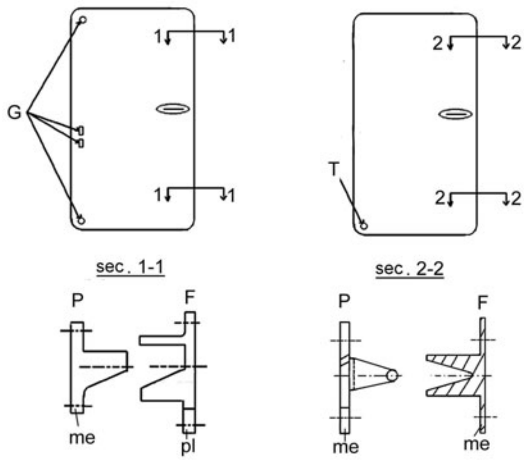


Fig. 5.167. Position and section of wedges to control sliding doors attitude. P: door; F: body side; me: metal; pl: plastic; G: rubber pad; T: rubber dumper.

Moreover, if the door is opened on a slope, it must engage a brake, capable of absorbing the whole kinetic energy of the door, without permanent yield of frames (door and body side) and rubber dampers.

5.4.3 Trunk Lid, Liftgate, Tailgate

Three box cars feature a trunk lid, the opening of which does not usually allow loading and transportation of large goods; this task is better performed by two box cars liftgate, the height, width and contour configuration of which must enable maximum ease of access. This goal can be met with an adequate shape of the liftgate opening, for instance by a forward cutting of roof upper liftgate border (Fig. 5.168), or by an optimization of the hinges system or by the addition of a tailgate under the lower border. For the same purpose, the tail lamp should be located on the body side, close to the liftgate, and be narrow and extended in height, since regulations do not permit tail signalling lights to be installed on movable parts. Also, the rear body side pillar should be extended in the X direction more than the Y direction, and the liftgate frame should be wrapped over the pillars instead of built in.

Materials and technology

Trunk lids, liftgates and tailgates are usually stamped with steel deep drawing sheets, thickness between 0.6 and 0.8 mm, both for outer and inner panel. The inner panels are often reinforced in the hinges and struts attachment zones. Usually, the two main panels feature a contour hemming. In some cases, liftgates

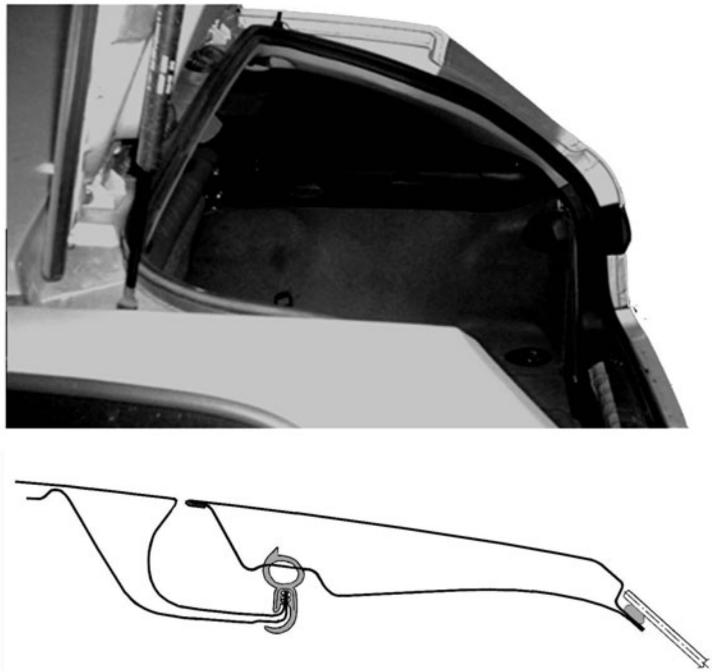


Fig. 5.168. Example of a cut forward liftgate opening. Below, mid liftgate and wide water drain channel section.

with a welded back window frame have been manufactured. Liftgates as well as trunk lids have been made up of high yield rephosforized steel, sometimes of aluminum or with an outer plastic panel (thermoplastic as Noryl GTX®, polycarbonate or thermoset, as BMC, SMC and ZMC).

Functional, structural and dimensional problems of liftgates and trunk lids are similar to doors' and even more relevant in case of split liftgates (i.e. with back window individually movable, already explained in glass chapter).

Kinematics and stop systems

Some kinematic properties of liftgates and trunk lids are worthy of investigation, even though the constituent components, including hinges, struts and stop devices, are also used in other movable parts.

The liftgate hinges are embedded in the rear roof cross member, closer to the side roof end than to the roof center line. They can be single joint hinges with fixed axis, each half hinge being fastened by one or two screws, when the roof has a small curvature. If the liftgate to roof surface border line has a relevant curvature, that kind of hinge cannot be used, because the liftgate rotation could cause interference with the roof. To avoid this inconvenience, an

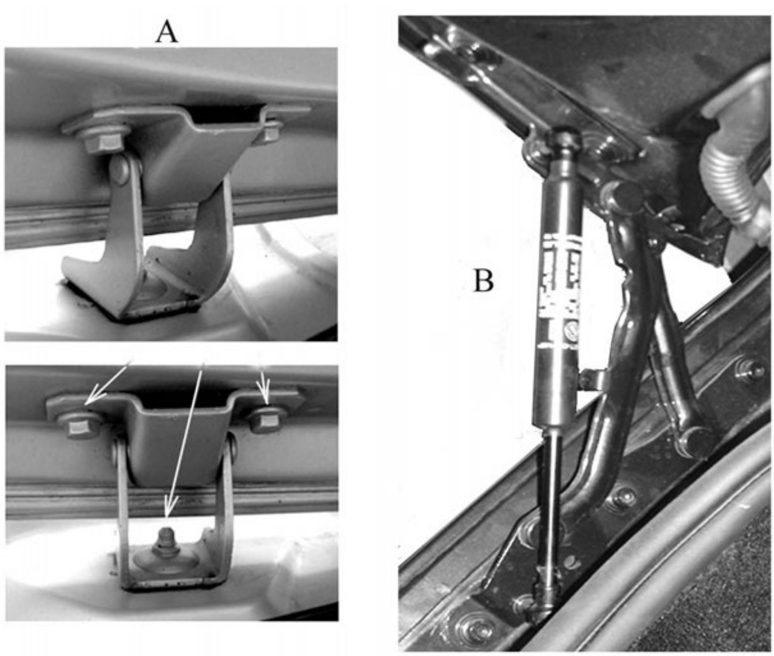


Fig. 5.169. Examples of liftgate single joint three screws hinge (A) and pantograph hinge (B).

articulated quadrilateral can be used (also known as *pantograph hinge*), the rotation center of which moves during liftgate motion (Fig. 5.169). These hinges feature a higher obstruction than the simple hinges and therefore are usually located close to the side liftgate end.

In the case of the trunk lid, where the border center below the back window is usually positioned behind the trunk lid side edges, single joint hinges would cause interference with quarter panels or with back window. In this case, pantograph or *gooseneck hinges* (Fig. 5.170.) can be used, of which the attachment to the body are hidden below the back window lower cross member. In any case, gooseneck hinges cause a relevant obstruction in comparison to pantograph hinges, as can be seem in the figure. The overall volume needed for the rotation of gooseneck hinges can interfere with the luggage volume: a suggested hinge choice criterion is therefore shown in Fig. 5.171.

On the other hand, pantograph hinges are not free from inconvenience altogether.

A typical design problem is their lack of stiffness in the liftgate or trunk lid closing position. In this geometrical configuration, the two hinge rods are parallel in practice and aligned to the rest position of the trunk lid, therefore the rotation center is at a relevant distance. The articulation play, though small, leaves the

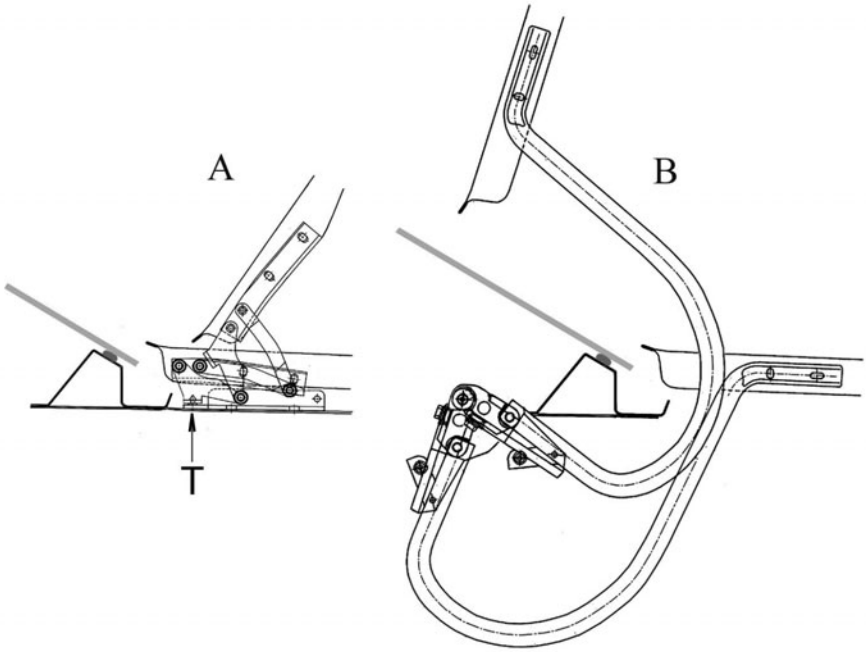


Fig. 5.170. Kinematic comparison between a pantograph hinge (A) and a gooseneck hinge (B), for the same trunk lid. The relevant obstruction difference can be noticed. T: stop pad for pantograph hinge, needed to face the typical closing lability.

hinge rods to exhibit mobility freedom resulting in a flexibility of the system orthogonal to the trunk lid surface. The weather strip reaction is sufficiently strong to lift the trunk lid, so that it fails to align with the quarter panels . Since the pantograph pins positioning cannot usually be changed, the problem can be solved by designing a depressed trunk lid closing position and pre-loading the hinges through an adjustable damper, in order to lift the trunk lid to the desired alignment.

It is interesting to compare the kinematic behavior of the different hinges: in Fig. 5.172, the trunk lid front end displacement and rigid rotation are compared.

Regarding the liftgate and trunk lid lift and support at rest, traditional springs can be used as well as torsion bars or gas struts which, despite their cost and thermal sensitivity, are the ones mainly used today. It is important to position the liftgate gas springs rods below, so that the oil in the cylinder can always keep the gaskets wet so as to maintain the internal pressure. Regarding the influence of thermal variations, the requested load at 20°C must theoretically be increased by 14%, to compensate the gas pressure reduction at –20°C and take account

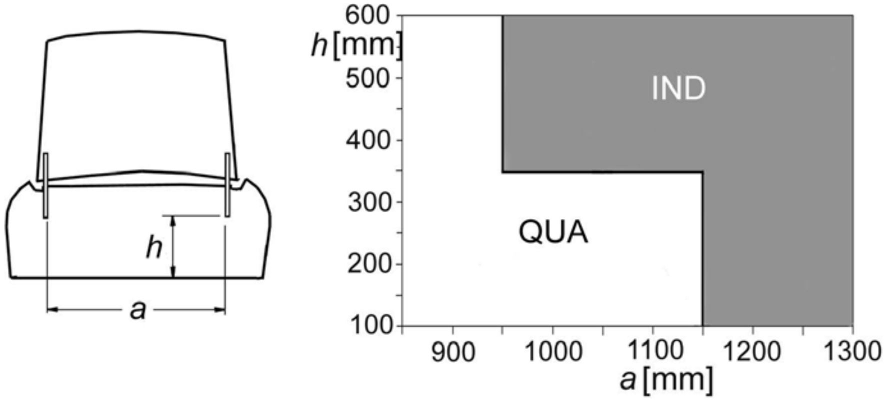


Fig. 5.171. Example of hinge type selection criterion for a trunk lid, as a function of the available space *a* between the hinges and the free heigth *h* between hinge and boot floor; QUA: articulated quadrilateral only; IND: both gooseneck and pantograph hinges adequate.

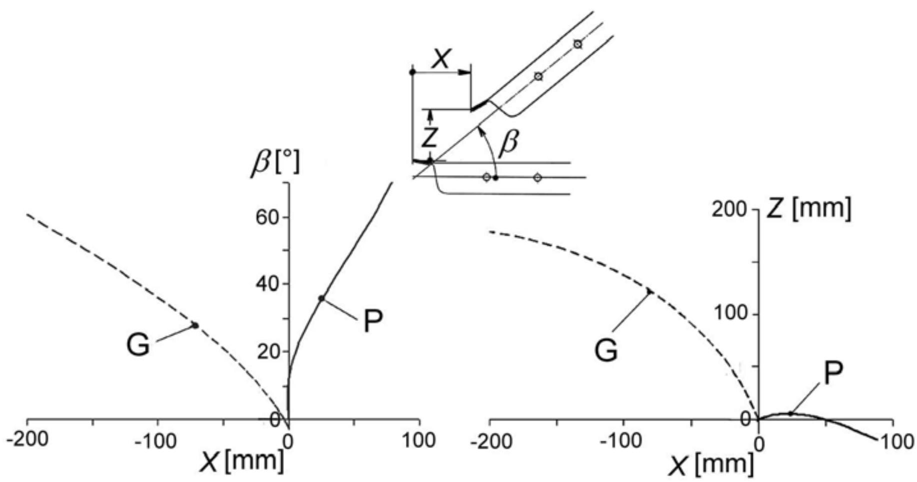


Fig. 5.172. Comparison of front end displacement and rigid rotation of a trunk lid with pantograph (P) and gooseneck (G) hinge.

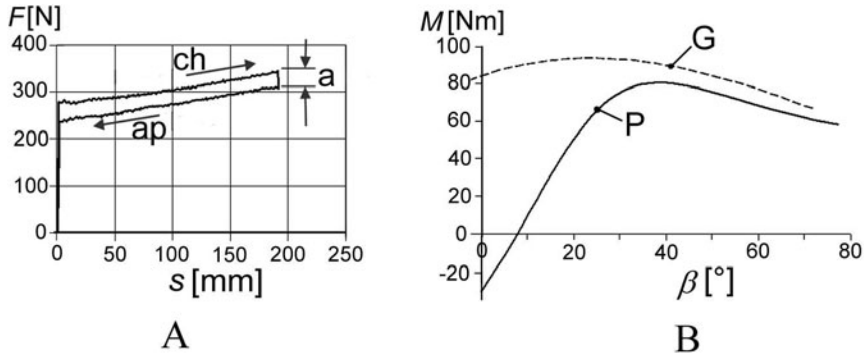


Fig. 5.173. (A): relationship between load F and displacement s of a gas strut rod. ap: liftgate opening; ch: liftgate closing; a: internal friction. (B): overall lifting moment M on a liftgate with two different hinge systems; P: pantograph and gas strut; G: gooseneck and tension spring. β: liftgate opening slope.

of the possible snow load. This means that, at +40°C external temperature, the gas springs shall provide a 22% higher load than requested.

The loading curve of a gas spring is shown in Fig. 5.173. In the same figure, a computed comparison is shown, between the lift overall moment of two gas springs connected with pantograph hinges and two tension springs connected with gooseneck hinges (related to the assemblies shown in Fig. 5.170 and taking into account the trunk lid weight). It can be observed that tension springs and gooseneck hinges provide a practically constant lift moment, while pantograph hinges and gas springs supply a variable lift moment which, for small opening angles, can close the trunk lid and therefore facilitate closure and avoid self opening during unlocking.

In both cases, to lock the trunk lid completely, some energy is needed at first latch contact and therefore some amount of overrun, usually stopped by rubber dampers, positioned at trunk lid side rear end.

Delivery testing

A liftgate as well as a trunk lid must comply with: repeated slamming cycles, hinge stiffness testing in three directions, outer panel dent resistance, operating loads at different temperature, misuse and climatic chamber tests.

Trunk lid and liftgate loads

As on doors, the latch module, including the movable devices, is usually fitted to the movable part, while the striker is fitted to the body rear cross member, with opening being performed by a handle or button located on the movable part.

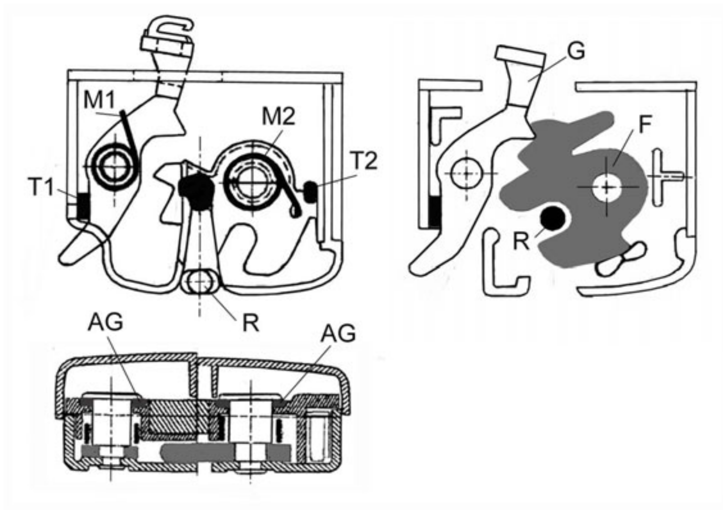


Fig. 5.174. Schematic sections of a liftgate lock. R: striker; F: fork; G: retention lever; M1, M2: torsion springs; T1, T2: rubber pads; AG: rubber rings.

If opening is operated from inside the vehicle or remotely, the latch module can be fitted to the body and the striker to liftgate or trunk lid.

Fig. 5.174 illustrates a liftgate lock with two rotating plates, a fork and a retention lever, each of which is acted on by a torsion spring: the right hand of the figure shows the safe closing condition. In the lower part of the figure, the hammered pins on rubber rings, to control play and tolerance, can be seen.

To maintain latch noise levels low, different solutions have been adopted, such as complete fork plastic over molding, low friction bush on retention lever pin and rubber pads to dampen lever overrun.

5.4.4 Twin Rear Doors

These back doors are commonly used on commercial vehicles, the hinges enabling vertical axis rotation angles of at least 180° and up to 270°, in order to take advantage of complete back opening width.

These doors are usually made of two steel plates, with hemming of the outer panel over the inner and featuring drawn surfaces on the outer panel (*raised panel*) ready for cutting and installation of the window.

The main properties that distinguish these parts from side doors are not only the height, but also the hinge and lock systems, and the waterproof design of the triple node (i.e. the upper node between the split doors).

Between the two movable parts, symmetrical or otherwise, a bulb weather strip is usually located, carried by the left half door, which is the first to be closed in the usual sequence. On the opening flange, another bulb weather strip

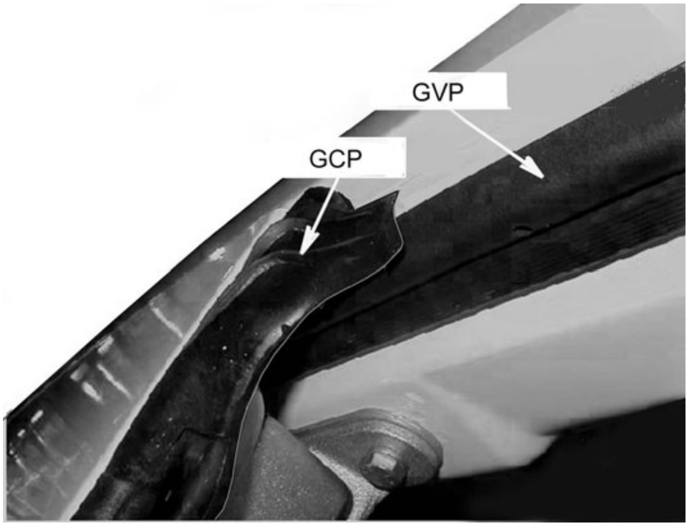


Fig. 5.175. Example of overimposed weather strips in the triple node (GCP: central door weather strip; GVP: body flange wather strip). Despite the complex molded form of central weather strip up end, water leakage can arise there.

is often snapped: in the triple node, both weather strips are overlapped and for that reason a sharp thickness variation of the sealing package takes place, this discontinuity being the cause of water leakage (Fig. 5.175).

The most reliable (but aesthetically unsatisfactory) solution requires a small continuous drip channel over the doors, belonging to the roof panel, in order to drain the most water possible from the roof surface; moreover, in the molded area of the central weather strip, further lips and water drain channels are designed.

The hinges are usually visible from outside, with a single joint and opening 180° or with double joint, manually operated, in order to permit 270° rotation of both half doors (Fig. 5.176): even in that case, priority is given to functional needs; the hinges often have large dimensions, and incorporate a brake and sometimes rubber dampers with magnetic retainers fitted to body in order to keep the door open.

Four locks are usually used, two for each half door, positioned as visible in Fig. 5.177. The left door (which is the first to close) engages the body at both ends: they can be of the type known as *cremonese* or single latches, with activation being performed via Bowden wires or metal rods via a handle at the middle of the door (Fig. 5.177), that can be actuated only if the right door is open. The right locks can be actuated by the exterior handle.

Delivery testing

Test specifications are similar to those of side doors and can be split between tests on the doors in white and on the trimmed door when fitted to the vehicle.

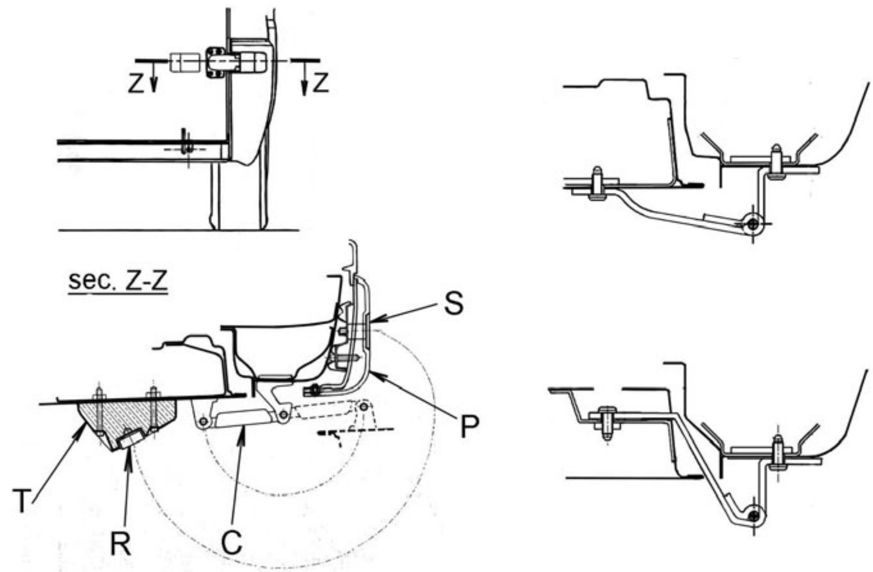


Fig. 5.176. Examples of rear twin doors hinges. C: double joint hinge, opening up to 270°; P: side bumper; T: rubber pad on door; R: magnet; S: striker for magnetic retainer. On the right, single joint hinges.

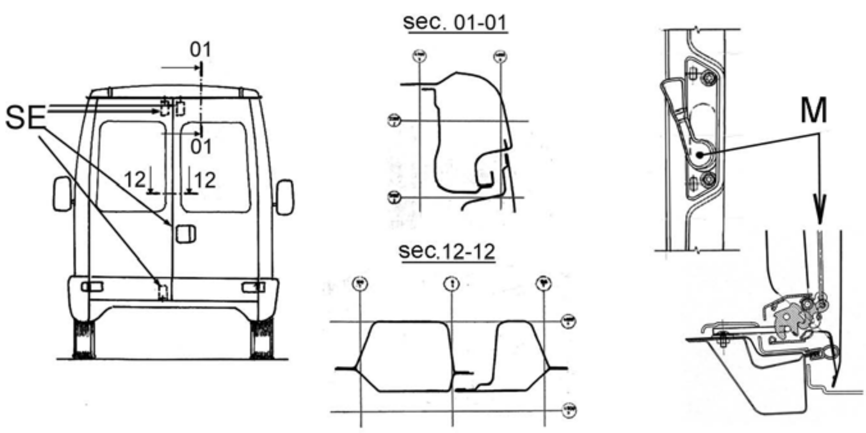


Fig. 5.177. Rear twin door locks (SE) and handle layout (M). Typical door/body 01-01 and door/door 12-12 sections. M: inner central handle with lower fork latch control by rod on left door.

Testing on doors in white (with examples of target value):

- Side total deflection under 200 N load < 6 mm; permanent yield < 0.35 mm.
- Transverse deflection at belt line under 100 N load < 1.2 mm; permanent yield < 0.2 mm.
- Vertical permanent yield under 400 N load < 0.5 mm.
- Lock fittings stiffness between 300 and 600 N/mm, depending on lock position.
- Strikers stiffness > 500 N/mm in X direction, > 1,500 N/mm in Z direction.
- Hinges fitting stiffness between 1,000 and 1,500 N/mm, depending weather the door brake is included in the hinge or not.
- Damping pads stiffness > 1,000 N/mm.
- Door brake stiffness (individually acting) > 600 N/mm.
- Handles or trim fittings stiffness > 100 N/mm.
- Door over-run at 270° < 12°, load at door end being 300 N.

Testing on vehicle (trimmed door):

- Vertical deflection under 1,000 N load < 11 mm; permanent yield < 1 mm.
- Wind gust – door slamming at 2 m/s: no damage to door nor body side.
- Cyclic fatigue door operation: 100,000 cycles without yield or break.
- Cyclic fatigue operation of 90° stop device: 50,000 cycles without any damage.
- Over-run fatigue: 10,000 cycles without any damage.
- Door to door and door to body alignment variation, under weather strip pressure: < 1 mm.

5.4.5 Hood

The function of the hood, for the great majority of cars, is to provide access to the engine compartment and related systems, part of the air conditioning system, a number of fluid tanks, the windshield wiper system, a relevant part of the electric harness and the front lamps.

In the past, hood openings to the front, back or side have been designed: among these, only the front opening can provide easy access to any area of the engine compartment. The progressive increase of service intervals has strongly

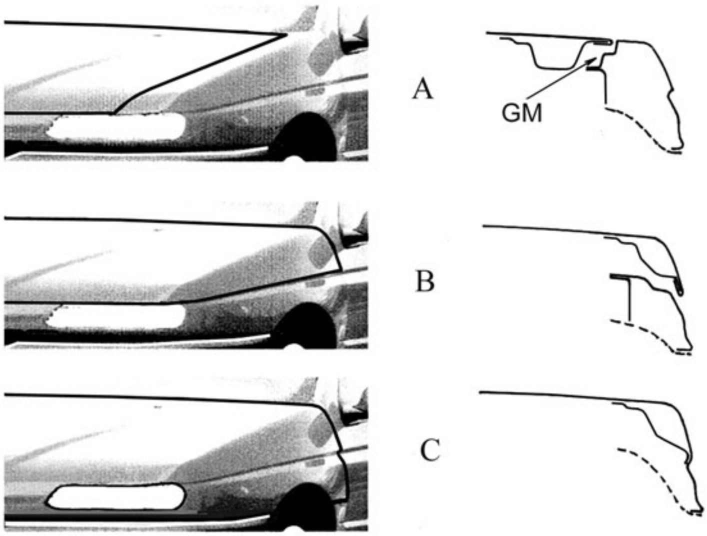


Fig. 5.178. Hood families. A: built-in; B: wrap over; C: with fenders; GM: masked play.

reduced the need to open the hood and therefore the need for remote opening control. Some new vehicles have already adopted a solution with traditional openings only with small flaps where service fluid fillers are located, while the full compartment can be opened in a service station by turning some form of simple device with specified tools.

The replacement of traditional hoods with simple cover panels can offer some advantages such as: weight reduction, cost reduction of panel and missing accessories, hinges, struts and latches and moreover a greater design freedom, which facilitate optimization of shape and stiffness for pedestrian impact.

At this point it is appropriate to analyze specifications and problems of traditional hoods.

Hood architecture

Traditional hoods can belong to three families: built-in, wrap-over and including the fenders (Fig. 5.178).

The choice of hood family usually depends on style, but engineering targets are still important, for example to avoid including fenders if possible.

In fact, a wrap-over hood can help mask body geometrical defects and achieve adequate overall stiffness. Moreover, parts contacting a pedestrian, in the case of an impact, can be made sufficiently crushable.

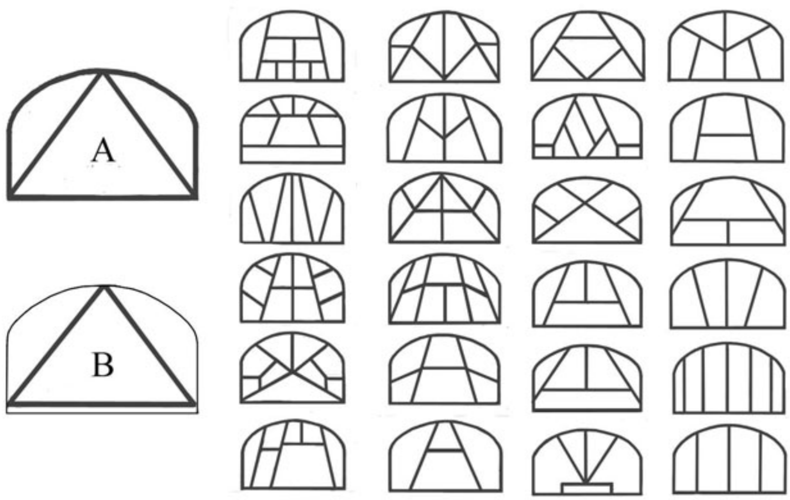


Fig. 5.179. Schemes of European and Japanese production hood frame, compared with two archetypes: A) border and diagonal frame; B) brace frame connecting latch and hinges and supporting an outer panel of increased thickness.

A built-in hood is usually the lightest, but can highlight any border defects, in partcular play to body unevenness and misalignment. The gap between the hood and fender must be stepped to feature the so called *masked play*, in order to cover visibility from inside the compartment. The stiffness due to steps and the lack of empty vertical volume in these areas, makes them relatively aggressive towards pedestrians.

A hood including fenders is much heavier, due to the need to provide adequate torsion stiffness and requires strong connection, support and lock devices. Moreover, its body border has a complex shape, that requires weather strips, pads and preferably two latches: it can be easily understood that a strong cost penalty affects that family of hoods.

Regarding the hood frame, the main task is to stiffen the outer panel and therefore, in principle, a contour frame and two diagonal bars connecting the constraint points (hinges and latch) are the reference archetype, capable of providing adequate torsion and bending stiffness.

Production hoods, on the contrary, feature a great variety of frames (Fig. 5.179) that require some further considerations.

First of all, in order to reduce investments, some hoods without contour frame have been designed with a thicker outer panel, down flanged on both sides, in order to increase stiffness. In most cases, in order to reduce the cost and package size due to the lack of space under the hood, a one piece inner panel has been designed with a great number of ribs positioned in the empty spaces. In that way, the inner panel thickness can be minimized and the stiffness distribution can comply better with pedestrian protection.

Materials and technology

The material selection is driven not only by cost and uniformity with other body parts, but also by performance targets: low weight, resistance to denting, high temperature (up to 90 °C), stone chipping, corrosion, slamming, and in terms of no apparent vibration, acoustical insulation, and pedestrian impact energy absorption.

With respect to these goals, the recommended materials are: aluminum, followed by zinc coated steel and thermoset plastics (S.M.C. - *Sheet Molding Compound* or R.T.M - *Resin Transfer Molding*).

Cost and traditional production facilities favor rephosphorized zinc coated steel sheets, although aluminum hoods are increasingly being adopted.

The outer steel panel can have a thickness of only 0.6 mm, while for aluminum the traditional thickness is about 40% higher than steel, mainly for stiffness reasons. Regarding dent resistance, as already explained in the body materials chapter, the relevant parameter is yield strength; correspondingly aged aluminum can compete with steel.

Thermoset plastics can offer an advantage for very small production volumes (with technology RTM) due to lower investments for dies. For medium production volumes, SMC can be used, when the hood shape, due to undercuts, cannot be drawn in steel. Otherwise, a SMC hood can cost twice that of a steel hood, without weight saving, because the lowest thickness to meet a class A surface in SMC can be 3 mm or even greater. Moreover, for all thermoset hoods, low temperature (< 110 °C) painting is recommended, therefore performed separate to the body, in order to avoid small surface blisters caused by gas expulsion. Although this problem may appear statistically irrelevant at first (just 1 or 2 blisters on 50% of hoods), in practice this means that 50% of hoods need return to the painting shop.

Regarding assembling technology, different processes to join inner and outer panel are available (Fig. 5.180).

Wrap-over and fender-including hoods are usually spot welded in the case of metal (as the side surface does not permit hemming due to their slope) and adhesive bonded in the case of plastics.

Built-in hoods feature contour hemming, with a small downflanged lip where the edge angle is less than 90°. Hemming can stiffen the hood border and, if adequately sealed, can protect against corrosion. On the contrary, welded metals cannot be protected except with plastic profiles snapped on the welded flanges, the reliability is not guaranteed. For that reason, zinc coated steel is used on both welded panels. At hinges, latches and struts fitting positions, a number of stamped reinforcements (thickness $1.2 \div 1.5$ mm) are usually spot welded.

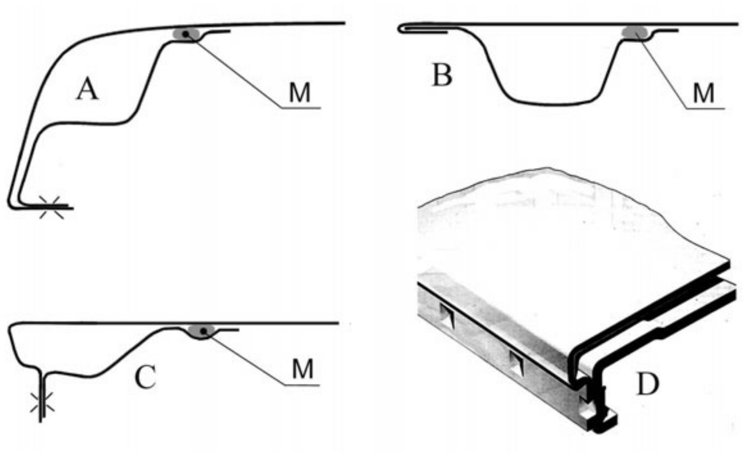


Fig. 5.180. A: welded wrap over hood or hood including fenders; B: hem built-in hood; C: welded built-in hood; D: clinched hood; M: damping mastic.

All assembly processes seal the inner joints of the two panels with a soft shrink-free mastic, extruded in a channel drawn in the inner panel, mainly to provide damping.

With a series of special configurations of hood panels side (Fig. 5.180), it is possible to assemble the hood with a local cold deformation and wedging process called *clinching*.

Joint, support and locking devices

Hoods may feature pantograph, single pin or gooseneck hinges; however it is the first type that is the most used. The kinematics are similar to the decklid with gas springs positioning and operation. However, due to the significant length of the hood and therefore to the higher elastic deformability compared to the decklid, it is important to select the best position and action angle to support the struts, both as regards gas struts and stiff manual rods.

A single stiff strut can be used for lightweight hoods, hand operated (mass less than 20 kg), while a single gas spring is not recommended, due to asymmetric hood stress that could cause hood torsion, especially in case of sudden pulses or misuse.

Referring to the scheme of Fig. 5.181, the strut reaction and the bending moment in the most stressed section can be easily computed, assuming the hood is balanced under a uniform distributed hood load, the resultant of which is P; the distributed hood weight is therefore P/X_C.

Supposing for simplicity that the hood gravity center is at mid length $X_C/2$ and that the rotation axis, in the computing position, is at the lower hood end, the total strut reaction R is:

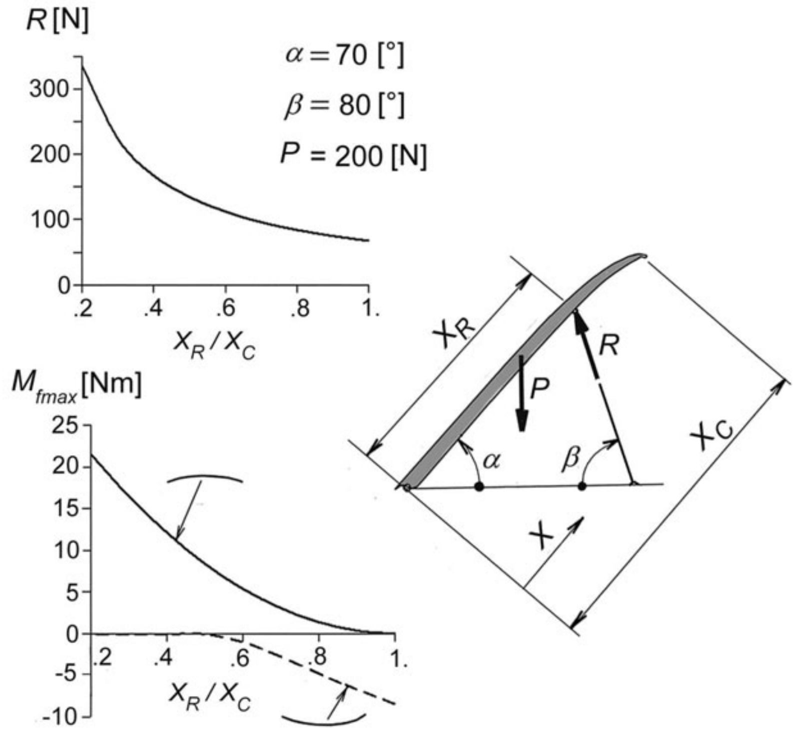


Fig. 5.181. Computed values of strut reactions R and bending moment $M_{f\,\max}$ for an ideal hood of mass 20 kg, as a function of strut position X_R.

$$R = \frac{P\cos\alpha}{2\cos(\alpha+\beta-90°)}\frac{X_C}{X_R} \tag{5.37}$$

Considering the positive bending moment, that increases the hood curvature, the maximum bending moment M_{f+} in the strut fitting section is:

$$M_{f+} = \frac{P\cos\alpha(X_C - X_R)^2}{2X_C} \tag{5.38}$$

Therefore both M_{f+} and reaction R increase as X_R decreases.

On the other hand, the negative bending moment M_{f-} due to the hood weight, the effect of which is to reduce the curvature, acts between the hood lower end and the strut fitting section, expressed as follows:

$$M_{f-} = \frac{P\cos\alpha}{2}\left[\frac{(X_C - X)^2}{X_C} - \frac{X_C(X_R - X)}{X_R}\right] \tag{5.39}$$

In order to determine the value of X for which the moment M_{f-} reaches its absolute maximum value, the following derivative is calculated:

$$\frac{dM_{f-}}{dX} = 0 \tag{5.40}$$

$$\frac{dM_{f-}}{dX} = \frac{P\cos\alpha}{2}\left[-\frac{2(X_C - X)}{X_C} + \frac{X_C}{X_R}\right] = 0 \tag{5.41}$$

which corresponds to:

$$X = X_C\left(1 - \frac{X_C}{2X_R}\right) \tag{5.42}$$

For this values of X , after some calculation steps the moment M_{f-} can be determined:

$$M_{f-} = \frac{PX_C\cos\alpha}{2}\left[\frac{X_C}{X_R} - \frac{X_C^2}{4X_R^2} - 1\right] \tag{5.43}$$

The maximum negative value M_{f-} is reached when X_R=X_C and the corresponding values are:

$$X = 0.5X_C \tag{5.44}$$

$$M_{f-}\min = -\frac{PX_C\cos\alpha}{8} \tag{5.45}$$

The best strut fitting is such as to minimize hood stresses, so that the absolute values of the positive and negative moments are equal:

$$M_{f+} = \frac{P\cos\alpha(X_C - X_R)^2}{2X_C} = -M_{f-} = -\frac{PX_C\cos\alpha}{2}\left[\frac{X_C}{X_R} - \frac{X_C^2}{4X_R^2} - 1\right] \tag{5.46}$$

After some steps, this expression becomes the following fourth degree equation:

$$(\frac{X_R}{X_C})^4 - 2(\frac{X_R}{X_C})^3 + \frac{X_R}{X_C} - 0.25 = 0 \tag{5.47}$$

When $\frac{X_R}{X_C}$ falls in the range between 0 and 1, this equation has the following solution:

$$\frac{X_R}{X_C} = 0.707 \tag{5.48}$$

This corresponds to the strut position that minimizes the hood bending stress.

The calculated value refers to the hood open condition, but a similar calculation can be made, in case of gas springs, in the maximum load condition when the hood is closed and locked. In that condition, the bent hood side border should always be aligned with fenders.

The hood lock includes a latch mounted on a body cross member and a striker fitted to the hood. The latch usually features two forks, one for standard locking and the other for safety locking, operated individually, the standard

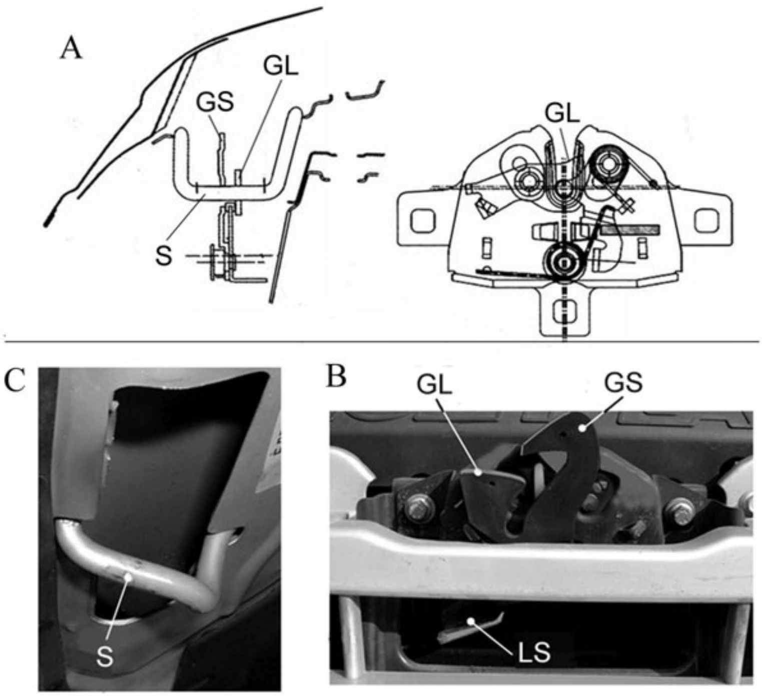


Fig. 5.182. Examples of hood latches, fitted to front radiator cross member. A: with split work (GL) and safety (GS) forks; B and C: one only fork for both functions; S: striker, welded to hood frame; LS: safety lever.

locking typically via a lever below the dashboard and the safety locking by a direct external lever (Fig. 5.182). The lever operation inside passenger compartment causes the first latch fork to rotate and let the hood rise under the action of dampers until retention by the safety fork is reached: this can only be operated by manual voluntary action from outside. The safety lever and fork must be designed in such a way that, even in the event of front end crush, the hood cannot be released. As the two fork can only move sequentially, they could be integrated into a single device, shaped in such a way to perform two consecutive rotations (Fig. 5.182-B.).

In addition to safety locking, the hood lock design should ensure protection to theft. For that purpose, the hood opening wire hose in the engine compartment must be protected using adequate covers.

The latch, positioned close to the longitudinal mid body plane and the two hinges provide the three isostatic dimensional constraints for the hood, but, in order to avoid vibrations and lack of alignment to body, two adjustable rubber dampers, positioned close to the side end, are usually included.

In the case of rigid support struts, the hood self-closing is performed by letting it drop from an appropriate height. In the case of gas springs, the hinges and spring pins are positioned in such a way that, for small opening angles, the gas springs feature the hood self-closing. Therefore, in any case, the hood reaches the closing position with some speed and its kinetic energy must be absorbed by elastic and damping pads in order to not exceed the maximum stress levels, specifically hood and body front cross member stresses. Moreover, the hood must be stopped before any contact, due to overrun or deformation, with headlamps which are usually adjacent to the hood.

A simple calculation can help understand the parametric values relevant to this event.

Considering the same hood used to calculate struts induced stresses, with a mass of 20 kg, i.e. weight P ≅ 200 N, the gravity center of which is at the middle of its total length X_C=1,000 mm. The potential hood energy E, when dropping from an angle α, is:

$$E = 0.5PX_C sen\alpha \tag{5.49}$$

The moment of inertia J of the hood, determined by considering a uniform mass distribution, is:

$$J = \frac{PX_C^2}{3g} \tag{5.50}$$

The kinetic energy at the run end is given by:

$$\frac{J}{2}\left(\frac{d\alpha}{dt}\right)^2_{end} \tag{5.51}$$

and, ignoring friction and aerodynamic losses, is equal to the potential energy E:

$$E = \frac{PX_C^2}{6g}\left(\frac{d\alpha}{dt}\right)^2_{end} = 0.5PX_C sen\alpha \tag{5.52}$$

$$\left(\frac{d\alpha}{dt}\right)_{end} = \sqrt{\frac{3gsen\alpha}{X_C}} \tag{5.53}$$

The speed V_f at hood front end, while contacting dampers, is:

$$V_f = X_C\left(\frac{d\alpha}{dt}\right)_{end} = \sqrt{3gX_C sen\alpha} \tag{5.54}$$

The corresponding energy must be absorbed by the dampers, the final deformation Z being related to E by the following equation (considering elastic springs of individual stiffness k without damping) :

$$E = 0.5(2k)Z^2 = 0.5PX_C sen\alpha \tag{5.55}$$

Therefore, assuming k is known, the final deformation Z, is given by:

$$Z = \sqrt{\frac{0.5PX_C sen\alpha}{k}} \tag{5.56}$$

Otherwise, for a given target of Z, the required damper stiffness k *is* determined:

$$k = \frac{0.5 P X_C sen\alpha}{Z^2} \tag{5.57}$$

Considering that the hood is dropped from height of 200 mm, thus with a starting angle of about 11°, if the maximum allowable deformation of the dampers is 10 mm, the required stiffness is:

$$k{=}0.5 \cdot 200 \cdot 1{,}000 \cdot \text{sen}(11°)/100{=}190 \text{ N/mm}$$

Which corresponds to a dynamic damper load of:

$$R_T = kZ{=}1{,}900 \text{ N}$$

The hood speed at first damper contact should be:

$$V_f = \sqrt{3 \cdot 9.81 \cdot 1 \cdot \text{sen}(11°)}{=}2.37 \text{ m/s}$$

and the energy absorbed by each damper is:

$$\frac{E}{2}{=}0.5kZ^2{=}0.5 \cdot 190 \cdot 100 = 9{,}500[\text{Nmm}]{=}9.5 \text{ J}$$

Even in the case of gas springs, the hood drop before dampers reaction is initiated should be only a few centimeters.

Moreover, the damper usually has a progressive stiffness and some damping; therefore the calculated values are a first approximation. In any case, these estimations provide an order of magnitude regarding an event that could result in relevant local deformation and contact with weak components such as headlamp glass.

In practice, the dampers height is typically a few centimeters, while their fastening type shall allow height setting, in order to position the hood in the static condition with a maximum misalignment of 0.5 mm with a small pre-load, in order to restrict vibrations and maintain a constant attitude.

Hood delivery testing

In addition to torsion and bending stiffness testing, with respect to oligocyclic slamming fatigue and denting caused by manual pushing or by stones, a hood must also comply with pedestrian and barrier impact safety testing.

The most critical test is usually pedestrian head impact, specified by the rating Euro NCAP, performed by two metal spheres which simulate the head of a child (2.5 kg) and an adult (4.8 kg), launched at 40 km/h against a number of specified points on the hood, at angles of 50° and 65° respectively (with respect to the horizontal).

The rating parameter is the Head Injury Criterion (see Volume II).

As previously mentioned, the critical design aspect of this test is the primary influence on head mass acceleration of the empty space available under the hood in addition to the hood stiffness. The empty space is established by the shape of the body and by the position of rigid subsystems in the engine compartment.

Dividing the allowed HIC limit (1,000) by the time interval of 15 ms (therefore 0.015 s), and calculating the root with exponent 1:2.5, the average acceleration a_{med}(g) allowed in the same interval can be determined:

$$a_{med} = (\frac{1000}{0.015})^{0.4} = 85 \text{ g} \tag{5.58}$$

Supposing that the average hood slope be 10°, the worst case hitting speed component V_T, orthogonal to the hood surface, of the sphere simulating the head is:

$$V_T = (\frac{40}{3.6})\text{sen}(65° + 10°) = 10.7 \text{ m/s} \tag{5.59}$$

Considering the most effective pedestrian protection condition, the reaction to the sphere and thus its acceleration is constant, and the relationship between the sphere stopping distance S , the sphere average acceleration a_{med} and the launch speed V_T is given by:

$$S = \frac{V_T^2}{2 \cdot 9.81 a_{med}} = \frac{10.7^2}{2 \cdot 9.81 \cdot 85} = 0.068 \text{ m} \tag{5.60}$$

In real cases, the acceleration will never be constant, and the recommended target HIC shall be lower than the HIC limit (1,000). Therefore the overall specified crushable space (hood frame plus empty space below) is up to 100 mm.

If such dimensional layout is available, according to body styling and adequate room in the engine compartment, the main design task becomes hood frame dimensioning. Otherwise, some active hood lifting systems must be adopted, controlled by a sensor system capable of identifying imminent pedestrian contact and operated by sufficiently rapid actuators (in practice, capable of lifting a hood in less than 45 ms). A number of different systems, mechanical and pyrotechnic, are currently available (Fig. 5.183).

Regarding front barrier impact, the hood should never penetrate the cabin space through breakage of the windshield. For this reason, the usual design falls into two families of solution: one featuring hinges and hood rear end clamping, the other central hood bending collapse.

The first is performed by hooks on the front body frame, capable of clamping the hinges and slots of the hood frame (Fig. 5.184).

The second is obtained by a local frame weakening (e.g. a smaller local section) in the central region of the hood. This weakening has no influence on the hood stiffness, but becomes the principal buckling section when the hood is compressed during frontal impact. As a consequence of collapsing, the hood becomes completely bent, rising the mid section and losing longitudinal stiffness.

5.4.6 Sunroofs

This chapter deals with the partially open roof, therefore excluding soft top and hard top for spiders and convertibles, already covered in a previous chapter.

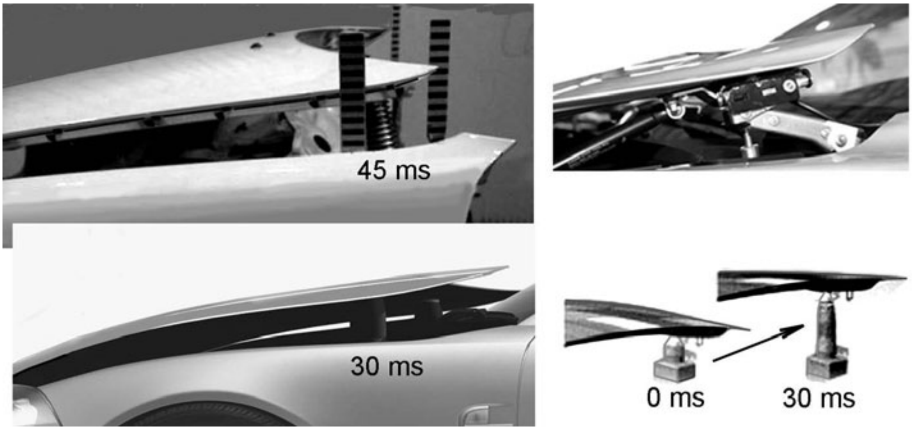


Fig. 5.183. Examples of mechanical (above) and pyrotechnic(below) devices to lift the hood in case of pedestrian impact. The operating time is in the range 30 to 45 ms.

Usually sunroofs are fitted to Sedans and Station Wagons. Their dimension in the X direction can vary between 200 and 1,100 mm, and in Y between 600 and 1,100 mm. They provide a number of benefits (cabin sunlight, sky visibility, outdoor feeling, increase of natural air flow, winter cabin heating with open sunroof, quick release of overheated air from cabin after a summer stop) offset by a number of relevant problems (waterproofing, rustles and turbulence at speed higher than 80 km/h, breaking risk when made of glass, cabin inner height reduction, dynamic body stiffness reduction).

The most common families of sunroofs are (Fig. 5.185):

- inbuilts, single metal or glass panel, sliding or tilting or pop-up;
- plastic coated fabric folding roofs;
- double panel or multiple stack panels, glass or metal.

Depending on production rates, car manufacturers can choose between two options: a) in house manufacturing of cars with cut roof, prepared to accommodate the sunroof module including frame and movable parts; b) transfer the operations of roof cutting and module insertion to external specialized body makers.

In both cases, the drawn roof panel, following cutting and down flanging of top opening, is stiffened by a frame, welded and adhesively bonded to the roof, featuring a channel to drain leakage water with small pipes in the edges close to body pillars where plastic drain hoses are fitted. In some cases, the top opening frame is assembled with roof bows (Fig. 5.186).

In the case of a glass sunroof, the supporting frame can be either single, screwed to the roof frame, or split, the two pieces being screwed either side

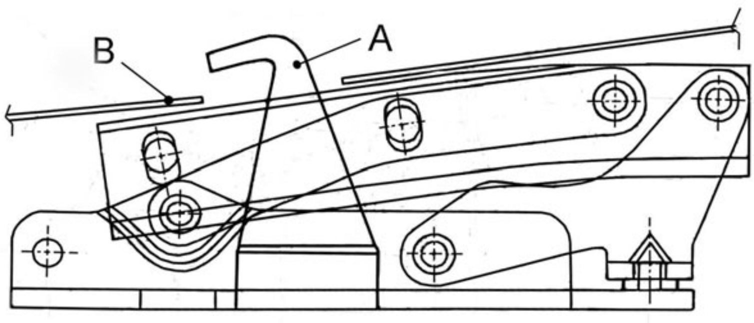


Fig. 5.184. Example of hook (A), integrated in the fixed half hinge, the task of which is to clamp firmly the hood frame (B), in the event of hood backward displacement during a frontal impact.

of the roof: in such solution, an external bezel is visible on the roof, but the precision required for mounting is much lower (Fig. 5.187).

The sunroof modules include a significant number of components for each individual task including: hinges, lift devices, slide rails, curtain rolling, made of plastic or cast aluminum (Fig. 5.188).

For water drainage, the hose size is usually not less than 7.5 mm; regarding materials, Rubber or Vinyl or Polyammidic plastic. PVC (for hot collapsing and narrow curves buckling) and Polypropylene (for heavy stiffness) hoses are not recommended. The minimum recommended curvature radius is 3 times the outer hose diameter.

Specifications and delivery testing

Typical sunroof performance specifications are:

- dimensional roof panel tolerances (max range ± 0.3 mm);
- Z and Y adjustment allowed (± 1.5 mm);
- maximum Z deformation while travelling: $<$ 2 mm for stiff sunroofs and $<$ 20 mm for fabric roofs;
- weather strip extraction load ($>$ 80 N/dm);
- overall components reliability, for a number of operation cycles up to 5,000 (average customers use) or to 12,000 (to grant 90% of customers). Fatigue testing must be performed in climatic chambers, with temperature cycling referred to standing vehicle (from –40°C to +90°C) and travelling vehicle (from –20°C to + 80°C) and relative humidity up to 95%;

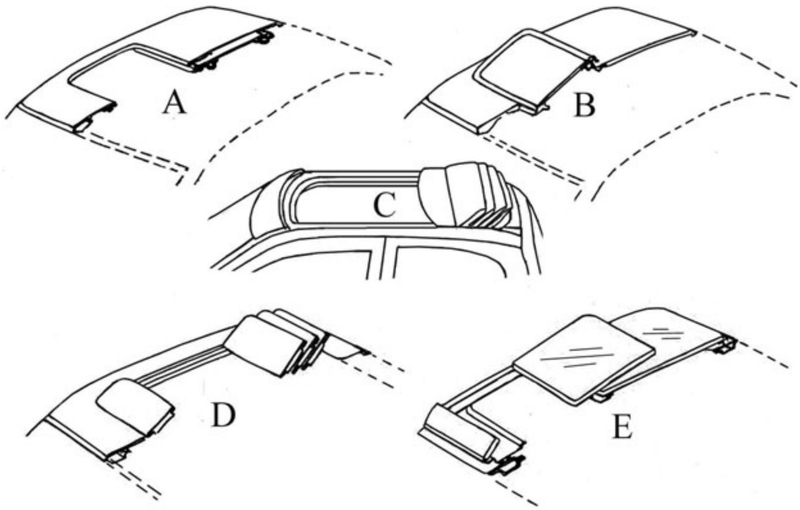


Fig. 5.185. Most usual sunroof families. A: single panel inbuilt, sliding inside; B: tilting or pop-up; C: fabric folding; D: multiple stack panels; E: two panels.

- regarding corrosion, all components facing wet conditions must comply with 500 h resistance in salt fog, whereas all other components with 100 h.

5.4.7 Window Glass Regulators

The task of the window glass regulator is to raise and lower the door window glass; in the chapter on doors, the glass and glass rails design and testing have already been covered.

Since the glass connection to the rails is performed using pins and brackets, it can sometimes happen that, due to the lack of supports or weakness, regulators become stressed by additional loads with respect to the usual up and down motion.

Today, in practice all window glass regulators are powered by electric motors; correspondingly the following description is limited to these systems. With respect to manual operation, the difference relates only to the energy being supplied by a handle instead of an electric motor.

Window glass regulator families

The following families can be distinguished:

1. arm and sector (pantograph and single arm);
2. single lift drum and cable (with or without wire hose);

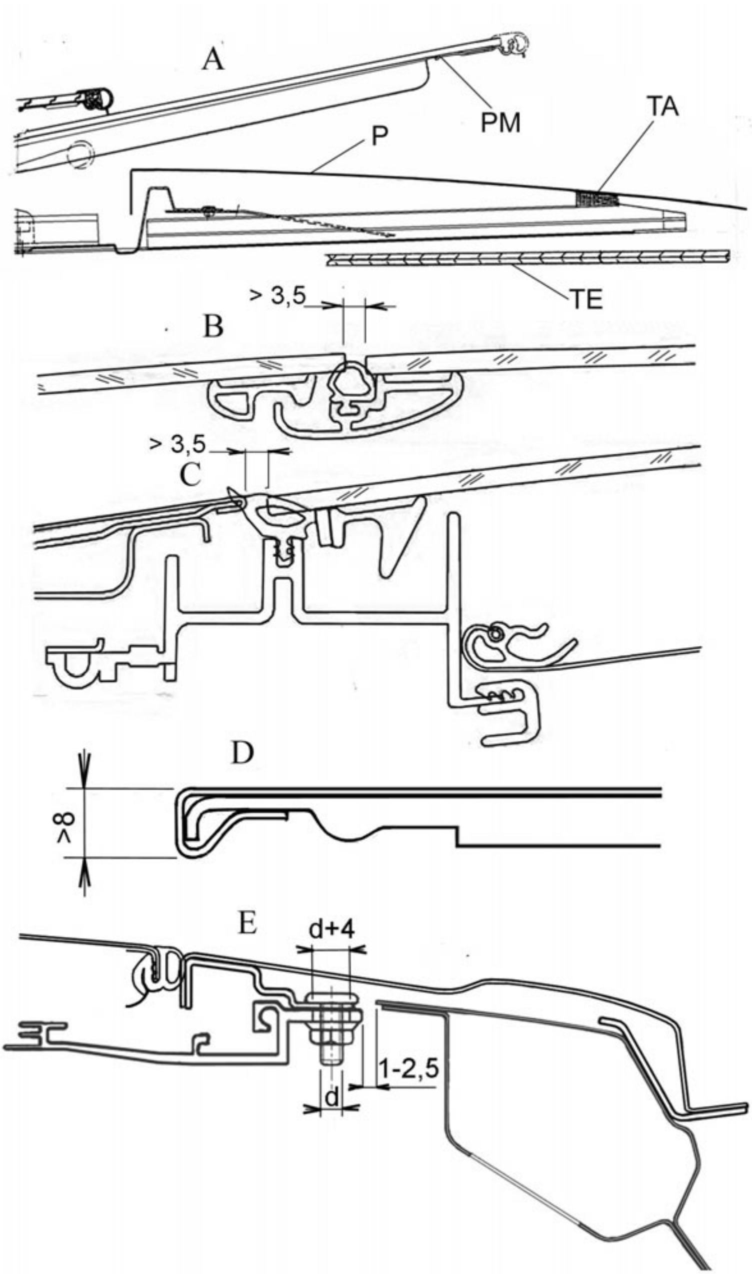


Fig. 5.186. Examples of different sunroof sections. A: sliding over roof P; PM: tilting movable panel; TE: trim curtain; TA: damping pad; B, C: glass multiple panels with the minimum specified gap between two glasses; D: metal sunroof; E: side section with critical dimensioning.

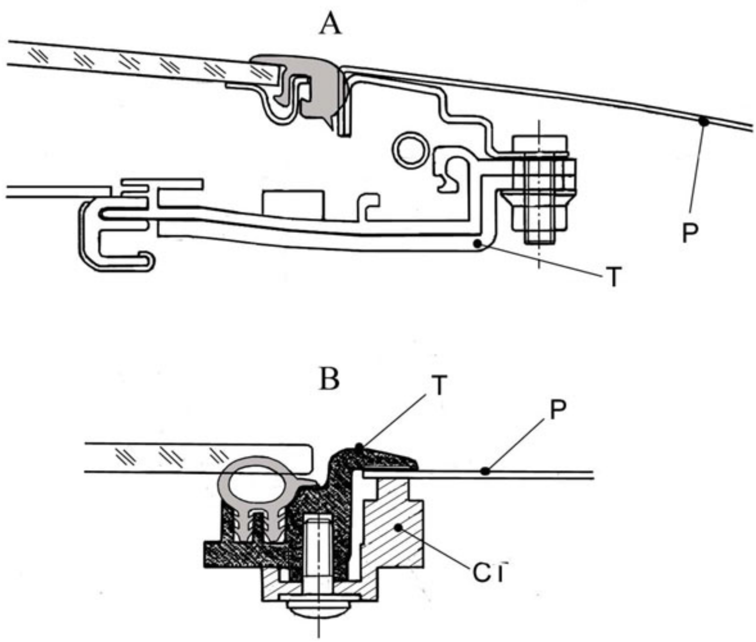


Fig. 5.187. A: glass sunroof carrying the weather strip, the frame being screwed to roof P; B: glass sunroof with weather strip fitted to frame T, screwed to an auxiliary frame CT with the roof panel P in between.

3. double lift;

4. worm type.

The appropriate selection relates to glass weight and supported loads, the door family type (with window frame or frameless), glass rails type, glass curvature, level of reliability and, of course, to cost.

Pantograph regulator

Fig. 5.189 illustrates an example of pantograph arm and sector regulator; the lifting mechanism includes two levers joined at the middle to form an X shape. When the horizontal levers end span is lowered, the mechanism height increases and the glass connected to the **e** rail is lowered. The figure shows the mechanism in an intermediate glass position. The A and B levers are joined close to their mid position. The B lever is divided into two welded pieces, enabling the rotary motion with respect to A; the joint is free from door constraints.

The **d** end of lever A is pin joined to the door inner panel and carries a toothed sector **b**, engaged by the **a** motor pinion. By inverting the motor polarity, the A lever can be rotated in two directions. The other three ends of the X mechanism

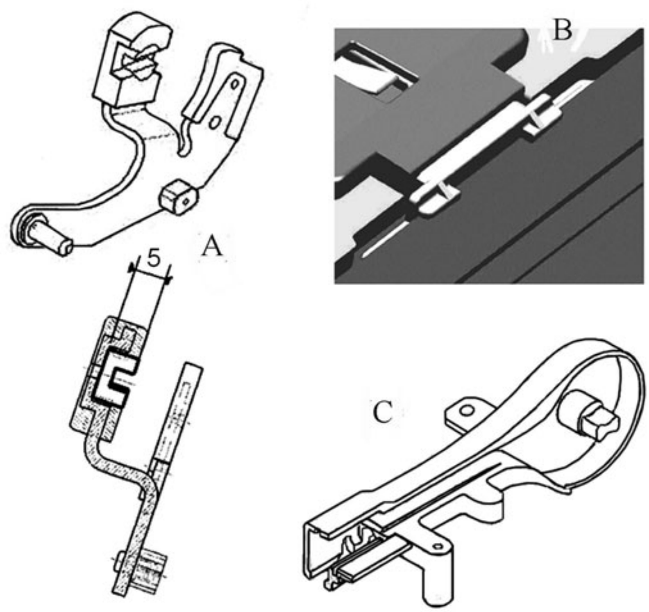


Fig. 5.188. (A): rear tilting lever for multiple panels sunroofs, with detail of a plastic insulating bush; (B) curtain slider; (C): curtain rolling support.

are free to slide inside rails **c** and **e**. Rail **c** is clamped to inner door panel, while rail **e**, where the last two X ends can slide, is clamped to the glass. Through rotation of the A lever, the angle between A and B changes, but the angle bisector direction, determined by the lines that connect the four joints, remains unchanged (vertical). This bisector establishes the glass displacement direction that is therefore rectilinear.

The glass is fastened at both ends of the movable rail using plastic clips, an example of which is shown in Fig. 5.190. The elastic bush **a** can be seen: its task is to avoid stress concentration on the glass and on the tooth **b** that engages the lower glass area in an appropriate sliding guide.

In the same figure, the sections show the mechanism dimensions. These devices must be far enough from door inner panel to avoid contact and thus vibrations or deformation of the entire loaded system.

Single arm regulator

For medium or small glass sizes, the above mechanism can be simplified to a slider-crank mechanism, in which the toothed arm is the rod, the end of which is engaged in a glass driving rail by a sliding connection, as can be seen in Fig. 5.191-A.

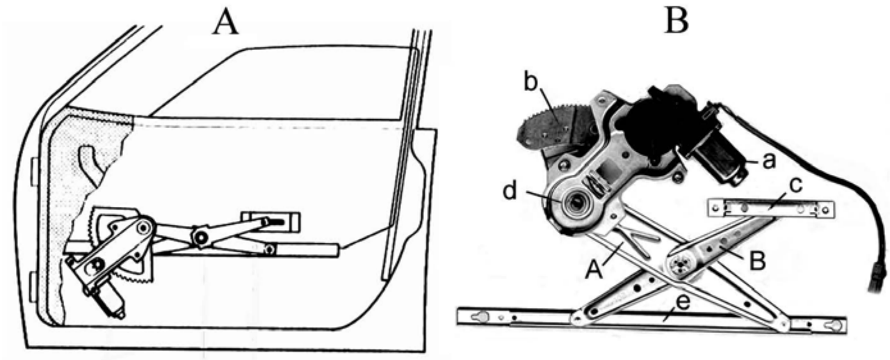


Fig. 5.189. Example of pantograph window glass regulator installed in the door (A) and regulator details (B).

Wire type regulator

The most simple regulator of this type has one single guide (Fig. 5.192), which carries a plate, denoted **a** in the figure. The bracket is pin joined to the glass (see Fig. 5.190). A metal wire **b** is clamped to this bracket and guided by two plastic hoses **c**, so as to meet the appropriate pipes. The cable is wounded over a drum **d**, actuated by an electric motor. The pipes **c** can be missing when the cable is in the plane established by the rail connection points and by the drum wound position.

An example of rectilinear guide, without pipes, is also shown in Fig. 5.191-B. The need for pipes is established by the space available inside the door cavity.

Double lift regulator

When glass size is high and/or the glass driving is performed by discontinuous door channel rails, a single guide is not sufficient to control tilting glass motion. In that case, two solutions can be adopted. The first is to glue on the back glass side a small slider, driven by a proper weather strip, located in the door back frame. The second solution, increasingly used, is to adopt a double lift regulator, connecting two sliders and the motor drum with a single cable, following figure "8" path (see Fig. 5.193).

Worm type regulator

Another wire regulator variant is shown in Fig. 5.191-C. In place of the wire, a flexible metal worm is used to both pull and push. In the last configuration it appears as a compressed spring: the outer spring profile, similar to a thread, can engage a wheel, along a defined sector, featuring a worm matching profile and actuated by an electric motor. The free end of the worm must be guided adequately and shaped according to the door obstructions.

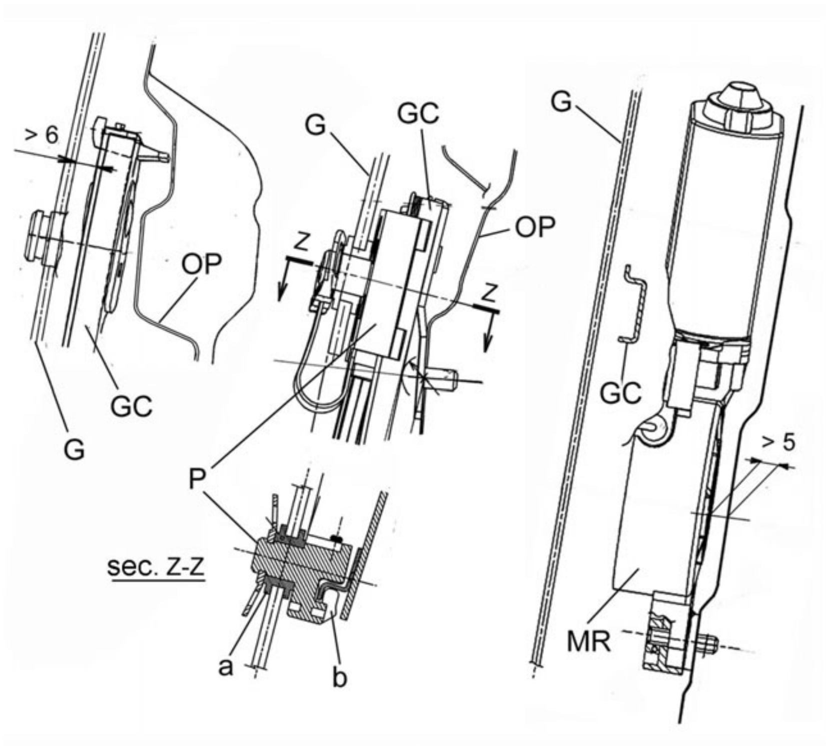


Fig. 5.190. Details of regulators drive pins and recommended minimum distances. OP: door inner panel; G: glass; GC: glass guide; P: slider vith clip on glass; MR: motor; a: elastic bush; b: engaging tooth.

Selection criteria

A statistical analysis of 130 European, Japanese and U.S. vehicles of different sizes, on the road in the year 2000, resulted in the breakdown shown in Fig. 5.194.

It can be noticed that pantograph regulators are more frequent in the case of large glasses or complex door channels (front doors, frameless window doors), often replaced by double lift regulators.

Single lift drum and cable regulators form the great majority in rear door applications (as glasses are smaller and more guided by door frame) and are used frequently on front doors, preferably together with a glass guide slider on door back frame.

Single arm regulators are frequently used on rear doors.

Instead worm type regulators are gradually disappearing.

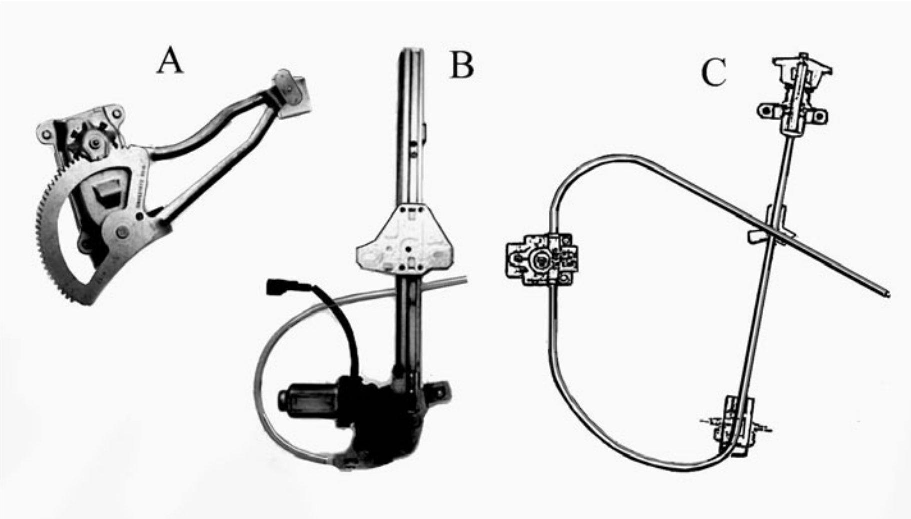


Fig. 5.191. Examples of regulators. A: single arm; B: rectilinear single guide; C: worm type.

Conceptually, pantograph regulators can support heavier loads and restrict glass tilting. The single lift and single arm regulators have a lower component cost.

Properties and specifications

The window glass regulator selection is made according to the above mentioned criteria.

The main specifications relate to kinematics (overall run, longitudinal and transversal freedom limit), treatment against corrosion of metal components, and surface treatment against friction of coupled components. Even the lubricant grease can be specified.

Regarding door fittings, it is important to note that fastening stiffness should be provided and access left to set the right 3 D position, in order to enable the correct positioning of mechanism, guides and glass with respect to door weather strips.

Manoeuver loads

In principle, manoeuver load is less important in the case of electrically actuated regulators. Nevertheless, even in this case, the required operating load should be as low as possible, as should the load changing along the up and down path. These phenomena are connected to the stick and slip mechanism; therefore it can be useful to specify not only the average reference and tolerance values, but also variance limits related to the regulator path. The load control is referred

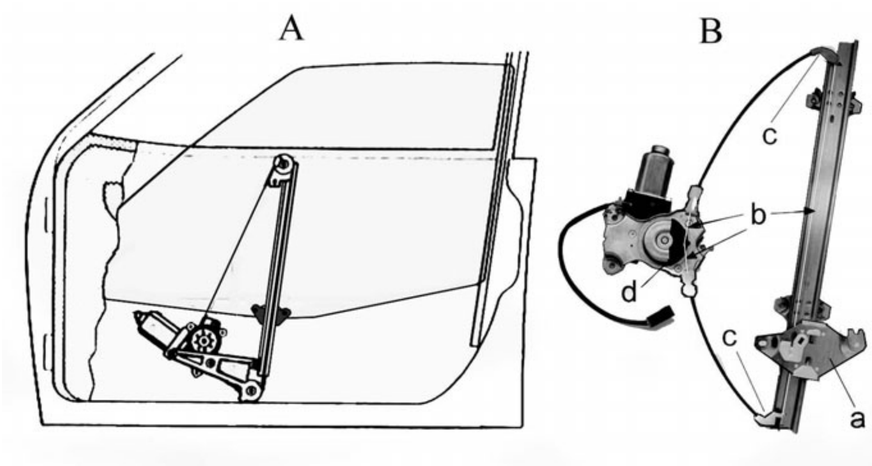


Fig. 5.192. Example of installation (A) and single drive wire regulator details (B); a: sliding plate; b: wire rope; c: connecting pipes; d: drum and motor.

to the absorption of electrical current and to circuit protection limits. In some applications, a low operating load allows the current absorption measure to be used as the threshold value to invert the regulator direction automatically; for instance, to prevent any risk of injury due to trapping a human part between door and glass, as requested by law.

It must be remembered that regulators load is not only related to the mechanism but also to glass, guides and weather strips installation quality. It is recommended to specify load limits even at extreme temperature (from –30°C to + 70°C) depending on vehicle use.

Reliability target

Even in the case of window glass regulators, the system durability target is the same as the entire body, without any service or part replacement. In order to comply with that target, window glass regulator reliability testing is made not only on the individual subsystem, but also on the completely trimmed door, mounted on real body sides. The fatigue tests are performed by door slamming at controlled speed, as the dynamic door deformations and the inertial component connected to regulator can apply their real stress conditions. The door operation cycles by customers can be considered to be 10,000/year for front doors and 3,000/year for rear doors. The average window glass rising and lowering cycles can be considered 3,000/year.

The operation loads must be within the specified range, even at component life end.

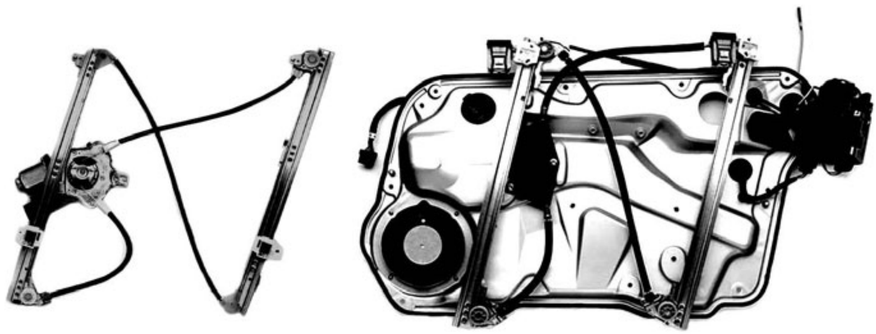


Fig. 5.193. Examples of double lift wire regulators, separate (left) and when fitted to the carrier (right).

Component evaluation

Rain chamber and humid-static chamber : the purpose is to verify the presence of water or humidity inside components, after rain or wash and the absence of operating loads change, due to corrosion.

Acoustical component characterization: the purpose is to specify noise reference values for up and down motion, door opening and closing.

5.5 Windshield Wiper

In this chapter, windshield and rear wipers as well as sprayers are examined.

The rear wiper is usually used on one-box or two-box cars or, in general, by vehicles on which the backlight aerodynamic flow exhibits heavy turbulence and therefore sprays water and mud from the wheels onto the back of the vehicle, while the boundary air speed is too low to clean off drops of dirty water.

The primary task of the windshield and rear wiper, to be considered also in terms of contributing to accident prevention, is to enable an acceptable outside visibility, wiping off water, mud or snow from the front and rear glass surfaces. With additional water sprayers, wipers must be able to clean the same surfaces, even if splashed by powder, mud or other solid contaminants.

Being a part of the vehicle safety system, wipers must comply with international regulations.

The main wiper system components, shown in Fig. 5.195-B, are:

- wiper blades (1), the task of which is to brush off water and included solids from the glass;
- arms (2), to drive the blades and press them against the glass with the specified load;

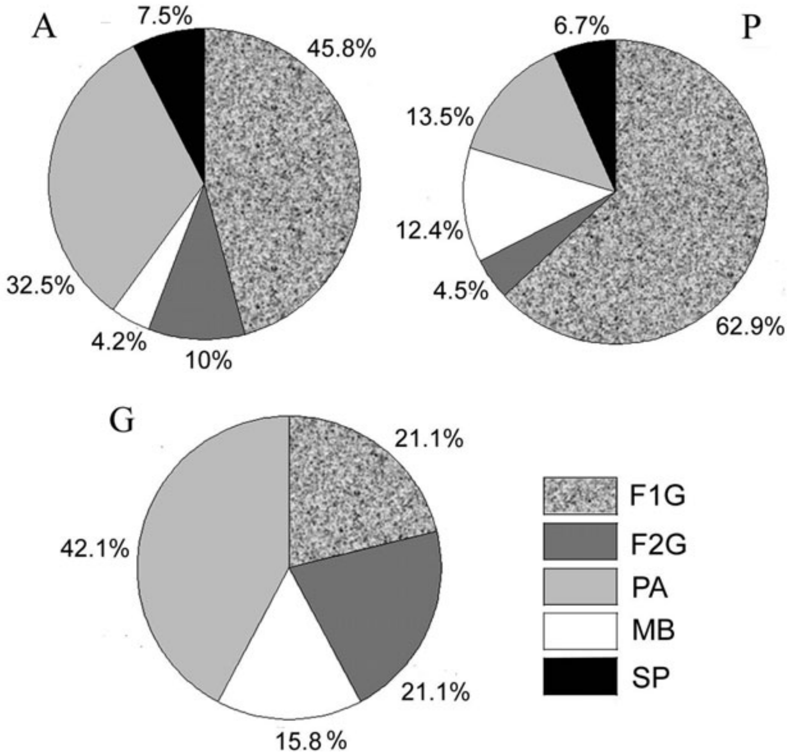


Fig. 5.194. Window glass regulators share on front (A), rear (P) doors with window frame, frameless window (G). Sample of 130 cars - year 2000. F1G: single lift wire regulators; F2G: double lift, wire regulators; PA: pantograph; MB: single arm; SP: worm type.

- the electric motor (3), to move the arms;
- the articulated system (4), which transforms the rotation of motor shaft into alternate arms rotation;
- the structural frame (5), which supports the assembly; its main task is to carry the assembly components, fitted and tested before car matching and to insulate car body from noise and vibrations from the different components.

Regarding the rear wiper, shown in Fig. 5.195-A, the system is simpler because the blade is single and therefore the parts are:

- the wiper blade (1);
- the arm (2);

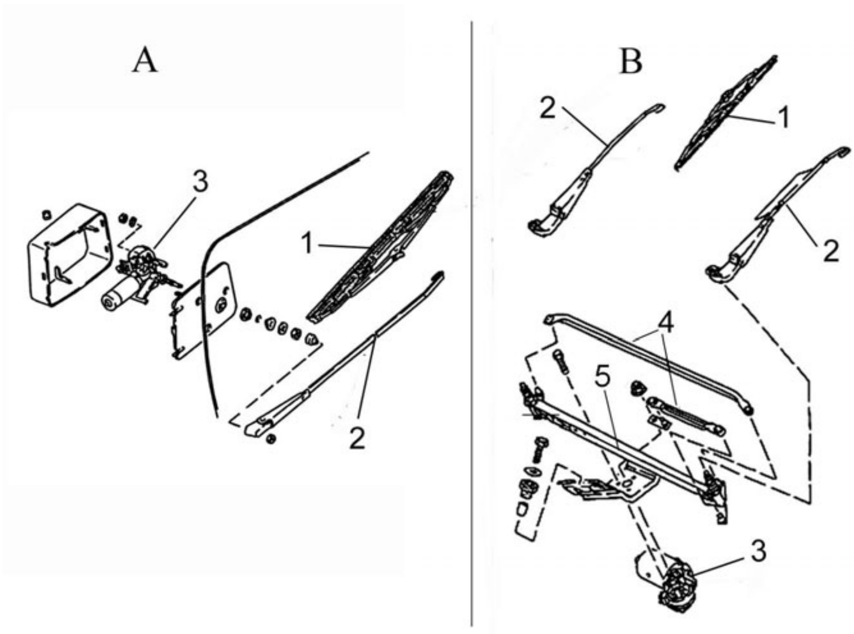


Fig. 5.195. A: rear wiper parts; B: windshield wiper parts.

- the motor (3), which includes the functions of structural frame and articulated system.

In both cases, the wiper system includes sprayers that can be independent or carried by wiper arms.

Wiper components

The rain brush presses against the glass an elastomeric blade, visible in Fig. 5.196: in details A and C, a view of the blade end is shown; detail B illustrates the rubber section of the wiper blade. The section is usually made up of two different elastomeric materials, 1 and 2. Part 1 has a lower hardness and therefore has a lower elastic modulus to provide the necessary flexibility. Part 2 has a higher hardness, higher stiffness and relevant abrasion resistance.

Part 2 is characterised by two edges 3 that press against the glass with the required pressure, in order to brush off water and mud. Part 1 has a narrower section that supplies lateral instability and two cantilevers 4 to limit side blade deflection in both wiping directions.

Part 1 is stiffened along its length by a metal elastic profile, which can be snapped on side ribs (as shown in detail B) or inserted into a cavity of part 1 (as shown in detail A). The stiffener helps press against the glass with sufficient pressure, even at some distance from the bow claws (one of them is shown in

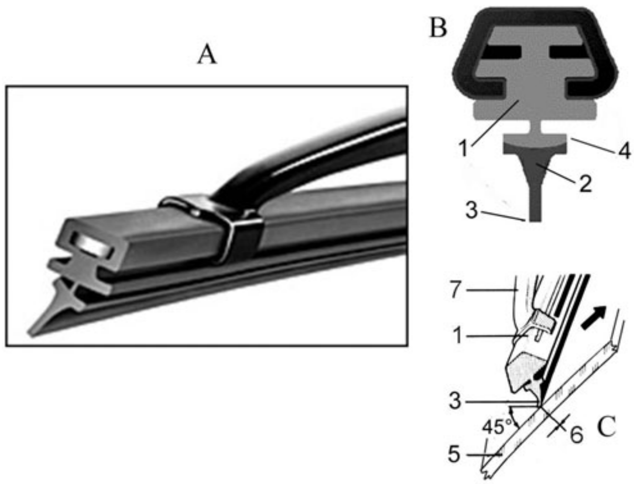


Fig. 5.196. Details of a traditional wiper blade.

detail C with number 7). Moreover, it allows the blade to change its curvature as a function of different glass contact positions.

Detail C shows the working attitude of a blade, according to the wiping direction, shown by the arrow. Due to the cited cantilevers, the blade contact end 6 is sloped about 45°, with reference to glass surface, in order to maximize contact pressure; the glass reference in the section is number 5.

The blade is pressed against the windshield by the load applied by wiper arms connected at mid blade, through a joint leaving a free rotation around an axis parallel to wiping direction. The joint load is shared by a set of bows, according to claws distance and independent of the blade configuration.

In Fig. 5.197, detail A shows an arm with two rank bows and three loading claws; in detail B a system with three rank bows, the first one (connected to the blade) features 8 claws, equally distributed. A second rank of two bows divides the load among four equal forces, applied to the mid points of first rank bows. In the same way, the third rank (one bow only) loads the second rank bows. In detail C, uniform load sharing is obtained by appropriate bow joint positions.

Through its bending stiffness, the blade is designed to avoid significant contact pressure reduction along the span between the claws. In fact, if the blade were infinitely flexible and extendable, the blade force on the glass would be zero except at the claw positions. Curve A in Fig. 5.198 shows a qualitative contact pressure distribution along this type of blade: it can be noticed that the diagram exhibits peak values at the claws and lower values away from the claws.

In the same figure, another load distribution for a different blade system is shown: in this case, the blade stiffener is a metal profile with a co-molded

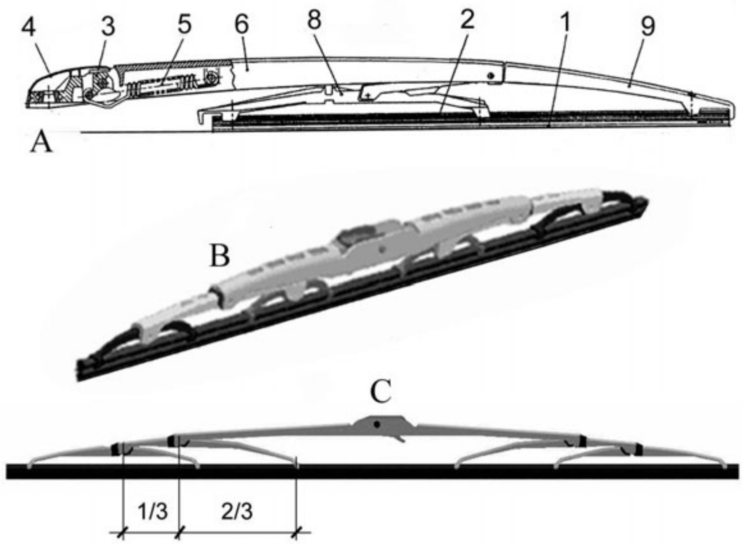


Fig. 5.197. Parts of a wiper arm (A) and examples of different blade supporting systems (B, C). 1: blade; 2: blade housing; 3: joint; 4: clamp; 5: spring; 6: arm body; 8: internal bow; 9: external bow.

elastomeric blade. In the free condition, the profile is bent (Fig. 5.198-C) in such a manner that in the glass contact condition, due to arm load, the profile curvature is lowered and the blade pressure becomes more uniform. The result is shown in diagram B of Fig. 5.198. In this case, the blade is more simple and can include a plastic profile (Fig. 5.198-D) with a spoiler effect, meaning that an aerodynamic load on the blade occurs, helping to avoid its lifting under certain wind conditions.

The arms press the blades against the windshield surface. Fig. 5.199 shows the system at rest. The arms have two joints: the first, closer to wiper pin, allows arm manual lifting for service and applies a specified load to the blade. The second shares the contact load uniformly between the two blade sides and allows their angle to follow the windshield slope. These two arm joints are approximately parallel and in practice their axis is orthogonal to the wiping rotation axis. The arms are usually fastened to their pivots through tapered toothed shafts.

One of these arms is displayed in Fig. 5.200-A, where the above view is from outside the car and the lower view from inside the car. In the lower view, a spring can be seen, the load of which defines the blade pressure against the windshield. The requested load at wiper blade joint is about 15 N/m, in the orthogonal direction to the glass surface: the load is related to the blade length. Some windshield wipers can move their post axially, according to vehicle speed, in order to vary the blades contact pressure, influenced by aerodynamic loads.

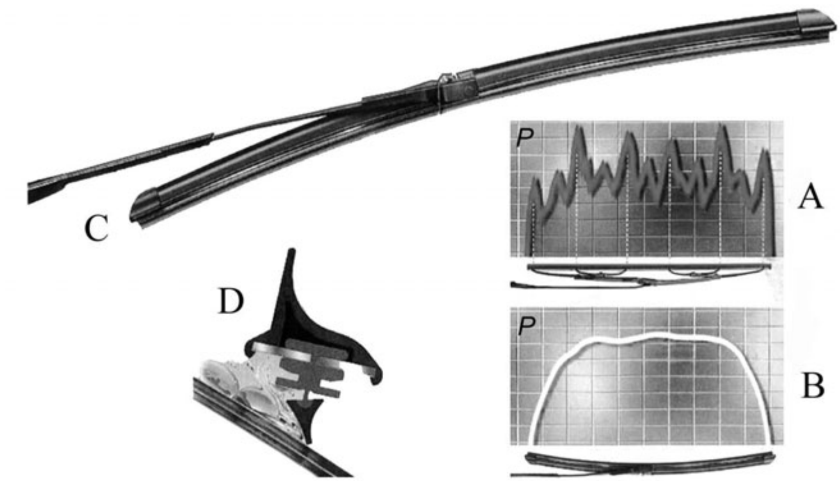


Fig. 5.198. Examples of a blade (C) with pre-bent stiffener; blade pressure qualitative diagram (A, B) for two blade types; blade with spoiler (D).

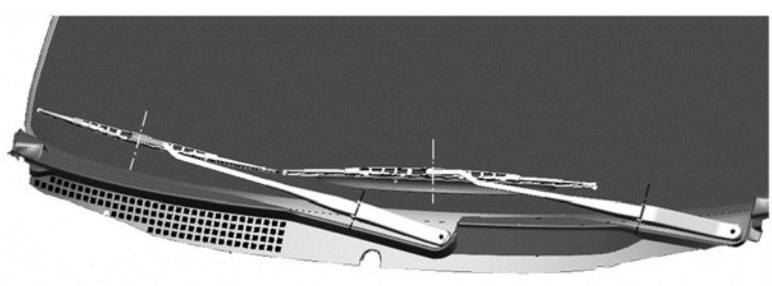


Fig. 5.199. Usual rest wiper position on windshield.

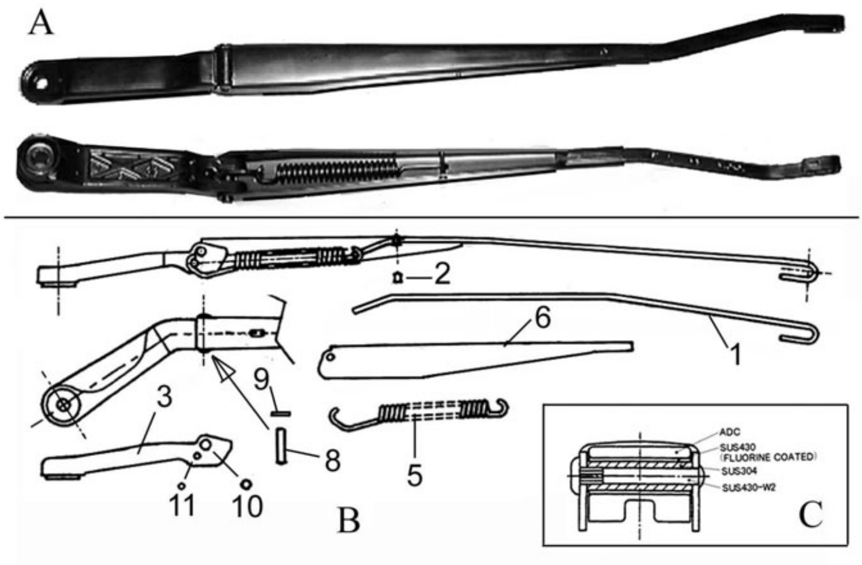


Fig. 5.200. Pictures of a wiper arm (A), a split view of its parts (B) and detail of a joint (C). 1: shaped stick; 2: rivet; 3: clamp; 5: spring; 6: body; 8: main joint; 9: washer; 10: bush; 11: spring pin.

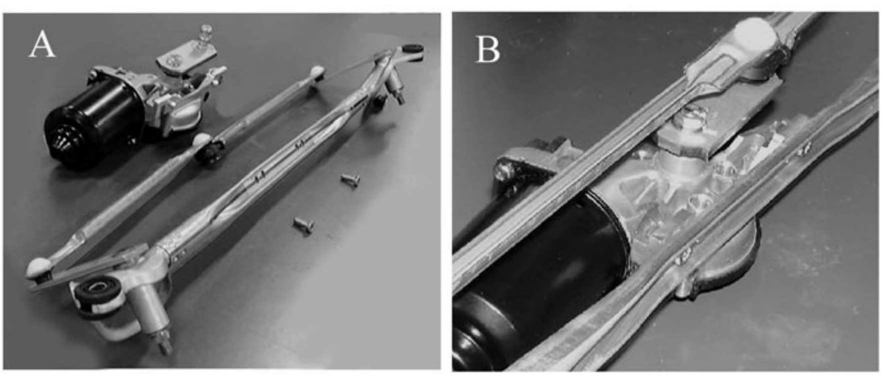


Fig. 5.201. Wiper driving system assembly with split motor (A) and detail of the motor connection to drive crank (B).

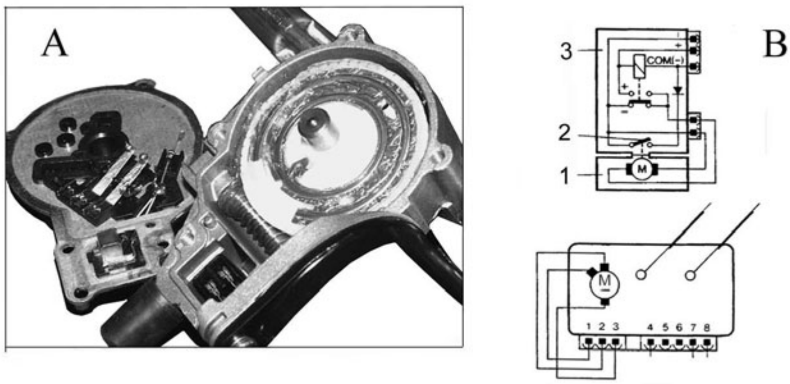


Fig. 5.202. Open wiper reduction gear (A) and electric scheme of the wiper system (B).

The driving system is shown in Fig. 5.201-A, where the kinematic drive system (in this case, a double articulated quadrilateral), the spherical joints (steel pin, nylon housing) and the split motor can be seen. The arm pivots are fastened to a structural bar, fitted to the body through two rubber bushes, for noise and vibration insulation.

The attachment forces are relevant: in fact, the average friction coefficient between the glass and blade can vary from 0.1÷0.6 on wet glass to 1÷2.5 on dry glass. In the case of two blades of length 600 mm, driven by 400 mm long arms, if the force per unit length is 15 N/m, the resulting moment on frame and motor could be 18 Nm.

Fig. 5.201-B shows a detail of the motor fitted to the support frame and the crank that drives the articulated quadrilaterals. The motor assembly, shown open in Fig. 5.202-A, includes an electric DC motor with collector, a permanent magnet stator and an endless screw reduction gear. The helicoidal wheel, usually made of nylon, has two contact paths, one of them being interrupted at an angle position consistent with wiper blades parking position. Two sliding contacts, made of copper blades, close the electric circuit with the two connected paths.

Fig. 5.202-B shows the motor electric control scheme. The motor collector is connected to two brushes, shown in the lower part of the figure. The brushes are connected to the commuting relay COM, shown in the upper part of the figure. In the present position, the motor is fed through the main brushes. In the other position, the main brushes are not connected, while a third brush is connected, until a series contact, which represents the contact paths on the wheel, becomes open. The motor then rotates until the blades are in their parked position.

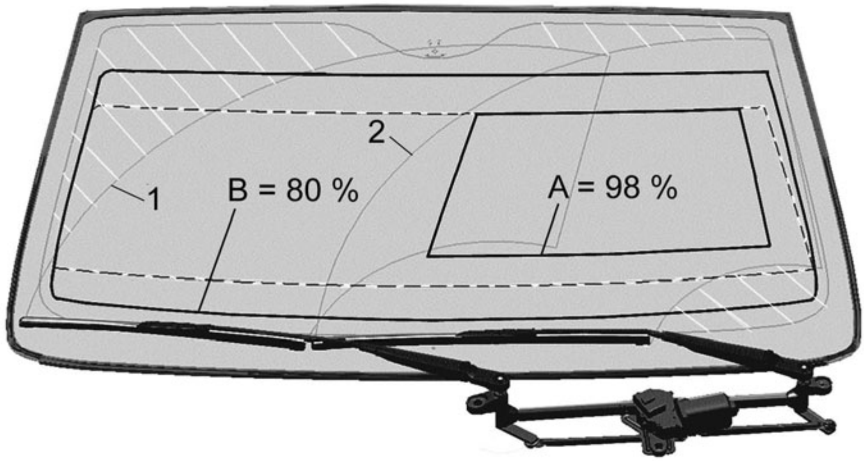


Fig. 5.203. Wiper blades brushed off area (1, 2) projected on the windshield and compared with the least visibility area A, B requested by International Regulations.

The above system performs the action illustrated schematically in Fig. 5.203. The different working angles of the blades, required for adequate cleaning (corresponding to continuous lines 1 and 2) of both sides (driver and passenger) can be seen. On the same figure, the border of the silk screen, that defines the transparent area of the windshield area. Two black continuous lines define the cleaning areas A and B according to regulations. The white dotted lines show the remaining non brushed areas.

It is important to observe that, in order to maximize the clean area, the blade on driver's side must be parallel to the windshield border in both run-end positions and, for the same reason, the passenger's side blade must be parallel to the windshield border in the parked position. Moreover, there is a central area where the windshield is wiped by both blades.

In principle, the different regulations are similar. European law defines two areas, respectively primary (A) and secondary (B), according to the driver's and passenger's visibility ellipsoids, displayed in Fig. 5.203. The first area corresponds to the windshield direct vibility zone. At least 98% of area A and 80% of area B must be brushed off by the operation of the blades .

Sometimes, in order to achieve an adequate cleaning, different length blades and different operation angles are needed. As a consequence of the above explained law, the shown system must feature a different design for right and left hand drive.

The driver's side blade length, measured on production cars, is between 400 and 700 mm whereas on the passenger's side it is between 350 and 700 mm.

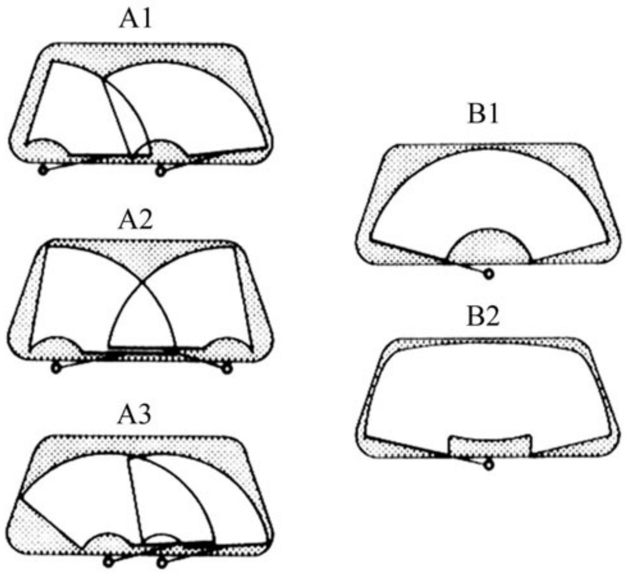


Fig. 5.204. Most common twin and single windshield wipers layouts.

Alternative wiper layouts are shown in Fig. 5.204. Schemes A1, A2, A3 refer to double blade wipers, with different driving kinematics. Of course the absolutely optimal layout does not exist, but the adopted solution is selected as a function of windshield surface shape. The symmetrical solution A2, for a relatively large windshield, has the advantage of complying with right hand as well as left hand drive vehicles.

Solutions B1 and B2 need one arm only. Solution B1 is compatible only with windshields with a width which is twice the height, meaning narrow cars: its advantage is a relevant cost reduction, offset by the fact that a large central windshield portion cannot be wiped. Solution B2 needs an additional radial arm displacement, provided using a gear complex mechanism, which enables an extensive clean area despite being one blade only.

Good performance can also be achieved without the complexity of the previous solution, with a passenger side wiper featuring a virtual center pivot, through an appropriately articulated quadrilateral. As shown in Fig. 5.205, the unwiped area can be reduced significantly. It can be noticed that, in this case, the wiped area is extended to the silk screen lower area over a large surface. The windshield must therefore be extended below the hood rear border in order to hide the arms and blades in the parked position. The main advantages are in terms of aesthetics and aerodynamics. There is no visual obstruction of the wipers when the system is not in use.

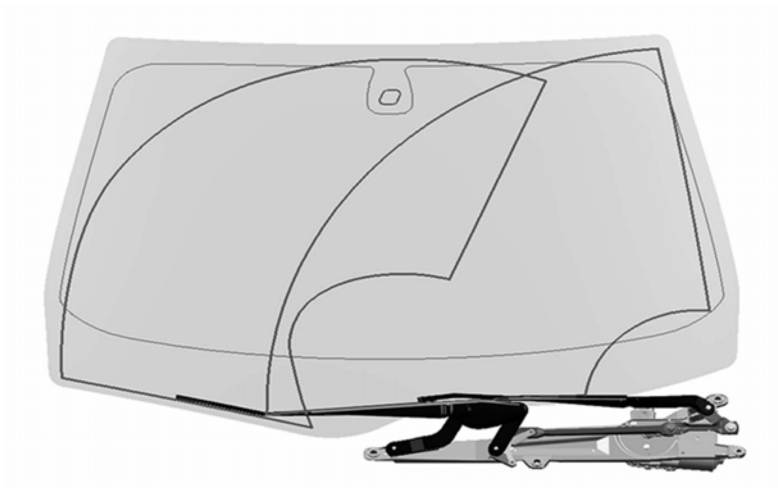


Fig. 5.205. Example of hidden wiper system, with articulated quadrilateral arm.

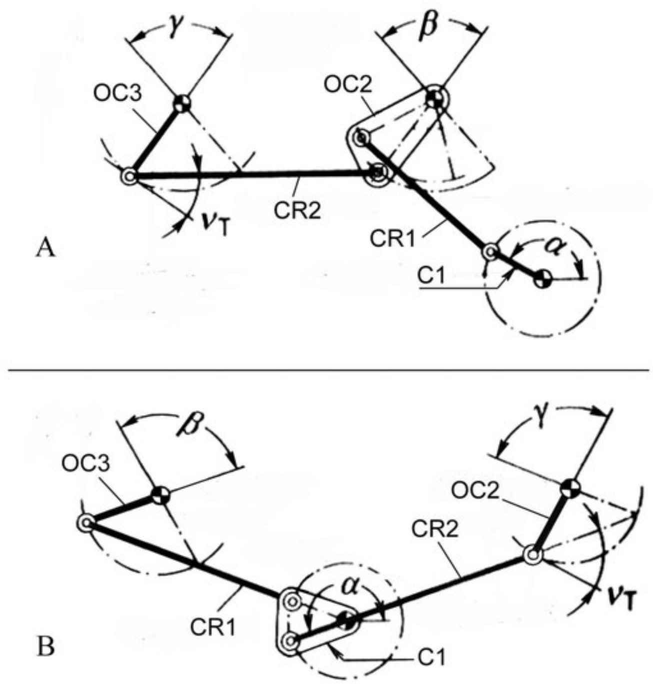


Fig. 5.206. Examples of wiper driving kinematics. C1: motor driven crank; OC2, OC3: oscillating arms; CR1, CR2: connecting rods.

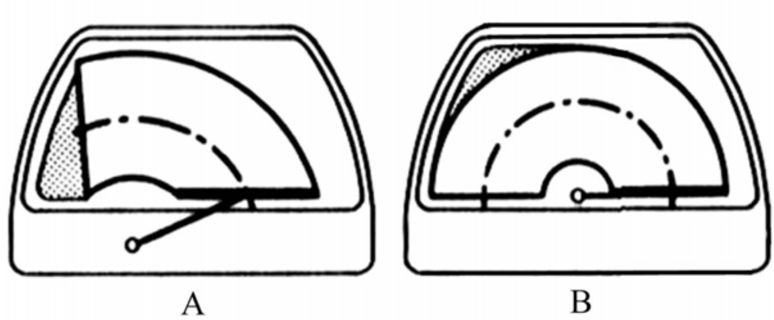


Fig. 5.207. Examples of hatchback wiper cleaned areas, in case of asymmetrical (A) and symmetrical (B) pivot position.

Wipers driving can be performed by different rod-crank kinematics, depending on the wiper pivot positions. In Fig. 5.206, two different schemes of connecting the motor to the blades can be seen. The difference between system A and B is explained by the different span between the pivots.

Crank C1, driven by the motor, rotates without rest. In solution A, the connecting rod CR1 drives crank OC2 with oscillatory motion which drives one blade and, through a second connecting rod CR2, crank OC3 which drives the second blade.

In solution B, crank C1 drives two rods, CR1 and CR2 and, through them, two cranks OC2 and OC3 with oscillatory motion. Importantly the pivots on the motor crank must be on different planes in order to avoid rod impact during rotation. With two opposite cranks on the motor shaft, a symmetrical motion of blades can be achieved.

The components geometry should be optimized according to the following criteria:

- arms cranks angular acceleration must be the highest close to the rotation inversion points, in order to avoid a significant reduction of blade angular speed before inversion.
- arm pivots must be adequately sloped towards the bisector of the angle between the extreme blade positions, in order to promote blade twist angle change at the inversion points.

It is possible to equalize the blade speed between the rotation inversion points by using electronically controlled motors, in which the rotation speed is changed with reference to the blades angular position.

The rear wiper always features one blade only, usually positioned according to one of the schemes shown in Fig. 5.207. Even in this case, the chosen solution is related to the backlight width/height ratio. The B solution can be adopted for backlights, the width of which is approximately twice the height. Further wiper

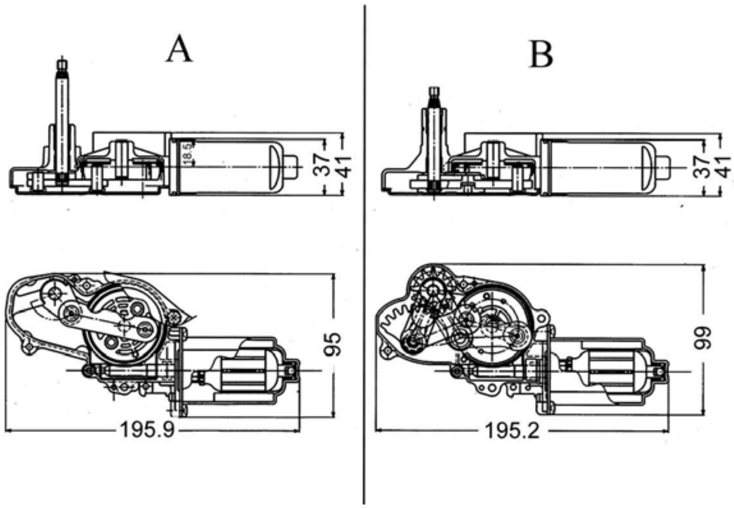


Fig. 5.208. Examples of backlight wiper mechanism: the B type amplifies the wiping angle.

positioning considerations must be related to the vision through the backlight from the inside mirror.

The rear wiper driving mechanism is simplified, or at least more compact, than that of the windshield due to the lack of a second blade. Fig. 5.208 shows two different driving designs: in both cases, a box houses an electric DC motor with permanent magnets which drives an endless-screw reduction gear. The helicoidal wheel drives the crank of an articulated quadrilateral, dimensioned to enable the angular stroke required.

The system shown in Fig. 5.208-B includes a special design to increase the angular blade stroke, even with small rods, consistent with a limited external obstruction of the assembly. The quadrilateral rod features a toothed profile which engages a reel keyed to the blade pivot. In this way, the angular blade run is the sum of the quadrilateral rod angle and rod rotation times the transmission ratio of the toothed profiles.

Moreover it is possible to suppress the rod-crank mechanism, by the use of an electronic controlled motor, in which the speed as well as the direction of rotation are driven with reference to the angular blade position.

Technical specifications and delivery testing

The wiper manufacturer must provide an installation drawing, with a demonstration of the system kinematic behaviour in the available space together with its compliance to regulations.

The main properties of the wiper design relate to its geometrical configuration, cleaning effectiveness, pedestrian safety, noise and vibration transmission.

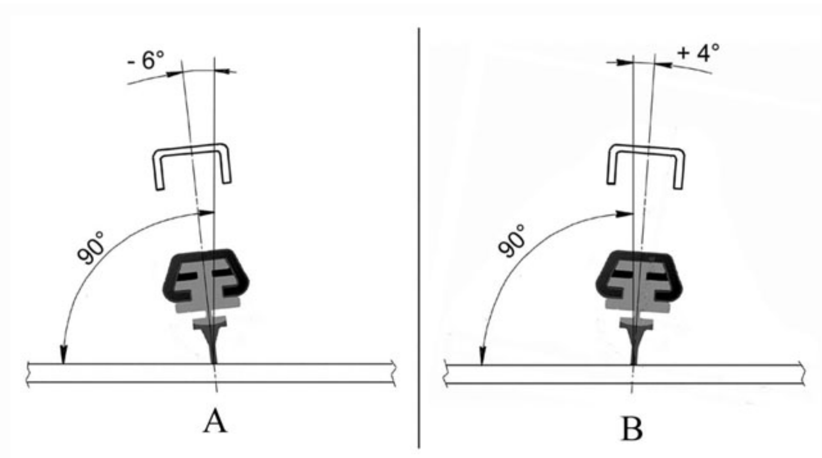


Fig. 5.209. Recommended twist angle for parking (A) and stroke end position (B).

Regarding the geometry, the main specifications establish the pivots mounting slope referred to windshield and, as a consequence, the blade attitude angle referred to contact point tangency, named *twist angle*. This angle is important for cleaning effectiveness as well as noise due to the wiper blade vibrations on the glass. Since it varies along the blade stroke, reference values and tolerances in different control points must be specified.

Fig. 5.209 reports some recommended values (from one manufacturer's specifications): in A the twist angle in the middle of the blade at parking position is reported. In B, the same angle at blade stroke end is reported. The 0° angle condition should be verified at about 2/3 of the stroke. At the blade end, the recommended angle is between 2° and 8° at the stroke start position, between -8° and -2° at the stroke end.

As concerns pedestrians safety, the sphere simulating the impacting head should never contact hard parts, such as the wiper pivot P or the bezel M (Fig. 5.210), in order to avoid that the value of HIC is $>$ 1,000. The test is made in two steps: first, the sphere is statically positioned at the hood rear end E (Fig. 5.210-A) and must be free from contact with the pivot or bezel. In the second step, the sphere is launched against the hood in the rearmost test position D (Fig. 5.210-B), with a slope of 50° to the horizon. While crushing the hood, the sphere should remain far enough from the wiper pivot: this is usually consistent with an empty space of at least 70 mm between the hood and pivot.

Regarding wiping effectiveness, in addition to the areas A and B to be wiped by 98% and 80% respectively (see Fig. 5.203), also the brush stroke frequency is specified as 65 strokes/min. If a second speed is available, the frequency must be 45 strokes/min.

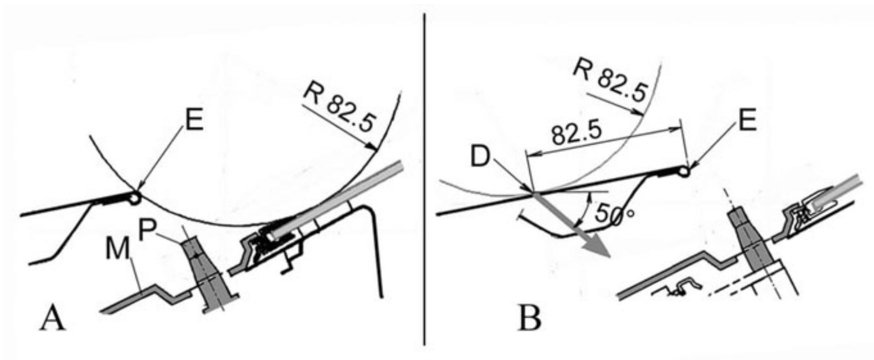


Fig. 5.210. Pedestrian head dimensional (A) and impact (B) verification. No direct contact of head with wiper pivot (P) or bezel (M) should take place.

Single arm wipers are penalized by this regulation, because they must brush off a wider angle in the same time, therefore with higher speed and acceleration levels. As a consequence, blade durability and arm stresses are strongly affected.

Regarding brush areas, results are generally better than those required by law, being usually close to 100% for every area.

Many windshield wiping systems feature an intermittent driving control, the frequency if which is between 5 and 30 strokes/min.

Many recently designed, electronically controlled windshield wipers are connected to an optical drop sensor on the windshield: wiping starts when the recorded number of drops exceeds a specified value. In this way, the frequency is set between a minimum chosen level and the maximum designed level.

Usually, in the design, a manufacturer specifies the materials to be used, electrical connectors type, the aesthetics of the visible part and the mechanism fitting devices to the body.

The last should ensure mounting stiffness, absorption of mechanism born vibrations, blades position and pivot attitude setting, in order to achieve the alignment with the glass surface required.

Regarding system durability, and thus reliability, usually $1.5 \div 3{\cdot}10^6$ cycles are specified, corresponding to estimated vehicle life.

Typically just the blades or their abraded part must be replaced during the vehicle life. In fact, after 6 months use, the blade starts deteriorating: in this case, replacing is recommended each year or at least 2 years, corresponding approximately to 10^5 cycles.

It is important not only to preserve component integrity but also performance level. To that purpose, every manufacturer specifies some reference bench testing with the car windshield, where the wiper system can be installed and driven, the glass surface being sprayed with water and sand, specifying the dimension and chemical composition of the sand to be used. The testing analysis refers not only to the durability of components, but also to the quality of vision through the glass.

Performance testing

In rain or wade specified conditions, the wiper system must ensure not only geometrical compliance with the surfaces to be wiped, but also really ensure adequate visibility in daylight and at night.

Aerodynamic testing

Related mainly to rustles and whistling, during wiping or with parked blades.

Snow start test

In the presence of snow, when the system is stuck due to snow or ice and is operated even by mistake, no breaking of mechanical or electrical parts should occur, at least for the time needed to free the blades. Furthermore it is recommended to provide a dead angle, close to the parked position, in which the automatic blades recovery circuit is not inserted in order to avoid motor action in the stuck condition after an on-off switching.

Noise test

The noise emitted by a windshield wiper can be perceived to be highly annoying in certain situations. For a noise specification, the reference conditions should be adequately selected, for instance when the system operates with a high friction coefficient between glass and blade. This condition is usually caused by a low water volume and by some organic pollutants such as exhaust residuals or washing tensioactive chemicals. In such conditions, stick and slip phenomena can occur between the glass and blades due to intermittent braking moments.

The noise sources can relate to:

1. Blade-glass contact, causing vibrations and beats on wiper arm.
2. Kinematic joints, transmitting beats at inversion positions or in the case of stick and slip wiping.
3. Motor and reduction gears.

As the characteristics of the emitted noise are different and only some of them are perceived as annoying, it is not sufficient to specify the overall noise emission (about 45 dBA); instead, a third-octave spectrum reference must be given, as shown by Fig. 5.211-1 and -2).

Sprayers

Fig. 5.212 illustrates sections of a stand-alone sprayer, that can be mounted on the hatchback or over the hood, or on the cowl louver under the hood. This device needs a selected fitting position, mainly in the case of the windshield, in

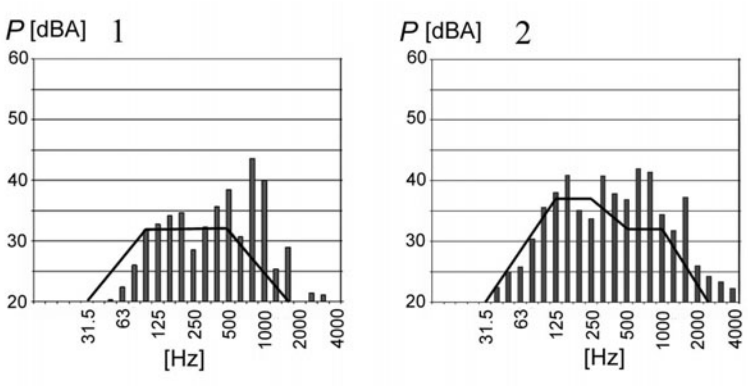


Fig. 5.211. Examples of overall wiper system noise spectra, measured inside the passenger compartment, at first (1) and second (2) speed, compared to the noise target (continuous lines).

order to avoid the influence of vehicle speed on the spray glass related angle. Usually this goal can be achieved if the sprayer is far enough from windshield base, for instance if it is mounted over the hood.

It is also possible to incorporate the sprayer in the wiper arm. In this way, the action of spray and wiping can be performed simultaneously, while sometimes missing in the case of stand-alone sprayers. The feeding of washing liquid is made through the same pipe that hosts the rear wiper pivot. Fig 5.213 shows two examples of sprayers incorporated in the rear wiper, compared to a hatchback mounted split solution.

5.6 Vehicle Lighting and Signalling

Projectors and headlamps are used to provide illumination of the roadway in darkness or reduced visibility conditions, in order to improve driver visual perception (lighting). Lamps, signal and identification lights are used to make a vehicle more clearly visible by other road users in reduced visibility conditions (signalling).

Lighting includes:

1. high beams;
2. low beams (meeting beams);
3. fog lamps;
4. auxiliary driving lamps.
5. daytime running lamps, mandatory in some European and U.S. countries.

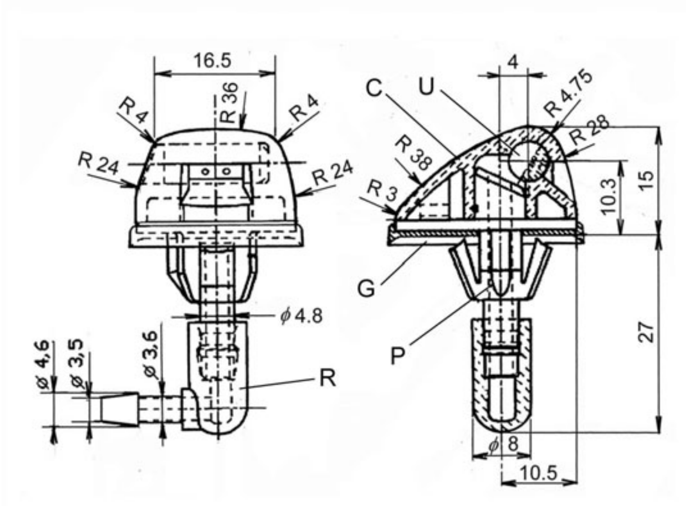


Fig. 5.212. Example of stand-alone sprayer. C: sprayer body; G: gasket; U: nozzle; P: pipe holder; R: pipe connection.

Signalling includes:

1. parking front and rear lamps;
2. side turn signals and side repeaters;
3. brake lamps;
4. rear fog lamps;
5. reversing lamps;
6. hazard flashers;
7. side marker devices and rear clearance lamps, when required.

Lighting, signalling and reflective devices are considered safety components; therefore their properties and performance are defined by law, as explained in the Regulations Chapter.

Projectors and lamps performance is related to human eye perception capability, which can adjust to different light conditions. The fitting parameters are retina sensitivity and iris opening; human eye reacts to a sudden light increase, through a quick iris contraction (glare) that causes a temporary visibility loss. To avoid this dangerous condition, the lighting system design should provide the highest possible luminance, without causing glare.

Human eye sensitivity is different from person to person and depends on age and light radiation wavelength. To calculate the sensitivity to radiation, the

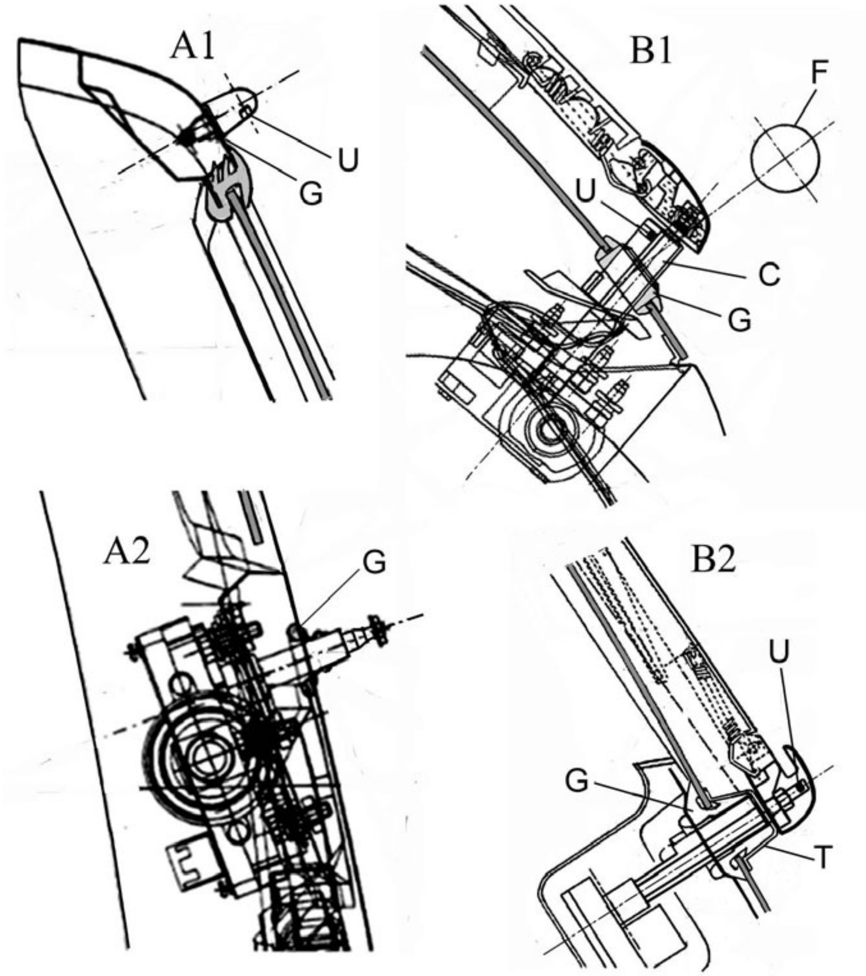


Fig. 5.213. Liftgate sections comparison among a stand-alone sprayer (A1), wiper mechanism (A2) and incorporated sprayer wipers B1, B2. U: nozzle; C: hollow shaft; G: gasket; T: gasket cover; F: glass hole projection.

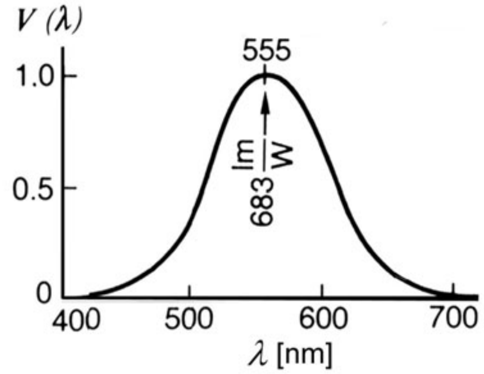


Fig. 5.214. Diagram of the human eye spectral sensitivity $V(\lambda)$, as a function of wavelength λ.

diagram shown in Fig. 5.214 is used: the maximum value is exhibited at 555 nm wavelength (corresponding to a colour between yellow and green). In such a condition, sensitivity is put equal to unity and the perceived luminous flux is 683 lm/W. The sensitivity diagram has a symmetrical bell shape and is equal to zero at about 380 nm (ultraviolet) and 780 nm (infrared).

To better understand lamp and projector performance, it is useful to recall the meaning of the main photometric quantities and their measurement units. The *luminous flux* is the optical power perceived by the eye, weighted according to its sensitivity at different wave lengths of radiation emission; the flux is measured in lm (lumen).

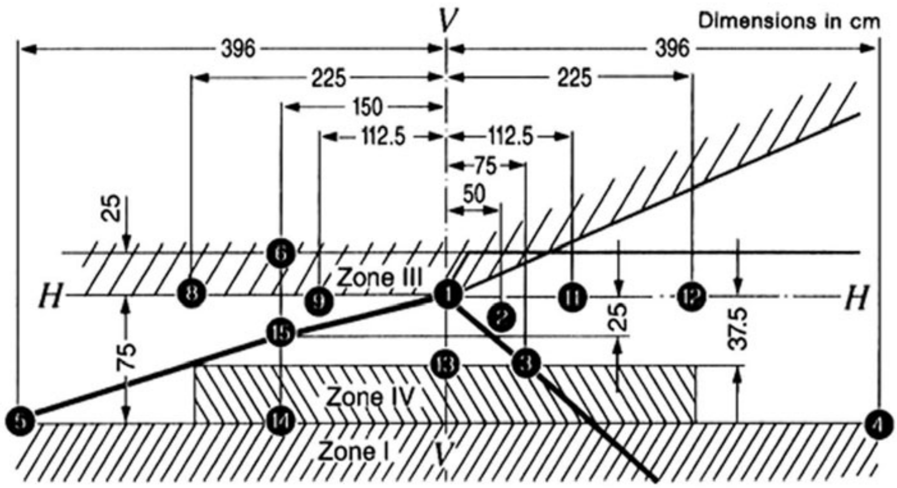
The *luminous intensity* is the ratio between the luminous flux and the solid angle of emission; intensity is measured in cd (candles). Candle definition is the light quantity emitted by a monochromatic light source of 1/683 W, irradiating at a wavelength of 555 nm, through a solid angle of 1 sr.

The *luminous efficiency* is given by the ratio of emitted luminous flux and the energy absorbed by the source. It is therefore measured in lm/W and cannot, by definition, exceed the value of 683 lm/W at 555 nm wavelength.

The *luminance* is the ratio between the luminous flux and the irradiated surface; it is measured in lx (lux), corresponding to 1 lm/m^2.

The last quantity is established by the projectors evaluation test, on a vertical screen at 25 m, defined by the ECE 20 Regulation, a summary of which is reported in Fig. 5.215.

It is important to bear in mind that, in the case of cars, each lighting device must not only comply with the law and customers functional requirements, but also contribute to the aesthetical car impression, according to styling criteria. The recent evolution of these components has in fact demonstrated their relevant influence on car personality. Therefore, the significant research, innovation and



Lower beam			
Measurement points	Specified lx values	Measurement points	Specified lx values
1. E_{HV}	≤ 0.7	Max. value in Zone I	$\leq 2\ E_{50R}$
2. E_{75R}	≥ 12	Max. value in Zone III	≤ 0.7
3. E_{50R}	≥ 12	Min. value in Zone IV	≥ 3
4. E_{25R}	≥ 2	13. E_{50V}	≥ 6
5. E_{25L}	≥ 2	14. E_{50L}	≤ 15
6. E_{B50L}	≤ 0.4	15. E_{75L}	≤ 12

Upper beam	
Measurement points	Specified lx values
7. E_{max}	> 48 $< 16 \times E_{75R}$ (< 240)
8. $E_{H-5.15°}$	≥ 6
9. $E_{H-2.55°}$	≥ 24
10. E_{HV}	$\geq 0.8\ E_{max}$
11. $E_{H+2.55°}$	≥ 24
12. $E_{H+5.15°}$	≥ 6

Fig. 5.215. Projectors luminance verification chart and values established by the Regulation ECE 20.

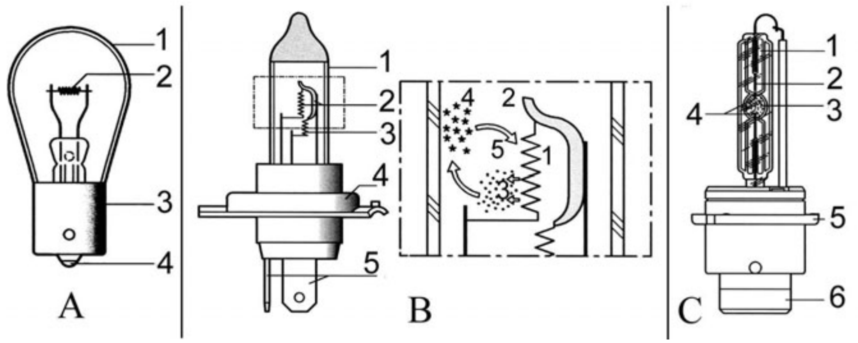


Fig. 5.216. Comparison between the most common projector bulbs. A: incandescent filament lamp; B: halogen lamp; C: gas discharge lamp.

technological application regarding lighting system is explained by technical and aesthetics goals.

Lighting sources

Today, vehicle lighting sources fall into three main families: incandescent filament, high-intensity discharge (HID) and light emission diodes (LED). Filament lamps use thermal energy to provide luminous energy emission: the lighting efficiency obtainable is less than 10%. They are further divided into tungsten incandescent lamps and halogen lamps.

The first type (Fig. 5.216-A) comprise a glass casing 1, which hosts a tungsten resistor 2, made incandescent by electrical energy. The lamp life is conditioned by the resistor, due to mass loss caused by high temperature sublimation. Also the lamp lighting efficiency is influenced by this phenomenon, decreasing with operation time, due to the bulb transparency loss, caused by sublimated tungsten condensing over the inner walls.

The base 3 of the lamp has a bayonet configuration, one electrode being provided by the base itself and the other being provided by a central contact 4, at the base bottom. There are single and double filament lamps: in the latter case, also contact 4 is double.

Halogen lamps use incandescent filaments also (Fig. 5.216-B shows a double filament bulb for high and low beam headlamp). The atmosphere in the casing is not an inert gas but Iodine and Bromine vapour. A halogen gas atmosphere enables tungsten filament heating at temperature close to its melting point (3,400 °C), resulting in higher lighting efficiency. The bulb aspect is different from the incandescent filament bulb for the overall shape and blade connectors type. In the figure, 1 is the casing, 2 and 3 the high and low beam filaments with a shield to conceal upper light projection.

On the right of the same figure, the solution that provides better, longer and more stable performance, is shown. Tungsten 3, evaporated from filament 1, reacts with the halogen component, resulting in a chemical gaseous composite 5, an halide, stable at temperatures between 200 and 1,400 °C. If the glass temperature is kept higher than 300 °C, the gas contacting the glass does not condense and releases the tungsten back onto the filament since it cannot lay permanently on inner bulb surface. To reach the desired temperature, the bulb is very close to the filament. The lamp durability is much longer than the incandescent filament lamp and the lighting efficiency consistently increased. Glass darkening over time no longer occurs; on the other hand, little oil or grease (even human) contamination causes glass breakage during high temperature operation.

The gas discharge lamp uses the light radiation emission from ionized gas, in the presence of an electric high intensity discharge arc. The lamp shown in Fig. 5.216-C has a discharge chamber 3 filled with noble gas (usually Xenon) and halogen composites for electrodes conservation. Electrodes 4 are housed in a glass casing 1, treated to avoid external UV rays transmission. Between the electrodes a spark, produced by a high voltage pulse, ionizes the gas with the emission of significant luminous energy.

This technology yields luminous energy values higher than in the case of halogen lamps and durability close to the vehicle lifetime. But the physical phenomenon which supports the system needs high tension AC. Therefore, an electronic device (reactor) is required, to transform the DC low battery voltage in a higher tension AC and control the tension values in the different operating steps. In fact, to start the arc, gas ionization is needed and the corresponding required voltage must achieve values between 6 and 12 kV. After arc ignition, it is possible to reduce the voltage to approximately 100 V (standard operating voltage).

The high temperature values of involved gas provide relevant luminance values. In Fig. 5.217, the luminance maps of an incandescent filament and a Xenon discharge arc are compared. It can be observed that, in the case of the filament, the luminance is weakened at both filament ends, due to heat transfer to the electrodes.

Fig. 5.218 shows a chart of standard automotive bulbs, for 6,12 and 24 V voltage: it can be noticed that the lamp bases are different in order to avoid wrong fitting. The incandescent lamp luminous efficiency can vary between 10 and 18 lm/W; for halogen lamps, between 22 and 26 lm/W; for discharge lamps, up to 85 lm/W.

LED (*Light Emitting Diodes*) are semi-conductor elements, made of special materials, for which charge displacement in the conductive direction emits monochrome luminous energy without significant emission of thermal energy.

Fig. 5.219 shows a single LED and an example of multiple LED. For the automotive market LEDs must be assembled in order to provide adequate luminous intensity lamps. For aftermarket only, today some LED assemblies are available (shown at lower right) that can replace incandescent lamps.

At the OEM application stage, LED are mainly used for tail lamps and for centre high mount stop lamps: assemblies are designed to fit the lamp shape.

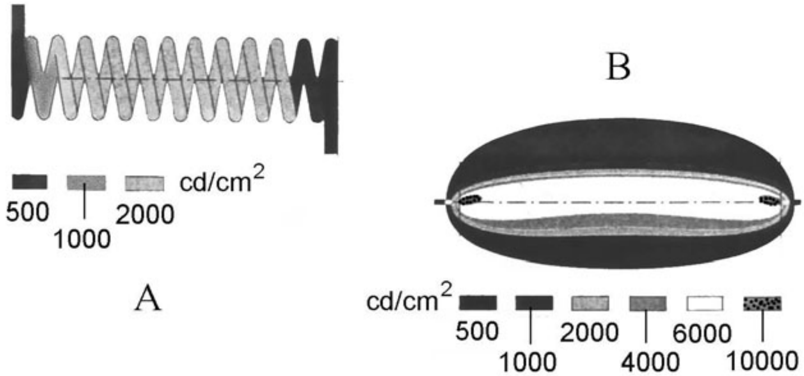


Fig. 5.217. Comparison between incandescent filament (A) and arc (B) luminance.

Luminous LED efficiency can vary between 40 and 80 lm/W, depending on the emitted light wavelength. Among LED advantages, also low thermal emission, durability similar to vehicle lifetime and ultra quick switch-on time (few nanoseconds) must be considered. The last factor is safety related; in fact, at 100 km/h, the lower time needed to switch-on the stop lamps, compared to an incandescent lamp, corresponds to 20 m of vehicle run.

Technological lighting alternatives

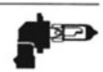
The most common lighting layouts for the vehicle front end are displayed in Fig. 5.220:

Sol. A) two optical elements, each performing two functions: high and low beam.
Sol. B) four optical elements, two of them providing high beam only, and two for low beam only or high and low beam.
Sol. C) six optical elements, four of them similar to Sol.B and two fog lamps.

Different headlamps can comprise different, sometimes combined optical devices; very often, the combined system includes parking lamps and turn lights. Today, the combined solution is preferred, not only due to the lower number of components, but also for a better aerodynamic configuration. Some recent headlamps that replace traditional lamps have a simplified appearance but are often complex combined systems.

The surface to be illuminated is conditioned by its required function and is performed by the luminous beam configuration, by the headlamp parts, therefore

Specifications for motor-vehicle bulbs (not including motorcycles etc.)

Application	Designation	Voltage rating V	Wattage W	Luminous flux lm	Base type IEC	Illustration
High/ low beam (not on new vehicles)	R2	6 12 24	45/40[1] 45/40 55/50	600 min/ 400-550[1]	P 45 t-41	
Fog-, high/low beam, driving lamps in quad system	H1	6 12 24	55 55 70	1,350[2] 1,550 1,900	P14,5 e	
Fog lamp, auxiliary driving lamp	H3	6 12 24	55 55 70	1,050[2] 1,450 1,750	PK 22s	
High/low beam	H4	12 24	60/55 75/70	1,650/ 1,000[1], [2] 1,900/1,200	P 43 t – 38	
Side-marker lamp	H6W	12	6	125[3]	BAX9s	
High/low beam, fog lamp	H7	12	55	1,500[2]	PX 26 d	
High/low beam/ fog lamp (E vehicles)	H8	12	35	800[2]	PGJ19	
High beam	H9	12	65	2,100[2]	PGJ19-5	
Low beam/ fog lamp	H11	12 24	50 70	1,350[2] 1,750[2]	PGJ19-2	
Turn signal/ stop lamps	H21W	12	21	600[2]	BAY 9s	
Low beam in quad system	HB4	12	55	1,100	P 22 d	

Application	Designation	Voltage rating V	Wattage W	Luminous flux lm	Base type IEC	Illustration
High beam in quad sytem	HB3	12	60	1,900	P 20 d	
Stop, turn signal, fog warning lamp, backup lamp	P 21 W PY 21 W[7]	6 12 24	21	460[3]	BA 15 s	
Stop lamp/ tail lamp	P 21/5 W PY 21 W[7]	6 12 24	21/5[4] 21/5 21/5	440/35[3] 440/35 440/40[3]	BAY 15d	
Side-marker lamp, tail lamp, tail lamp	R 5 W R 10 W	6 12 24 6 12 24	5 10	50[3] 125[3]	BA 15 s	
License-plate lamp, tail lamp, backup lamp	C 5 W C 21 W	6 12 24 12	5 21	45[3] 460[3]	SV 8,5 X SV 8,5	
Position lamp	T 4 W	6 12 24	4	35[3]	BA 9 s	
Side-marker lamp, license-plate lamp	W 5 W/ W 3 W	6 12 24	5/3	50/22[3]	W 2,1 x 9,5 d	
Low/high beam Bi-Litronic low beam (since 1991)	D1S[5]	85 12[6]	35 ca. 40[6]	3,200	PK 32 d-2	
Low/high beam Bi-Litronic low beam (since 1994)	D2S[5]	85 12[6]	35 ca. 40[6]	3,200	P 32 d-2	
Low/high beam Bi-Litronic low beam (since 1996)	D2R[5]	85 12[6]	35 ca. 40[6]	2,800	P 32 d-3	

[1] High/low beam, [2] Specs. at test voltage of 6.3 V; 13.2 and 28.0 V, [3] Specs. at test voltage of 6.75 V; 13.5 and 28.0 V, [4] Primary/secondary filament, [5] Gaseous-discharge (HID) lamp. Definition of standards in progress. [6] With ballast unit, [7] Amber version.

Fig. 5.218. Chart of different bulb families and related vehicle application.

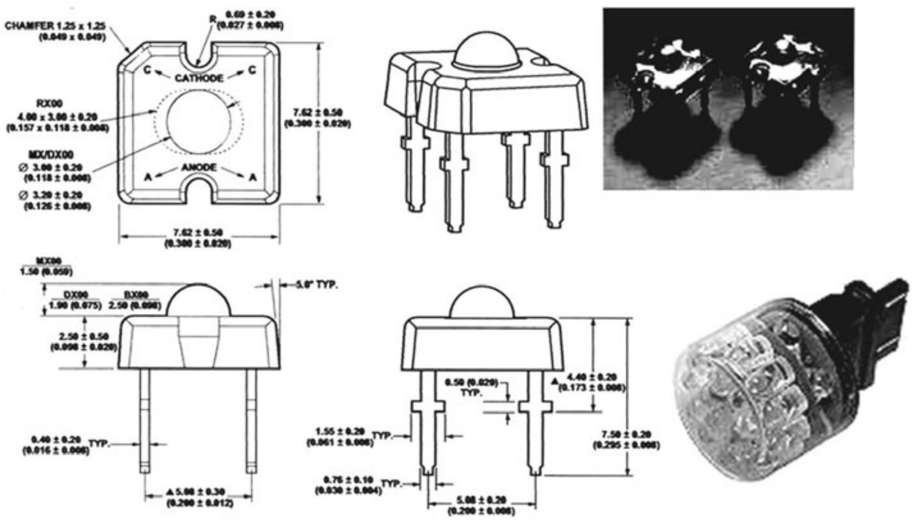


Fig. 5.219. Dimensional properties of a single LED and example of a multiple LED assembly lamp (below, right).

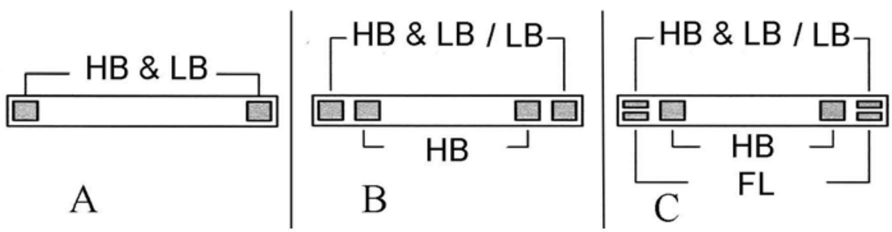


Fig. 5.220. Most common headlamps layouts. HB: high beam; LB: low beam; FL: fog lamp; &: combined; /: alternative.

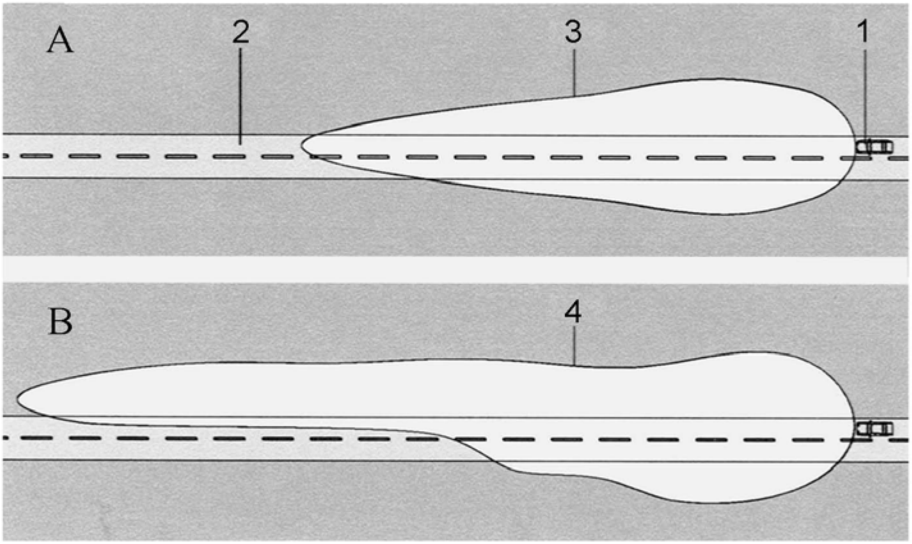


Fig. 5.221. Comparison of ground light distribution patterns (3, 4) of a fog lamp (A) and a low beam headlamp (B).

through headlamp parts design. With reference to Fig. 5.221, symmetrical illumination is achieved by front fog lamps (low range and large illuminated area) and by high beam headlamps (long range, without vehicles meeting). Asymmetrical illumination is performed by low beam headlamps, in order to increase the visibility of road border, without glare for meeting vehicles.

So different beams can be obtained with a combination of reflection and refraction devices.

To provde a practical example, in Fig. 5.222, lines that connect points with the same luminance value are shown, measured over a plane surface at 25 m from the vehicle and over the road surface, for a couple of headlamps. It can be noticed that the values, even in compliance with law limits, are different; below the criteria to be adopted in order to achieve the best light distribution are explained.

Since the luminous sources have limited extension when compared to the illuminated surface, they can be considered as point sources which should provide a uniform flux on the spherical surface with the source as centre. In order to obtain a luminous beam oriented towards the road surface and defined by a designed border, combined use of reflectors and refractors (lens and prism) is required.

It is well known that a light source positioned in the focus of a parabolic mirror (Fig. 5.223) or, in general, of a reflecting surface with circular symmetry and parabolic section, provides a light beam parallel to the paraboloid rotation axis

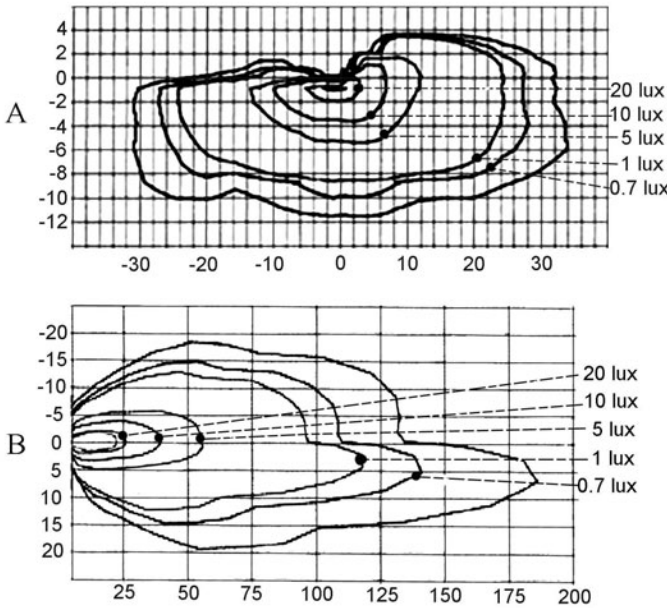


Fig. 5.222. Iso-luminance curves for a couple of headlamps, recorded over a vertical plane orthogonal to the light beam at 25 m distance (A) and over the road ground (B).

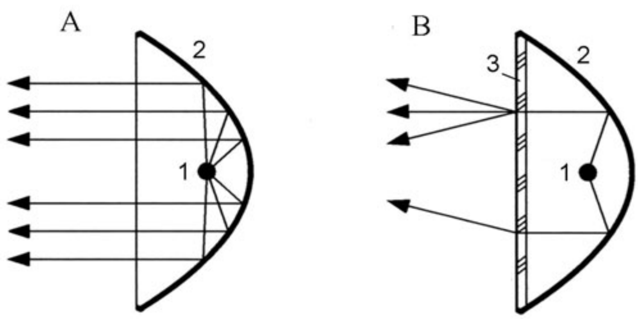


Fig. 5.223. Reflection of light rays, emitted by a source 1, positioned in the fire of a parabolic mirror 2, without refractors (A) and with a refraction device 3 (B).

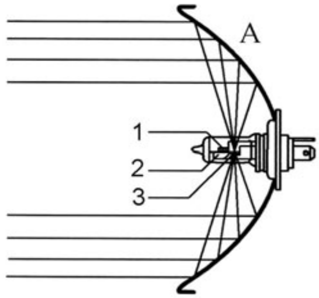


Fig. 5.224. Operating scheme of high beam (A) and low beam (B) double filament bulb headlamp. 1: low beam filament; 2: shield; 3: high beam filament.

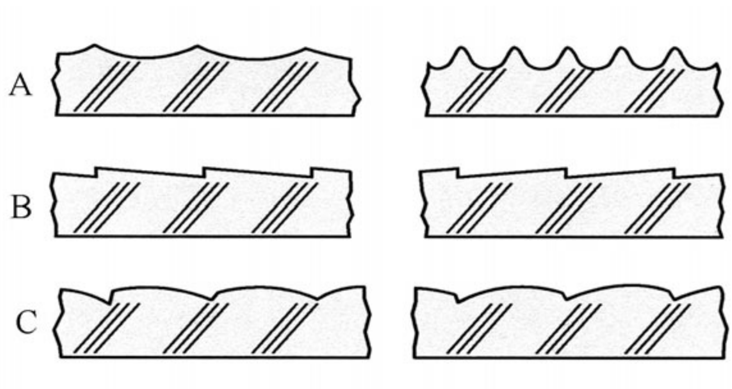


Fig. 5.225. Different surface configurations requested to supply lens (A), prism (B) or combined (C) performance.

(optical axis). Such a light beam provides an illuminated surface with luminance values uniformly decreasing as the distance from the source is increased. This result, not being optimized, is modified until the desired target is achieved, by the addition of refraction devices or the use of headlamps made up of a combination of different geometrical paraboloid segments.

In the most simple case of circular headlamps featuring high and low beam, it is possible to obtain two different beams (Fig. 5.224) with a double filament lamp. The high beam filament 3 is placed in the parabolic mirror focus and provides a luminous beam parallel to the optical axis, parallel in practice to the vehicle driving direction. Instead the low beam filament 1 is positioned forward of the focus to obtain a sloped light beam, referring to the optical axis. In that case, a shield 2 is needed below the lower filament in order to avoid an upward directed light flux.

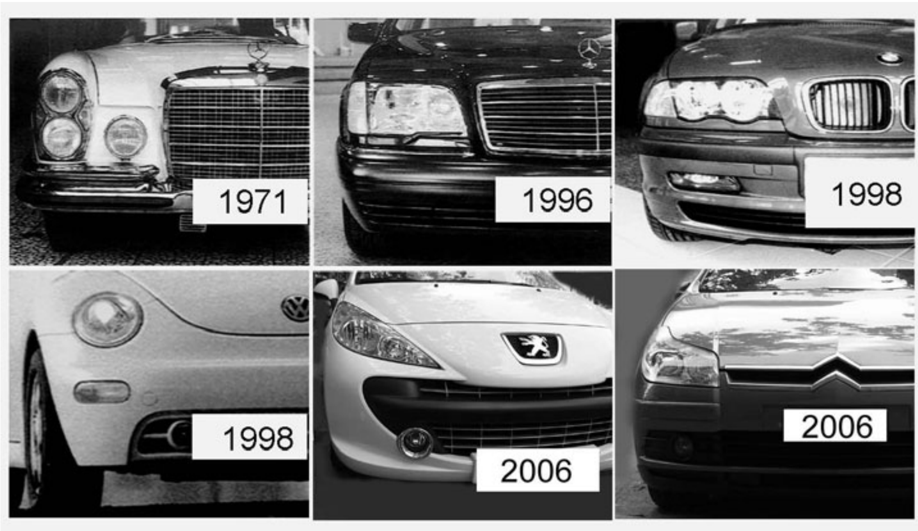


Fig. 5.226. Examples of headlamp evolution over the recent decades.

The desired asymmetry and the illumination of the virtual lamp base image (that supplies no reflecting surface) can be obtained by featuring lenses and prisms, usually vertical or projector centric, on the headlamp glass. In Fig. 5.225-A and -B, the shape of these devices and their combination, as in type C, can be seen. It must be remembered that prisms can only deviate a parallel rays beam, while a lens can change the exit angle as a function of incidence angle, making a parallel light flux convergent in a focus for instance.

For technical and aesthetics reasons, such simple headlamps are no longer in production. Fig. 5.226 shows different headlamps types.

Among the families of headlamps in use today, the first is that of computed surface reflector (or a reflector surface not made of a single parabolic mirror). They can be made with clear glass (as in Fig. 5.227) or prismatic glass (as in Fig. 5.228). In practice, the difference between the two solutions is only aesthetic, apart from the lower optical absorption of clear glass without prisms. In both cases, the reflector surface is a plastic substrate with deposition of vacuum vapourised aluminum layer. The achieved reflection factor is about 90%, but can be degraded by one half, in case of oxidation, due to atmospheric agents.

In the figures two different technical solutions for the reflecting surface are shown.

In Fig. 5.228-B, a single reflector combines the reflecting surface of a fog light 1, low beam 2, parking light 2a and high beam 3. The reflecting surfaces are somewhat different from the previously explained rotational paraboloid. These surface segments are computed using a special software, CAL (*Computer Aided Lighting*), starting from the desired ground distribution luminance and returning

Fig. 5.227. Example of headlamp with clear glass (A) and computed reflector surface (B). Numbers 1, 2, 3 refer to single computed surfaces.

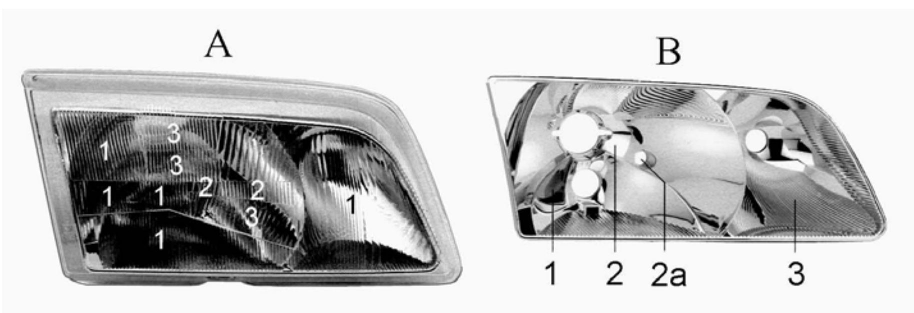


Fig. 5.228. Example of prismatic glass (A) and computed reflector surface (B). Number 1, 2, 3 refer to single computed surfaces.

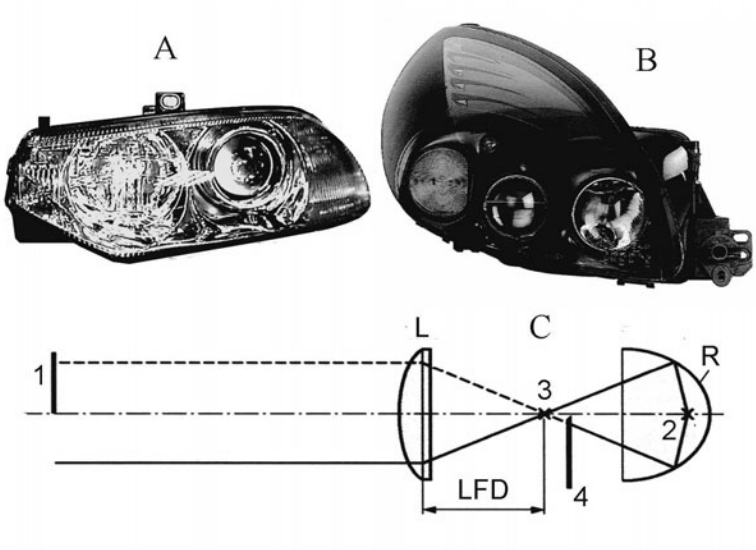


Fig. 5.229. Two examples of polyellipsoidal reflector headlamp (side (A), centre (B) positioned) and functional scheme of a polyelliptic (C) projector. 4: shield.

the reflecting surface shape, the prisms and lenses needed to achieve the target, according to the position and intensity of the chosen light source.

In this type of headlamp, the lens is fitted flush to the body in order to obtain good aesthetics and aerodynamics. Instead the reflector has some degree of setting freedom, with respect to the lens and the structural housing, used at the mounting stage and for angle resetting with vehicle loading change.

Usually, the presence of multiple light sources requires the design of a natural air flow cooling circuit inside the headlamp. Adequate solutions must be invented in order to provide air circulation without water and mud ingress that could damage the reflector and lens optical properties.

In the shown example, light distribution is committed not only to the reflector, but also to lens refraction devices of Fig. 5.228-A, where the task of refractors is essentially to create an asymmetrical light beam.

In the case of clear glass, the reflector has a more complex shape, as in Fig. 5.227, where, in the low beam segment 1, an auxiliary mirror 1b is visible, the shape of which is designed to deviate part of the light to the right road side. Surfaces 2 and 3 are used for high beam and fog light respectively.

Fig. 5.229 introduces another clear glass headlamp family in which polyellipsoidal elements, on the left side (A) and between (B) other lights, are inserted.

The polyellipsoidal projector (Fig. 5.229) is made up of a light source positioned in focus 2 of a mirror R, with ellipsoidal surface with focuses 2 and 3. The light emitted by the source positioned in the first focus is reflected to focus 3. This is also the focus of a plane-convex lens L with focal distance LFD which

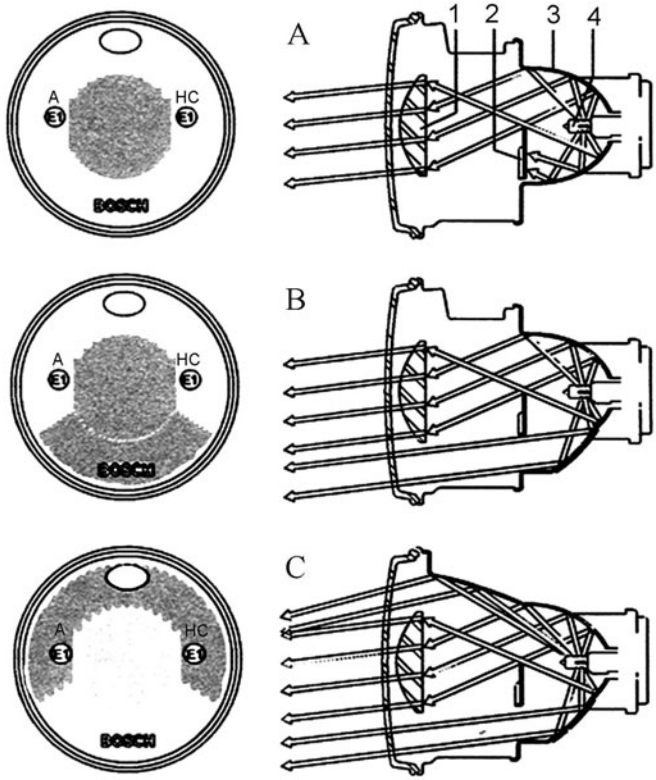


Fig. 5.230. Examples of combined configurations of computed reflecting surfaces with a polyelliptic unit 3, focus 4, shield 2, lens 1.

transforms the rays conveyed in its focus into a beam, parallel to the optical system axis. A shield 4, positioned inside the projector, provides its virtual image 1, cutting off the light where necessary.

The advantage of such a solution is the low projector diameter, which allows the design of small effective projectors, therefore facilitating the aerodynamic configuration of the car front end. This type of projector can be combined with other similar units or with computed surface headlamps.

In Fig. 5.230, some assemblies of computed surface reflectors and polyellipsoidal element are shown. The conventional section, adequately covered by prisms, aims to improve luminance of areas close to the car. It is possible to design a highly effective headlamp with the visible, apparently simple, shape of an headlamp of the fifties.

Gas discharge bulbs can be used with all the optical configurations listed above, bearing in mind that a double source for the combination high-beam

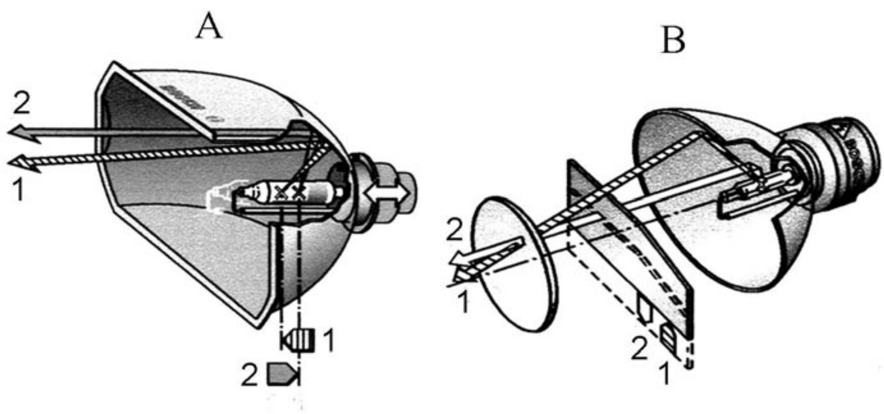


Fig. 5.231. Commuting low beam - high beam solutions for gas discharge lamps. A: movable bulb; B: movable shield; 1: low beam; 2: high beam.

low-beam is not available: in that case, two sources or an axially movable bulb (as shown in Fig.5.231-A) must be used. In the last solution, a device moved by an electrical motor can position the source in the different places designed for the high-beam and low-beam. As an alternative, the projector can feature a movable shield (Fig. 5.231-B) that covers the requested non illuminated area, in combination with the low-beam.

Fig. 5.232 shows a section of a complete projector, featuring a polyelliptic element. The outer housing 2 fixed to the body and the inside optical element 3, that can be sloped, can be seen. In fact, as already mentioned, in a modern headlamp the outer housing must be flush to the body and therefore must be fitted once, during the vehicle mounting process. On the contrary, the inside element must be free to slope, even by manual control, in order to set the right optical beam incidence depending on car attitude. Also, weather strips and gaskets (e.g. 5) enable waterproofing or at least protect the lamp from atmospheric agents. The rear part 4 of the projector can be opened in order to replace the bulb.

European regulations require a headlamp attitude regulator, so as to change the optical axis reference to the body, the purpose being to maintain a constant axis direction with whatever body pitching attitude due to the actual load. The use of a manual regulator is mandatory and requires electrical step motors to set the headlamps angle at stepped levels depending on load related conditions.

As an alternative, the setting system could be automated and related to body pitching angle. In Fig. 5.233, two sensors 3 and 6 measure the suspension stroke; the regulator, which changes the headlamps angle as a consequence of sensors detected signal, can be static or dynamic. The last one can take into account not only the static suspension load change (as required by law), but also the changes due to inertial (accelerating and braking) body forces.

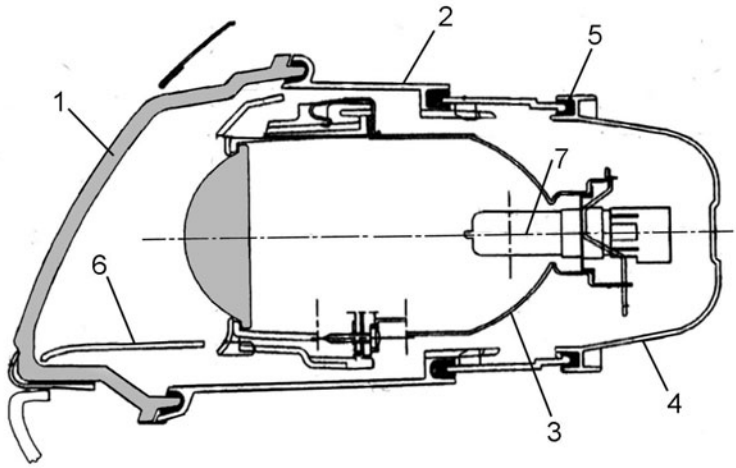


Fig. 5.232. Section of a polyelliptic projector. 1: clear glass; 2: plastic housing; 3: polyelliptic unit; 4: service cover; 5: weatherstrip; 6: shield.

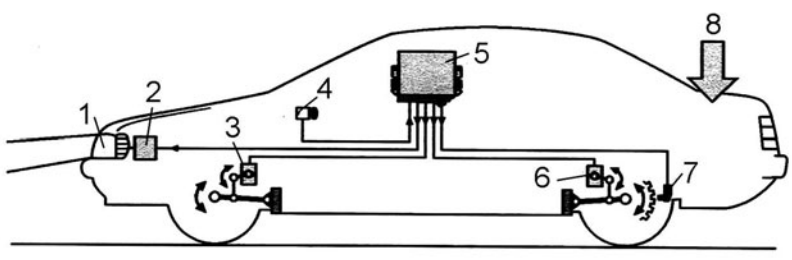


Fig. 5.233. Scheme of an automated headlamps attitude control. 1: controlled beam; 2: actuator; 3, 6, 7: sensors; 4: selector; 5: control unit; 8: applied load.

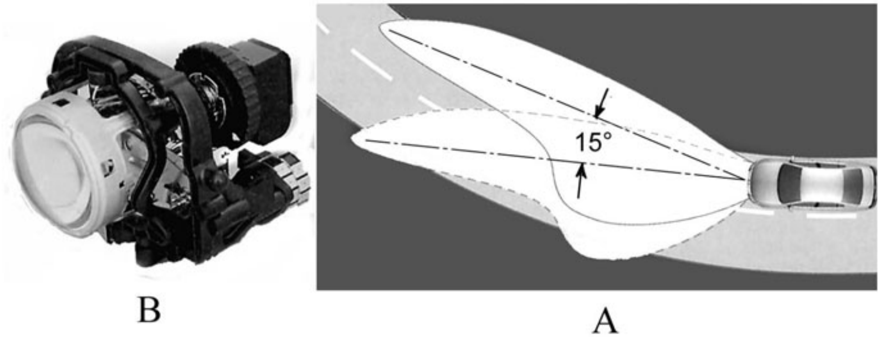


Fig. 5.234. Principle of luminous beam rotation related to steering (A) and rotating gas discharge polyelliptic projector assembly (B).

The difference between the two systems requires more powerful actuators so as to change the system attitude in shorter times. In the case of static setting, the system records car speed in order to evaluate body acceleration and clear such contribution from suspension sensors recordings.

The automated attitude setting is mandatory when using gas discharge lamps.

Cornering lights

Regarding headlamps innovation, automated cornering systems have recently been put in production. The principle, invented a long time ago, relates to a luminous beam rotation around a vertical axis as a function of the curved road path (Fig. 5.234).

These systems use polyelliptic gas discharge projectors or LED projectors, actuated by electrical motors, with dynamic rotation range of $\pm$ 15° and static range up to 35° for parking maneuvers.

Technological tail lights solutions

Even in this case, the optical system includes reflectors and refractors, the latter being usually performed by the transparent cover. Reflectors can even be missing and such an optical system is termed "*direct light system*", instead of "*reflector system*".

Refraction can be provided by prisms or lenses, or a combination of both.

Also, intermediate optical systems exist where a refraction device is positioned between the light source and the transparent cover. Moreover, the light beam color, mandatory for signalling lamps, can be supplied by the luminous source or by transparent elements.

At this stage it is appropriate to examine some technological alternatives in use today.

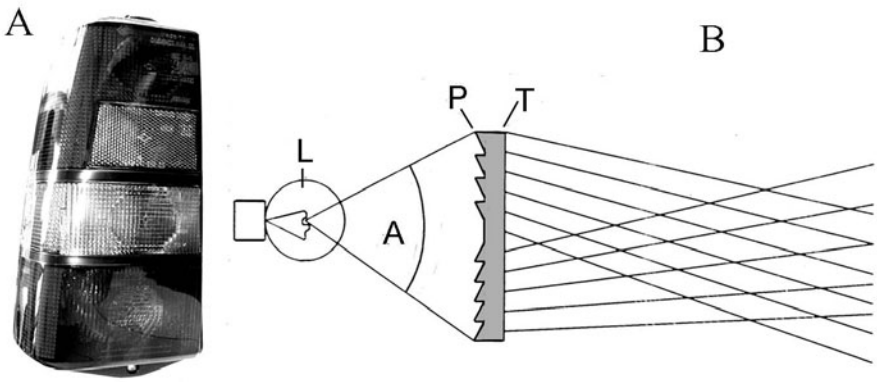


Fig. 5.235. Example of direct light tail lamp (A) and related operating scheme (B). P: prisms; T: transparent element.

Fig. 5.235 presents the simplest direct light optical system: Fig. 5.235-A shows the result, while Fig. 5.235-B illustrates the optical operating scheme. A prism assembly P, positioned on the inner surface of a transparent element T, colored as required, distributes the luminous flux emitted by the source L within the solid angle A. Each prism has an angle depending on its position, related to the source. The main advantage is low cost, balanced by a low optical efficiency due to the loss of all the light emitted out of the solid angle A.

An increase of efficiency can be obtained with the same concept by the scheme of Fig. 5.236, in which a special shaped Fresnel lens can transform about 50% of the bulb emitted flux into a parallel light beam, sloped as in the previous solution in order to achieve the requested diffusion angles.

Higher efficiency can be achieved using reflection elements: the result can be seen in Fig. 5.237-A; a possible optical scheme is shown in Fig. 5.237-B, in which a reflecting parabola P is present. This solution is consistent with circular optical elements or, due to the relevant required optical efficiency, with a rear fog light of a combined signal lamp. In that case, the parallel rays reflected by the parabola are diffused according to the requirements using lens elements supplied by the transparent element L.

As an alternative, for more complex shapes, the reflector can have a computed surface, metal coated or painted. The difference is the lower optical efficiency for the painted surface, balanced by a more uniform appearance of the illuminated lamp. In fact, in the previous case, a dark zone appears, corresponding to the lamp base, and differently illuminated zones are visible corresponding to the solid direct lighting angle.

A special (intermediate optics) element with Fresnel lens, positioned in front of the bulb, can transform even this light beam, diverging from the luminous source, in a parallel rays beam, as shown in Fig. 5.237-C.

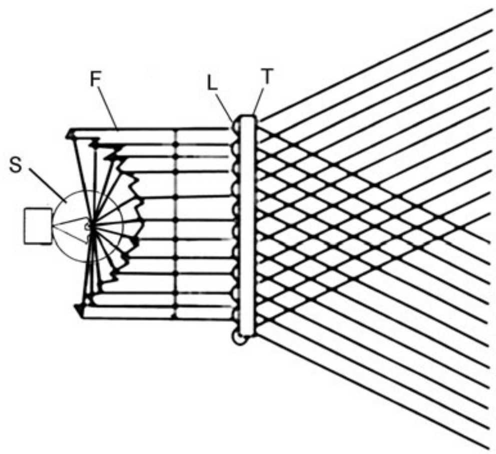


Fig. 5.236. Scheme of a lamp featuring a Fresnel lens F between the bulb S and the combination lens L + transparent T.

For all the solutions presented previously, the light beam color is given by the transparent element.

If the desired transparent cover color is different from that required by the provided light beam, different solutions are available.

The first option is to position a colored filter between source and transparent element, as in Fig. 5.238-A. In that case, the resulting color is given by the sum of filter and cover colors. For instance, with a pink uniform cover, white light can be obtained with a light blue filter and an orange light with a green filter.

A second solution is possible using a computed surface reflector SC, a colored glass LC bulb and a clear transparent element, visible in Fig. 5.238-B.

A third solution can be supplied by an external transparent clear cover T and internal shaped filter LFP, including prism and lens elements, as in Fig. 5.239-A.

In the last two cases, the result is similar aesthetically to the lamp shown in Fig. 5.239-B.

A rather different appearance is obtained in the lamp of Fig. 5.240-B, where the outer color is uniformly red, while different color light beams are emitted as required through the lamp cover. In such a lamp, an intermediate optic system with high contrast lenses is provided (Fig. 5.240-A). In this case, the optical element includes stamped lenses, positioned on the inner surface in such a way to concentrate the light in focal lines, directed between the ribs stamped on the outer surface. The stamped ribs are painted in the desired color, for example red. A further transparent clear element is positioned in such a way to provide the required diffusion angles, through adequate lenses. In such a solution, when the lights are off, the visible lamp color is that of the intermediate ribs coating.

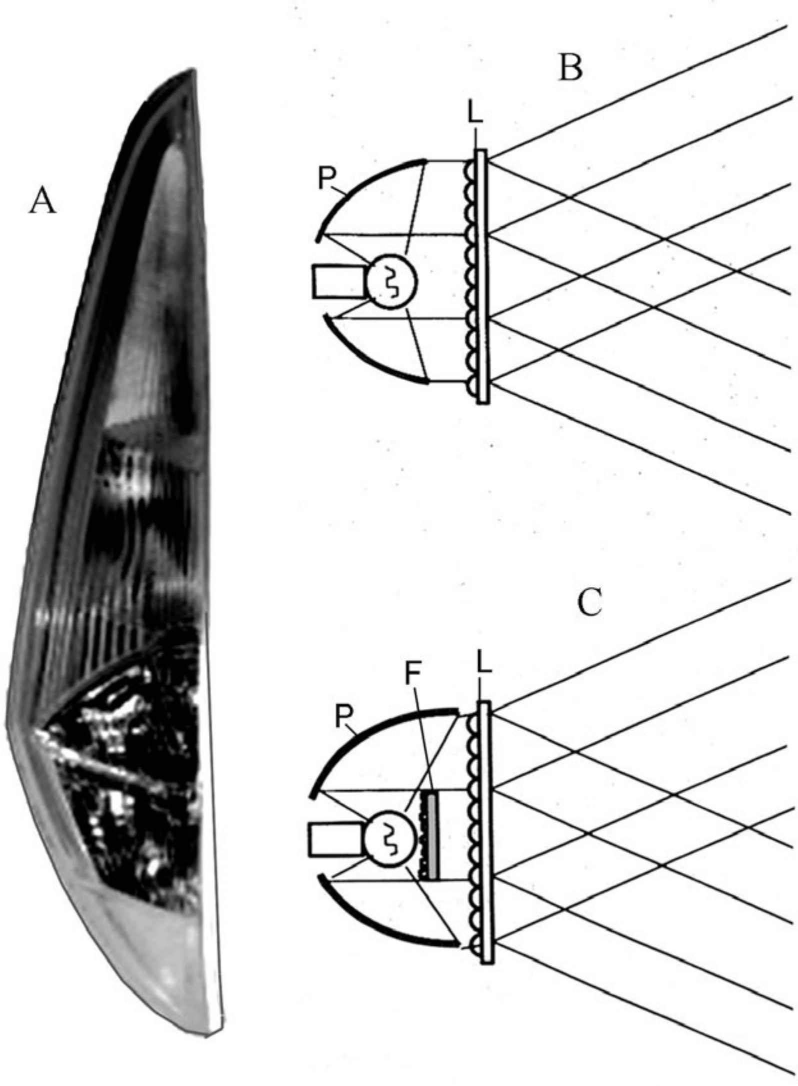


Fig. 5.237. Aesthetic perception (A) of a tail lamp with internal reflecting elements and related optical schemes (B, C). B: combination of reflecting parabola P and lens L; C: combination of reflecting parabola P, Fresnel lens F and multiple lens L.

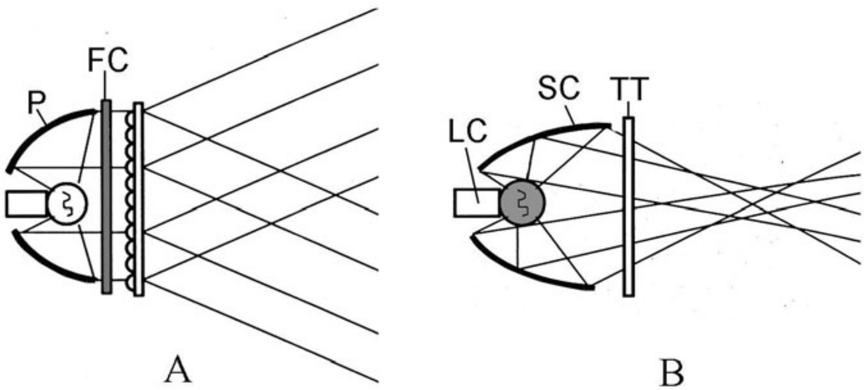


Fig. 5.238. Lamp schemes where the visible color is provided by a colored filter FC (A) or by a colored bulb LC, combined with a clear element TT (B).

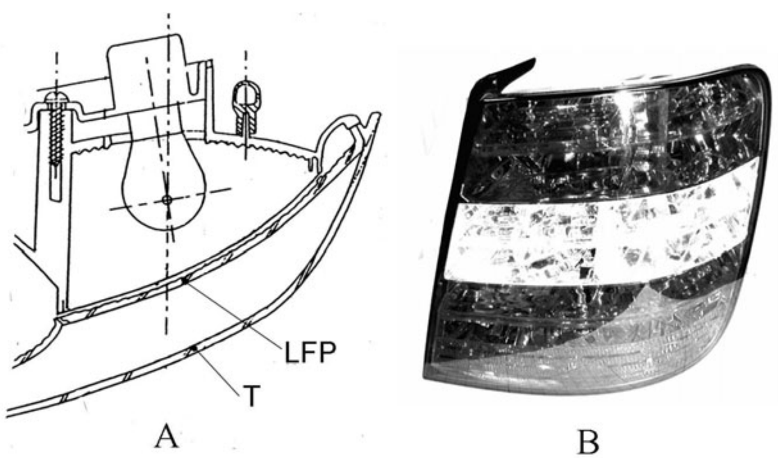


Fig. 5.239. A: section of a colored tail lamp, provided by a lens LFP, including filter and prisms, combined with a clear transparent T; B: image of the same lamp.

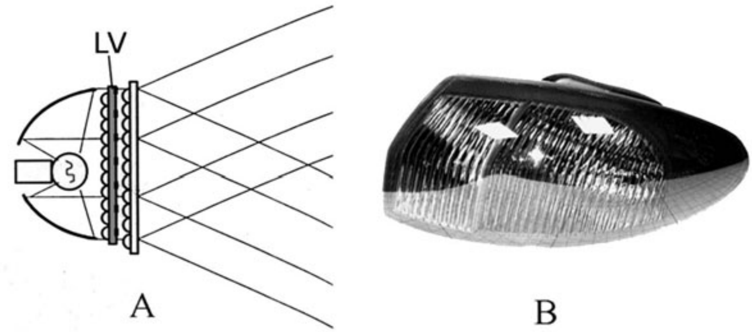


Fig. 5.240. Optical scheme (A) of a lamp with intermediate optical element LV featuring painted stamped ribs and its aesthetic appearance (B)

When the lights are switched on, that color will no longer appear, being covered by the light emission of the colored beam.

In the case of luminous LED sources, the optical system must be adapted, as in Fig. 5.241-B, to a number of light sources, the emission angle of which is very small. The result is shown in Fig. 5.241-A.

Finally, Fig. 5.242 shows the section of a multiple tail lamp. The transparent cover and the parabolic surfaces are waterproof and permanently assembled, the reason being to improve resistance to atmospheric agents. The assembly is fitted to the body and flush appearance is only provided by the part dimensional tolerances. Bulbs can be changed from inside, and their base is usually fitted to an insulating plate which provides the printed electrical circuits for bulbs feeding. These circuits group all electrical connections in a single connector to car wiring harness.

Technical specifications

Headlamps and signal lamps are usually made by specialized suppliers. The drawings that specify their function and configuration belong therefore to two different families: OEM drawings and supplier drawings.

The first family includes an overall graphic description and the technical specifications, in order to explain the functions to be performed on the vehicle and the performance target. These technical specifications integrate the contract between supplier and vehicle manufacturer.

Supply assembly drawing

This drawing is used to provide a general description and graphic display of the assembly. Only vehicle manufacturing critical target are reported, i.e. only obstruction and fitting dimensions needed for the correct assembly installation.

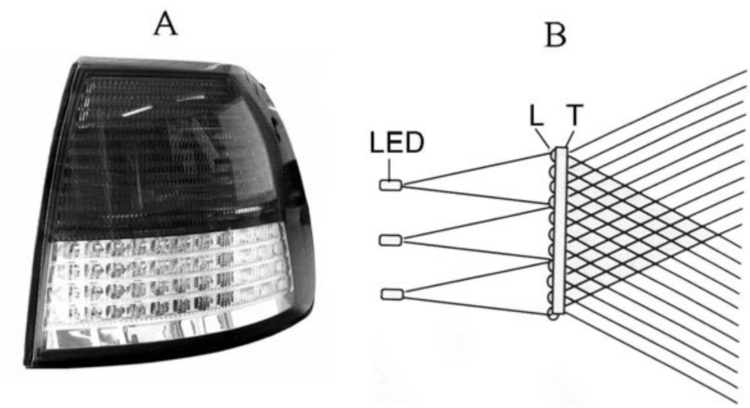


Fig. 5.241. Appearance (A) of a LED tail lamp and optical scheme (B).

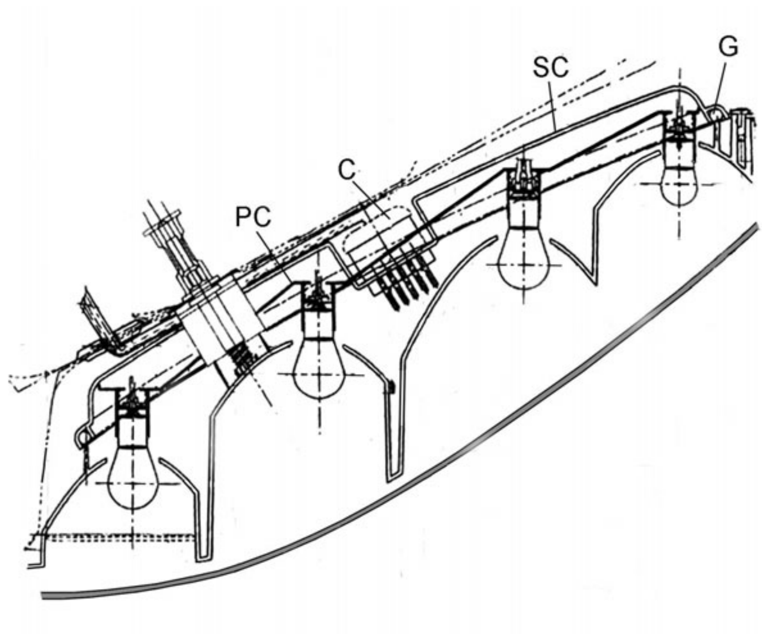


Fig. 5.242. Section of a tail lamp. PC: bulb holder plate with printed contacts; C: system connector; SC: internal removable cover.

Properties and target

This drawing includes the target list to be achieved by the component and the constraints on supplier design freedom, specified by the vehicle manufacturer.

In the first list, the legal regulations, referred to the vehicle market area, are included. Among the constraints, all prescriptions suggested by the experience of the vehicle manufacturer are included, together with field back up of previous suppliers and competitors bench marking.

The main targets refer to the type of bulbs, electrical connectors, glass and reflectors materials, colors, external fitting and to an aesthetic reference model.

Regarding external fittings, stiff mounting should be ensured, screwing torque enabling long vehicle life and 3D geometrical reset availability (in order to ensure flushing with body volume). The type of mounting is usually related to body and trim assembling in the lamp area.

The reference in terms of aesthetics is usually provided by a registered sample, made in a mass production process, approved by the vehicle manufacturer regarding aesthetics and by the supplier in terms of feasibility.

Light beam distribution

This issue is usually additional to law requirements. In fact, the desired light beam distribution is specified in a more detailed way and with narrower tolerance range, anyway within the regulation target.

In the case of headlamps, the target is an effective and uniform lighting of the ground surface; the specification should therefore require:

1. absence of luminous target exceeding areas;
2. absence of shadows or dark spots;
3. absence of light escape or reflections on body outer parts;
4. high width of the luminous beam;
5. overall visibility (according to the state of the art).

Since the purpose of these requirements is to specify the desired overall result, it can be better deployed by a ground luminance map measured through a reference sample mounted on the vehicle.

In the case of a tail lamp, the essential specifications relate to emitted flux uniformity, mostly from the aesthetics point of view. Such target is essential for parking lights, that can be observed from outside without glare risk.

Reliability target

The reliablity target refers to component durability in the vehicle practical use; in the case of headlamps as well as signal lamps, the durability target is the same of overall vehicle life, without service or parts replacement, except bulb replacement for burning or heavy crash consequences.

It is important not only to preserve components integrity, but also the performance level, ie. maintain the effectiveness of reflector and refractors. Therefore, no water, humidity or powder ingress should be allowed; in the case of their presence inside a headlamp or tail lamp, the absence of visible condensation on transparent parts should be ensured.

Delivery testing

The type, purpose and testing procedure for single components or vehicle assembled components are listed below. Each test that can be performed independently of the production vehicle is much more effective as it can be conducted at any step of the vehicle developing process.

Low speed crash

Front and rear impact against pendulum at low speed ($5 \div 7$ km/h). The test involves bumpers and body performance, while any contact with headlamps or tail lights should be avoided, in the worst crushing condition. To understand the concept, it is useful to observe the gap between bumper end and headlamps shown in Fig. 5.232.

Hood drop

Verification of headlamp parts resistance, as the hood drops from open position. The test involves the dampers and hood lock effectiveness and requires a safe gap between headlamps and hood.

Paved track test

The purpose is to verify components fatigue resistance and absence of light fluttering. The test can be simulated on a vibration actuator with just the component assuming the attachments acceleration spectrum is known.

Manual vehicle pushing

The purpose is to verify absence of deformations or breaks after a manual pushing.

Rain chamber test

The purpose is to verify the absence of chemical deterioration on reflecting surfaces or light crossed devices and the absence of corrosion.

Puddle crossing

The test is made on special tracks, to verify absence of water ingress or condensation.

Luminous beam evaluation

Verification of the luminance target map achieving.

Bulb, headlamp and tail light replacement

To verify the practical feasibility of such operations, with usual tools and in specified timing.

Aerodynamic testing

To verify the absence of rustles or whistles due to the mounting plays of front lamps or to their shape.

Headlamp washing

To verify the absence of thermal shock structural damages caused by washing sprays over hot headlamps and the absence af abrasion, when brush wipers are used.

Light beam orientation

Luminance map verification, in the different body pitching designed conditions, due to typical loading conditions.

6
Body Interiors

6.1 Restraint System – Safety Belts

6.1.1 General Issues

Restraint systems, encompassing all the devices inside a car that can mitigate the consequences of a collision, represent the most important aspect for ensuring the achievement of the safety objective imposed by the legislator or required by Euro NCAP or US NCAP (see Volume II).

Seat belts and air-bags are the restraint systems that are responsible for keeping the vehicle occupants in the right position, so that the occupants avoid sustaining injuries beyond the expected limits due to impact against passenger compartment components during rapid deceleration following a crash.

According to European regulation, the occupants of the car, properly wearing their seat belts, must be protected. In this context, clearly evident is the importance of the components, the mission of which is to ensure that, during the events which could create injuries, the occupants of the vehicle are kept in the correct position avoiding any impact against the interior parts.

This function must be carried out without penalizing the comfort and freedom of movements, which are necessary for handling the car.

This following analysis of safety belts covers the aspects concerning the installation of the system on the vehicle and the typical characteristics of each component. But before commencing this analysis, it is interesting to briefly summarize the history of safety belts. The first patent of a system of belts to restrain a person on the seat of the car, was filed by a French man called Lebeau in 1903;

L. Morello et al.: The Automotive Body, Vol. 1: Components Design, MES, pp. 439–661.
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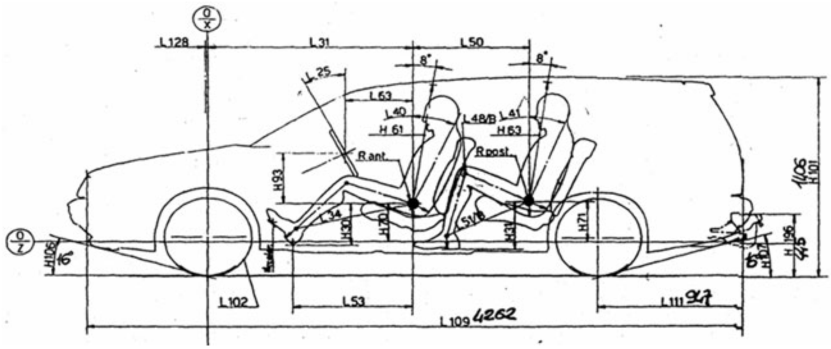


Fig. 6.1. Habitability scheme.

instead the first three-points belts for cars date back to 1956, the results of studies by Nils Bohlin, a pioneer of safety in Volvo, and Bertil Aldman.

The publication of Ralph Nader's book "Unsafe at any speed", in which he openly denounced the existing safety problems on many American and imported cars, provided a decisive contribution to the general perception of this problem and around 1960 the US government issued the first federal law in this respect.

The first obligation to install seat belts on vehicle was promulgated in the state of Victoria (Australia) in 1970, then becoming the first nation to prescribe them all over its territory in 1972.

6.1.2 Seat Belt Anchorages

In order to properly address the issue of seat belts anchorage, one of the requirements of vehicle homologation, it is necessary to define essential terminologies:

- R and H points;
- effective anchorages;
- size S;
- $\alpha 1$ and $\alpha 2$ angles;

R and H points

With reference to a habitability scheme (the arrangement of passengers in the car) e.g. as shown in Fig. 6.1, R is defined as that point on the SAE habitability dummy (usually 50 percentile male) which identifies the right position of the occupant corresponding to his knuckle joint between the femur and the hip.

This point represents the main reference for the habitability design of a car. In our case, it is the reference for the definition of, seat belt anchorages for the front and rear seats.

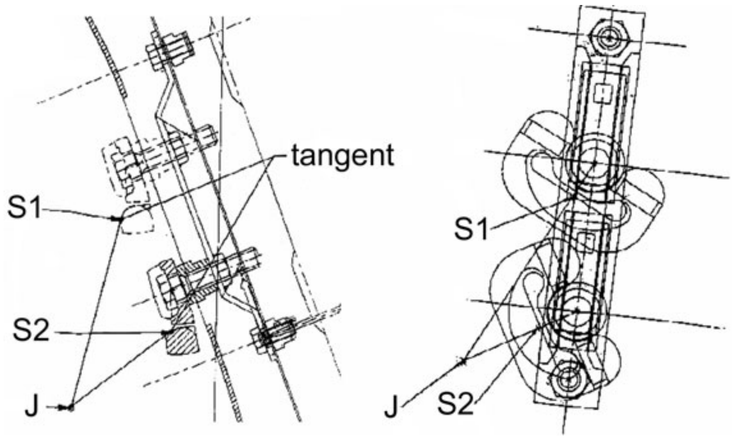


Fig. 6.2. Anchorage points: S1 and S2.

Instead H point is the actual R point measured using a specific dummy. Theoretically this point should be in the same position as the R point, but considering manufacturing tolerances, it is allowed that the H point be located within a square 50 mm wide around the R point.

Effective anchorages

Effective anchorages are the points positioned on their respective components, in particular: Pillar loop, anchor bracket, slide bar, buckle, tongue and retractor in which the belt changes direction during use, or rather the points at which the webbing should be fixed to assume the same configuration when the belt is fastened. These items must be reported to the occupants of both front and rear seats.

For the front seats, for example, the S points identify the effective upper anchor points, and the L points the effective lower anchor points.

The S points are two, S1 and S2 and correspond to the high and low positions of the height adjuster of the seat belts, as can be seen in Fig. 6.2.

Instead the L2 point corresponds to the buckle (Fig. 6.3)) and L1 corresponds to the anchor bracket, for five-door vehicles, or to the slide bar in three-door vehicles.

S size

The S size is the distance, in millimeters (Fig. 6.3) between the S points and the plane xz passing through the R point of the front seat occupant, or rather the longitudinal middle plane of the front seat.

J point

The J point is the point on the shoulder where connection with the webbing is made when the seat belt is fastened.

$\alpha 1$ and $\alpha 2$ angles

$\alpha 1$ and $\alpha 2$ are the angles made between the lines through the point L1 and L2, respectively, and the line of a horizontal plane passing through point R itself.

Determination of areas/anchorage allowed points (effective anchorages)

Although specific software exist for the definition of the areas and allowed points of anchorage, it is interesting to consider the methodology used to define the attachments of seat belts covered by the R 96/38 regulation: "Anchorage for adult safety belts for front seat occupants".

Upper anchorages

When the parameter S is known, the operations to identify the area in which the effective anchorages must be located are summarized in the following three phases:

Phase 1 (Fig. 6.4), determination of point C. First plot the R point on the body reticule and then the axis of the dummy torso passing through R, and quote the angle between this axis and the vertical line passing through the R point; plot the C point on the vertical line passing through the R point 450 mm above the R point, and draw a horizontal line passing through C.

Phase 2 (Fig. 6.4), determination of points J, B and D. Draw the segment RZ 530 mm long on the torso axis from the R point, and then a perpendicular line at the torso axis, passing for Z at 60 mm. The J point is on this perpendicular line, towards the front of the car.

Point B is defined by the formula:

$$BR = 260 + S.$$

If S $\geq$ 280 mm, and the car-manufacturer has opted for the formula:

$$BR = 260 + 0,8S,$$

the vertical distance RC is 500 mm.

Point D is defined by the formula:

$$DR = 315 + 1,8S.$$

If S $\geq$ 200 mm, segment DR becomes 675 mm.

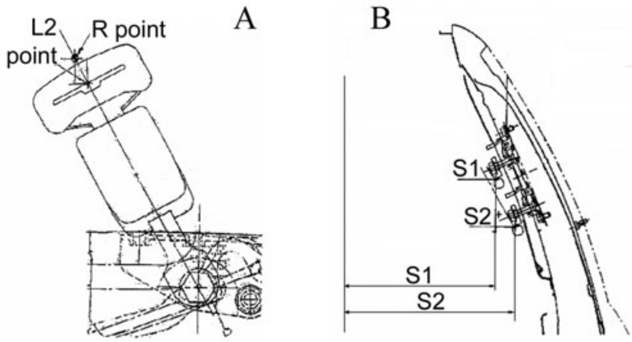


Fig. 6.3. A: determination of L2 point; B: S dimensions.

Phase 3 (Fig. 6.5), determination of the allowed area. Draw a line passing through point D, inclined by 65° with reference to the torso axis (clockwise); for rear seats, this value can be reduced to 60°.

Then draw a line passing through point B and inclined of 120° with reference to the torso axis (clockwise); the intersection of the two lines passing through points D and B determines point F.

The area allowed for the highest anchorage point S is included between the planes FN, FK and CY, all determined in function of the S dimension, as shown in Fig. 6.5.

The N, Y and K points show the direction taken by the straight line only and are not a limitation of the installation of the pillar loop. These requirements are not binding positions in x direction; however Directive D 96/38 provides that the installation of any seat belt of whatever seat must enable the belt to be readily available for use and easily recoverable without requiring specific training or practice.

The trajectory taken by the webbing must ensure correct restraint to reduce the risk of injury in an accident and, at the same time, not compromise comfort.

In addition, for a two-door car with the upper anchorage point on the B pillar, the installation of the seat belt safety system must be designed so as to not obstruct access and/or egress from the rear seats.

In association with the widespread application of height adjusters to enable better belt routing without penalizing the retention, it is necessary to consider the R point in the most unfavorable position, i.e. with the seat down and completely back, and verify that the two effective anchorage points are in their respective authorized areas, determined in accordance with the S1 and S2, sizes. See Fig. 6.6 for reference.

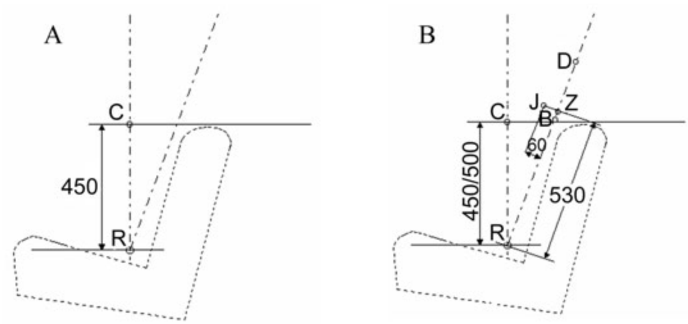


Fig. 6.4. Allowed areas, phase 1, A: determination of point C; phase 2,B: determination of point J, B, D.

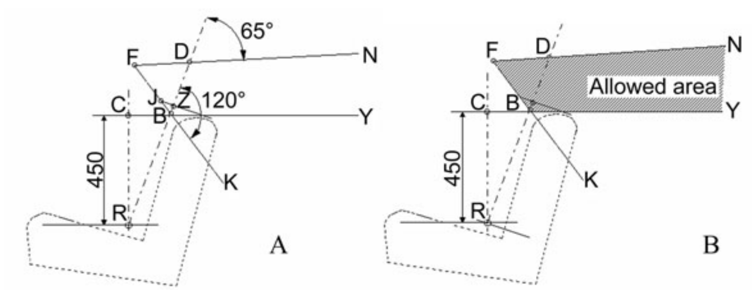


Fig. 6.5. Phase 3, determination of allowed area.

Authorized area S1 is the area included by N1/F1 planes and the intersection of F1/K1 planes with CY. Authorized area S2 is the area included by N2/F2 and the intersection of F2/K2 planes with CY.

Lower anchorages. Also the position of the effective anchorage points, (buckle L2 side, and the opposite to buckle, L1 side) is established by D 96/38: These points must be positioned so that the angles formed by joining point L1 or L2 and the horizontal line passing through the R point are included:

- Between 45° and 80° for the L2 point (non-constant angle);
- between 50° and 70° for the L2 point (constant angle);
- between 30° and 80° for the L1 point (non-constant angle);
- between 50° and 70° for the L1 point (constant angle).

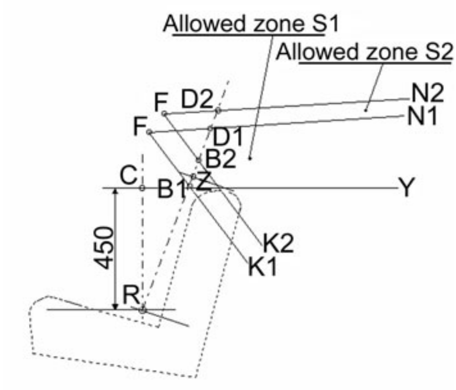


Fig. 6.6. Determination of allowed areas for S1 and S2.

For the front seats, the above-mentioned limits must be respected in all seat positions.

Determination of the L2 point when α2 angle is not constant and the buckle assembly is anchored to the floor, (see Fig. 6.7). Plot on the body reticule the R point and orient the buckle assembly in alignment with the R point. Then draw a half-line from the R point (set all back) and orient to 45° and another one to 80° both clockwise from the horizontal plane passing through point R. Repeat this operation for the R point (set all frontward).

In the case of seats fitted with height adjustment, the checks of the angles must be made in all positions that can be assumed by the R point; the effective anchorage point L2 must be inside the defined areas and the angle obtained for each position of R point must be shown on the drawing.

Determination of the L2 point when α2 angle is constant, and the buckle assembly is anchored to the seat, (see Fig. 6.7).. After having positioned the R point and oriented the buckle assembly as described above, draw a half-line starting from the R point (all back position) with an inclination of 50° and another half-line with an inclination of 70° both clockwise with reference to the horizontal plane passing through R point.

Considering that, when the buckle assembly is fixed to the seat, α2 does not change even if the seat is moved, the process to define the L2 point is straightforward since it is only necessary to position the R point in one of its stroke ends (for example all backward).

Determination of L1 point when α1 angle is not constant and the bracket is anchored to the side frame, (see Fig. 6.8). When applied, the anchor bracket is oriented towards the R point, as usual positioned to the body reticule, a half-line is drawn from the R point (all backward), inclined of 30°, and another half-line inclined of 80°, both clockwise with reference to the horizontal plane

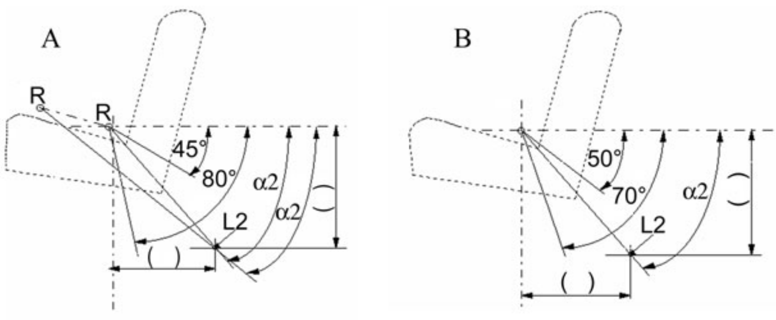


Fig. 6.7. A: determination of point L2 with $\alpha2$ not constant, buckle assembly anchored to the floor; B: determination of point L2 with $\alpha2$ constant, buckle assembly anchored to the seat.

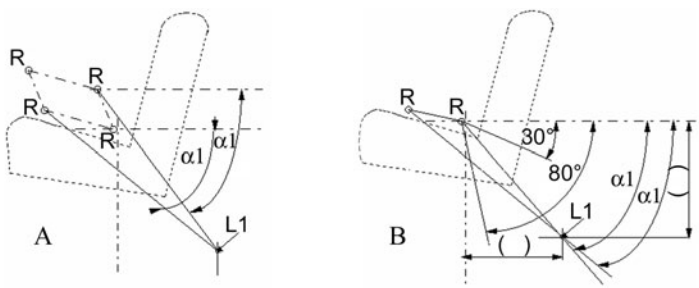


Fig. 6.8. A: determination of point L1 with $\alpha1$ not constant, bracket anchored to the side frame, seats with the height adjustment; B: determination of point L1 with $\alpha1$ not constant, bracket anchored to the side frame.

passing through the R point. The operation is repeated with the R point in the advanced position.

In the case of seats with height adjustment, the procedure should be applied for the extreme positions, as shown in Fig. 6.8.

The L1 point must be inside the defined areas; angles for each extreme point must be shown on the drawing.

If the actual anchorage point is on a slide bar, as generally happens in two-door cars, the procedure to determine the position of L1 is modified as follows: Draw a half-line joining the R point and intersecting of 90°, the line on the tangency point of the slide bar internal part, closer to the R point.

In the case of seats with height adjustment, the R points that are considered must be in the extreme position, i.e. the one that determines the minor and

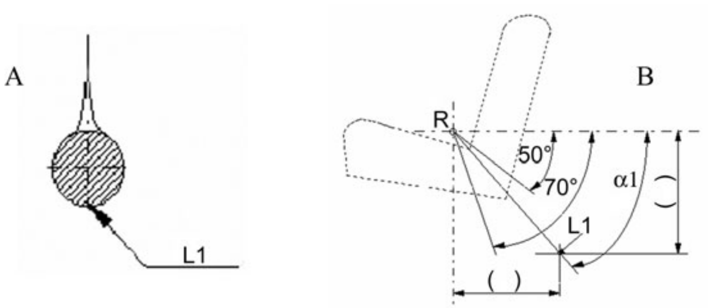


Fig. 6.9. A: transversal section of slide bar, with in evidence the L1 point; B: determination of L1 point when $\alpha 1$ angle is constant and the bracket is anchored to the seat frame.

the major angle possible for the different position of the R point. It is therefore necessary to declare the $\alpha 1$ angle obtained in respect to the admitted angles (see Fig. 6.9).

Determination of L1 point when $\alpha 1$ angle is constant and the bracket is anchored to the seat frame (see Fig. 6.9). After the anchor bracket is oriented towards the R point, draw a half-line inclined of 50°, from R point (all backward) and another half-line inclined of 70° clockwise from the horizontal plane passing through R point. Again, as already seen for L2, with constant angle, the $\alpha 1$ angle does not change if the seat position varies.

The effective anchorage point must be inside the areas defined before and the angle obtained from the R point in the extreme position must be shown in the drawing.

Belt routing

The correct definition of anchor points, and the relative angles, enables the correct belt routing to be defined in order to obtain the most effective restraint without creating negative effects (for example secondary lesions) with maximum comfort. As an example, it is appropriate to consider the S points; if S1 and S2 are too high, the contact of the shoulder with the seat belt is clearly not optimal and the restraint is not effective. If S1 and S2 are too low, the restraint is effective but, in the event of a collision, it is possible that a secondary lesion of the shoulder occurs.

Since the occupants of the car sit on the seats, it is clear that, if the attachment points of the seat belt are on the seats and have the same possibilities for movement, the belt routing is certainly better in comparison to the case in which the attachment points are positioned totally or partially on the body of the car.

For this reason nowadays the anchor of the buckle, which determines the L2 point, is located on the seat whereas in the past it was located on the floor of the car. Today the anchor bracket, which determines the L1 point and that used to be placed on the side frame, is often placed on the seat (clearly only in four-door cars).

Finally the adoption of the seats with all the three anchor points of the seat belts on the seats (all belt to seat), is possible by moving the retractor from the central pillar on to the seat itself, completes the optimization of the belt routing and comfort.

Currently, however, the all belt to seat solution is used only in limited and specific applications.

6.1.3 Analysis of Seat Belts Components

These components are essentially standardized, because the same component is used on different cars and by different car-manufacturers. Small differences can be only generated by specific conditions for belts installation. The main traditional components are (Fig. 6.10):

- Webbing;
- pillar loop;
- height adjuster;
- buckle assembly;
- retractor;
- anchor bracket.

The following must also be added:

- Load limiter;
- pretensioner;
- active control retractor (ACR).

The webbing

The webbing is the component of the safety seat belts that has the mission of physically restraining the occupants on the seat. It consists of a fabric with structure, warp and weft, woven with techniques and materials in such a way as to provide high resistance to breakage and severe aging cycles. Today the webbing is designed to resist loads in the order of 2,500÷3,000 daN.

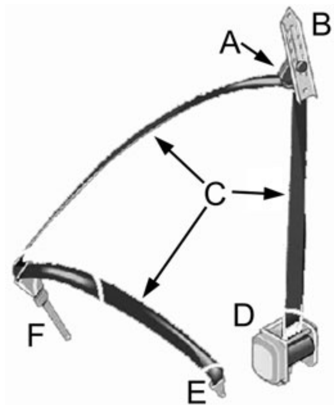


Fig. 6.10. The main traditional components of the safety seat belt. Components: Pillar loop A, height adjuster B, webbing C, retractor D, anchor bracket E, buckle assembly F.

The webbing is also responsible for the so-called comfort of use, which is determined by the perception of the user when the seat belt is worn. A webbing which is soft and smooth with low transverse stiffness is usually perceived better in terms of comfort than a webbing with hard edges.

To improve the comfort of the seat-belts during use, at the end of the manufacturing process the webbing is subjected to special treatments by immersion in baths with solutions to lower friction and improve the tactile sensation.

In particular, by working on the side closure of the warp during the texture process, it is possible to obtain a softer webbing edge. In this way the contact between the webbing and the occupant's body does not give rise to discomfort (Fig. 6.11).

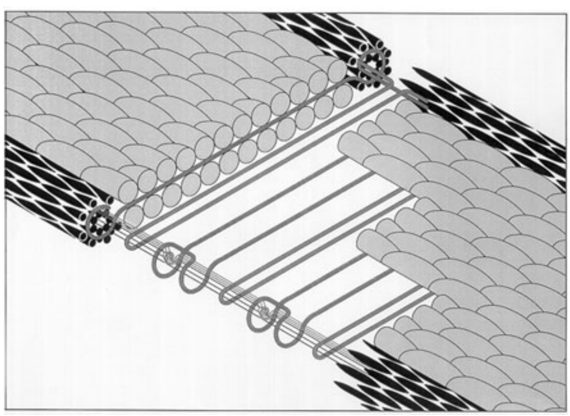


Fig. 6.11. Webbing structure.

The pillar loop

In practice the pillar loop is the effective upper anchor point which can either be fixed, if anchored directly to the central pillar, or mobile in terms of height with the seat belts height adjuster. The most common implementation uses a metal ring covered with an in-moulded plastic material. Also solutions made entirely of steel exist, as shown in Fig. 6.12.

The pillar loop has adequate tensile strength as required by the seat belts system and guarantees that the surface, in contact with the webbing, is without roughness in order to avoid wear which, over time, can cause breakage.

Although this component appears to be quite simple, it is critical in terms of the stresses that must be endured and damage to the webbing that could result. For this reason, the pillar loop is designed to resist impulsive loads, and prevent the webbing running through it very quickly during the impact or becoming twisted over its width which may cause significant abrasion and result in breakage of the webbing.

The solution for the pillar loop, i.e. in-moulding, uses a plastic material which represents its point of weakness since the presence of gaseous occlusions or very small cracks inside the plastic could lead to a brittle fracture of the covering and possible breakage of the webbing.

The fully steel solution is more expensive but offers the advantage of being less sensitive to production process variations and during impact, the deformation of the steel can contribute to energy absorption (Fig. 6.12).

Fig. 6.12. A: pillar loop; B: tongue.

The buckle assembly

The buckle is the component of the seat belt to which the tongue is engaged, made with plastic material in-moulded on a metal insert similar to the pillar loop; see Fig. 6.12.

The buckle assembly is composed of a coupler contained in a plastic casing equipped with a release button which must ensure release operation always, particularly following an accident, and provide a link to the real anchor point. Today, as already mentioned, the real anchor point is placed on the seat (Fig. 6.13), whereas in the past it was located on the floor; the link can be made with a metal cable or flat metal.

The height adjuster

This device is installed on the central pillar (B pillar), according to the procedure described previously for the definition of effective anchor points, S1 and S2, and is designed to enable the appropriate positioning of the webbing on the shoulder of occupant, according to different population percentiles (i.e. people of various heights). It comprises a slide-shaped device with a mobile part sliding in a track, and a fixed part to which the cursor can be fixed in the chosen positions. The pillar loop is fixed on the cursor (Fig.6.13).

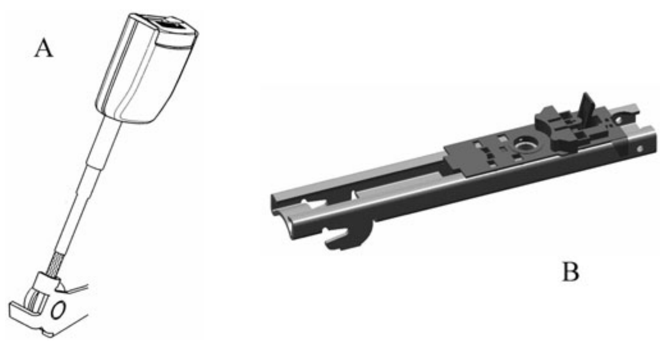


Fig. 6.13. A: buckle assembly; B: height adjuster.

The retractor

The retractor constitutes the heart of the safety belt system, having the task of wrapping the webbing on a spool, enabling the unwinding and ensuring that the seat belt does not cause the unwanted sensation of excessive shooting or impediment to occupant movement, which may be caused especially if extraction of the webbing is blocked when not required to do so (Fig. 6.14).

Instead the locking of the webbing is standardized by the regulation R 16 and is governed by two independent systems: The geometric and dynamic system.

The geometric system causes the locking of the belt when, due to external events (deceleration, shock, etc.), the car moves by a significant number of degrees compared to the reference horizontal position.

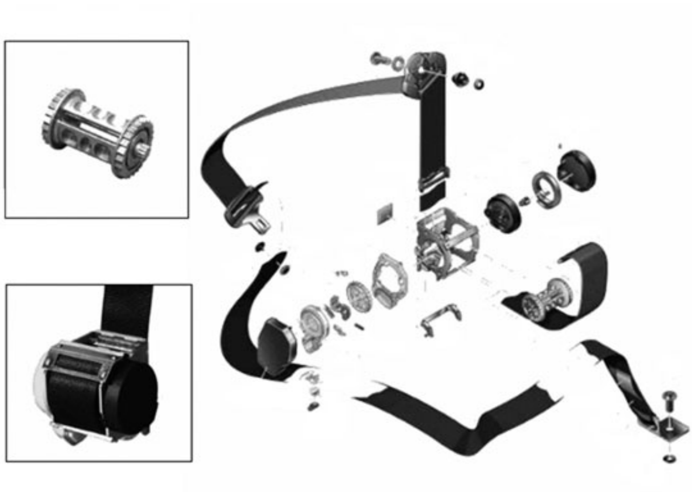


Fig. 6.14. The retractor.

It must never stop angular variations not exceeding 12° and should always block over 27°. This system is managed by a metal ball pendulum that triggers the locking system starting from a nominal position.

The dynamic system intervenes when the retractor undergoes significant deceleration or the webbing is extracted abruptly, i.e. with high acceleration, from the retractor. The locking is achieved using both the same system described previously and a helical spring that drives the lock spring if the acceleration exceeds the specified limit.

In any case, from the instant the spool is locked, no more than 50 mm of webbing can be extracted from the retractor. Clearly, being a critical component in terms of occupant safety, the retractor must satisfy many requirements:

- Locking:
  - Up to 0.3 g no lock (it must never get blocked up);
  - over 0.45 g must lock (it must always get blocked up).
- tensile strength >14.7 kN;
- length of the webbing 2,500÷3,000 mm.

The load limiter

To retain vehicle occupants with safety belts without penalizing the comfort or create secondary injuries is a relatively complex task; the load limiter represents

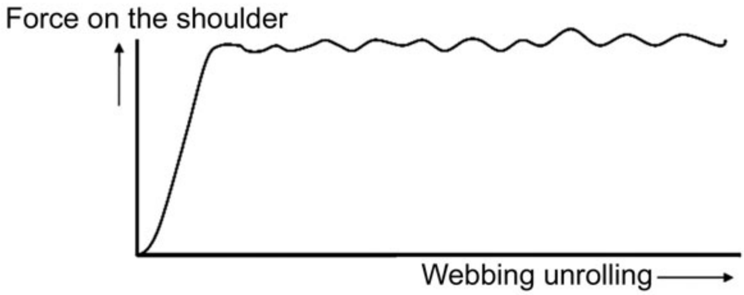


Fig. 6.15. Load limiter; force - unrolling diagram.

a valuable aid to reach the goal, thanks to the use of the pretensioners, by now almost standard, which are analyzed below.

The load limiter, nowadays practically an integral part of the retractor, has the task of limiting the force transmitted by the belt to the shoulder and the chest during an impact, so as to mitigate any effect on the occupants.

Part of the load limiter is the torsion bar, located in the retractor. During impact, it twists around, enabling a limited and controlled unwinding of the webbing so as to limit the force exerted on the occupant and thereby mitigating damage to the shoulder and chest; see Fig. 6.15.

The principle of operation of the load limiter is shown in Fig. 6.16: Spool 1 of the retractor is connected to torsion bar 2, (spring/pretensioner side); torsion bar 2 is connected to the teething 3 (mechanism side); locking bar 4 engages with teething 3.

Extraction of the webbing, due to the effect of the load applied, causes the spool to rotate and determines the torsion of the torsion bar 2 that slightly loosens the drawing of the belt.

The Pretensioner

Pretentioners have been introduced in order to increase the efficiency of seat belt retention. These are normally used by the occupants of the front seats and to a lesser extent by occupants of rear seats.

Pretensioners increase the effectiveness of the seat belts because they reduce the slack, i.e. the clearance of the webbing on the spool, the effect of clothing worn by the occupants or incorrect sitting posture (OOP, out of position).

The action of the pretensioner is represented in the diagram in Fig. 6.17, illustrating the strength retention over time of a seat belt without pretensioner.

The presence of the pretensioner, which provides an additional retention force only when needed (i.e. during impact), can reduce the static strength of the retention system resulting in an increase in comfort which helps improve active safety.

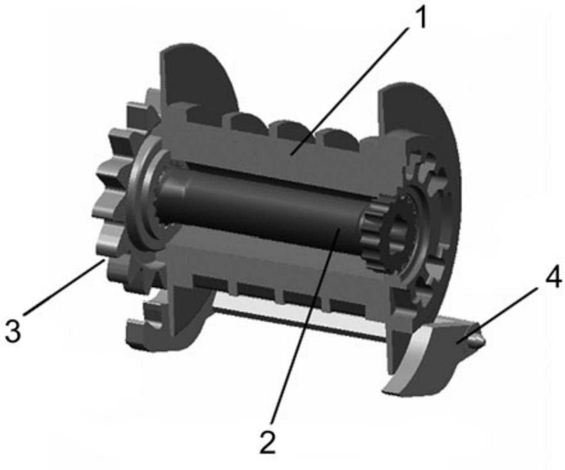


Fig. 6.16. Load limiter: 1 Spool, 2 torsion bar, 3 toothing (mechanism side), 4 locking bar.

Pretensioners can be installed on the safety belts system, on the buckle assembly or on the retractor.

In addition to the product strategies of the car manufacture, the choice depends mainly on the seat configuration because, if the pretensioner is on the buckle assembly, it exerts a priority action on the pelvis whereas, if the pretensioner is installed on the retractor, the priority action is on the chest.

For example, in case of a seat that does not limit the submarining effect (when occupant slips forward in frontal impact), it is better to install the pretensioner on the buckle assembly.

Recently manufactures, especially of higher segment cars or when the target is excellent evaluation in terms of passive safety, have begun to adopt two pretensioners, one for the retractor and one on the anchor bracket (L1 point). Apart from improving the retention, the double pretensioner enables also the sequencing of the two pretensioners according to the type of impact and position of the seat occupant. It also enables a modulation of forces applied to the occupant and reduces the action time of the safety belts system.

Pretensioners can be classified depending on the system of generation of the force, mechanical or pyrotechnic, and depending on the sensors that activate the pretensioners, mechanical or electronic.

The mechanical force generator of the first pretensioners uses a metal spring, such as those of underwater fishing guns, activated by a mechanical sensor. In this case the pretensioner is installed on the buckle assembly. Today pretensioners are practically all pyrotechnic with electronic sensors, examined in detailed below.

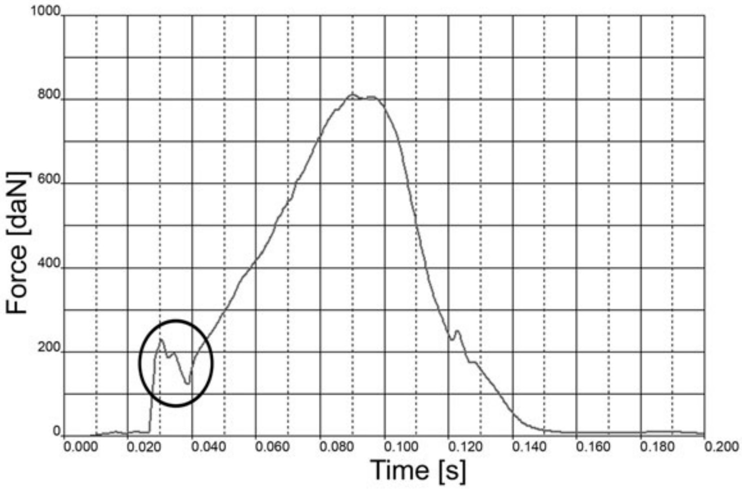


Fig. 6.17. Diagram of strength retention vs. time of seat belt system without pretensioner.

However it is useful to first describe the solution of pyrotechnic pretensioner on the retractor with mechanical sensor, which is realistic only for a car without air-bag.

Pyrotechnic pretensioner on the retractor with mechanical sensor

This system, represented in Fig. 6.18, consists of two-level sensors with two masses: M1 and M2 (M1 mass being much larger than M2), and two respective opposing springs, m1 and m2.

In normal car running conditions, springs m1 and m2, causing the trigger G to remain engaged with mass M2, do not permit the sliding of the block cap Pb and, consequently, the movement of percussion pin P. In the case of no fire event, i.e. an event that does not trigger the intervention of the pretensioner, the vehicle deceleration provides the mass M1 with an energy which is not sufficient to cover all the stroke S1 and all the stroke S2 along M2 mass.

Therefore M2 mass, interacting with the trigger G, does not permit it to rotate at the fulcrum f and allow the block cap Pb to release the percussion pin P which would activate the pyrotechnic charge C. M1 and M2 masses consequently return to their initial positions.

In the case of a must fire event, shown in Fig. 6.19, the vehicle deceleration value provides M1 mass with sufficient energy to cover the distance S1 and pushes M2 mass for the entire distance S2; mass M2, covering the entire distance S2, releases the trigger G which, rotating at the fulcrum f, allows the block cap Pb

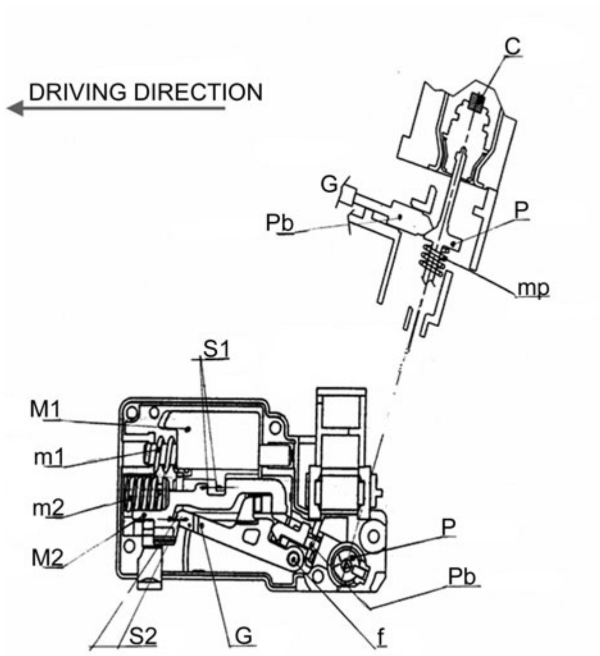


Fig. 6.18. Pirotechnic pretensioner on the retractor with mechanical sensor in no fire condition. C pyrothecnic charge, G: trigger, P percussion pin, P_b block cap, m_p percussion pin spring, S_1 stroke, S_2 stroke, M_1 mass, M_2 mass, m_1 spring, m_2 spring, f fulcrum.

to scroll and release the percussion pin P that strikes the pyrotechnic charge, causing its activation (i.e. explosion).

Examining Fig. 6.20, where it is possible to observe how the retractor and the pretensioner can be considered to be a single component fixed at the base of the B pillar (central pillar), it can be seen that the activation of the pyrotechnic charge C triggers the propellant PG placed inside the container CP.

Propellant combustion develops a gas pressure which generates a force that pushes up the rack-piston PC, making the gear wheel RD1, which is connected to RD2 (RD2 is meshed with the gear wheel BD and inverts the spool rotation), rewinding the webbing a few centimeters.

After each activation of the pretensioner, the belt suffers permanent damage and therefore the safety belts system must be replaced.

If the seat belt is not fastened, the device shown in Fig. 6.21 explains how to inhibit the pretensioner's activation.

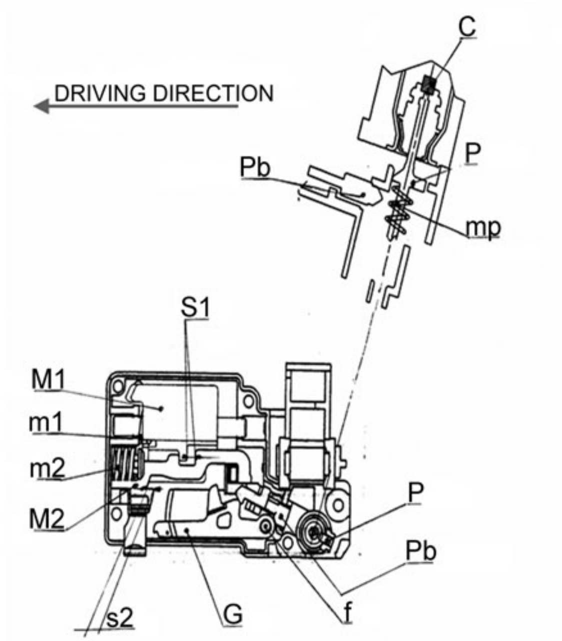


Fig. 6.19. Pretensioner with mechanical sensor, in must fire position. C pyrotechnic charge, G trigger, P percussion pin, P_b block cap, m_p percussion spring, S_1 stroke, S_2 stroke, M_1 mass, M_2 mass, m_1 spring, m_2 spring, f pivot.

This device consists of:

1. A sliding SC which moves into a guide obtained in the sensor's cover CS,
2. a spring ms which pushes the sensor against the webbing enveloped on the spool of the retractor.

When the value of the diameter of the webbing enveloped on the spool is at the maximum level (belt not fastened), the protuberance PS, located at the bottom of the sliding SC, interposes itself between mass M2 and the sensor cover SS, thus preventing the movement of the mass and consequently the possible activation.

When the value of the diameter of the webbing enveloped on the spool is reduced (belt fastened), the spring ms pushes up the sliding SC, so freeing the protuberance PS of the mass M2, thus allowing it to move and then active the pretensioner.

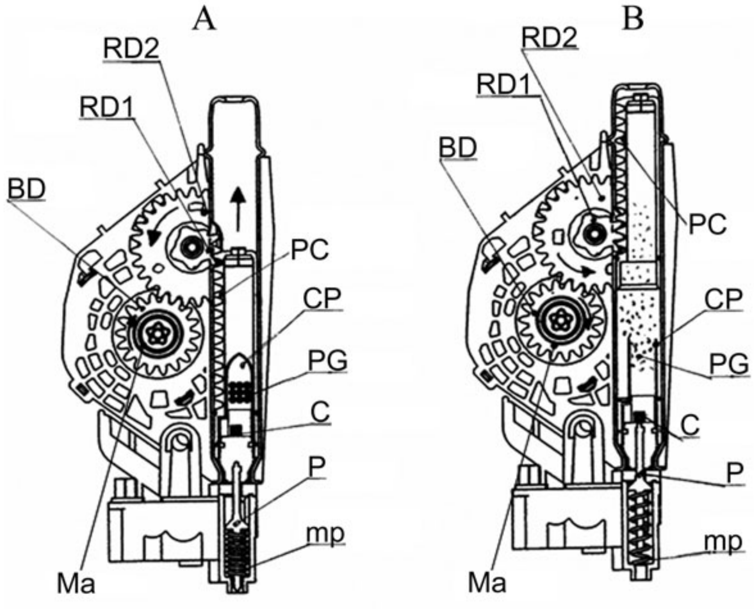


Fig. 6.20. The retractor of pyrothecnic pretensioner before (A) and after (B) activation. RD_1, RD_2 and BD gear wheels, Ma mandrel, mp percussion pin spring, P percussion pin, C pyrothecnic charge, PG propellent, PC rack-piston.

Pretensioner on the retractor with electronic sensor

In this case, the pyrotechnic charge of the pretensioner is triggered by an electrical signal which arrives by electronic deceleration sensors, located appropriately on the car and managed by electronic control unit of the car safety system.

When the software receives the signals by the sensors that register a situation as a severe impact of the vehicle, it sends an electrical signal to the pretensioner that triggers the pyrotechnic charge CP. The propellant PG burning develops a gas pressure which generates a series of movements, as seen before, which determine the rewinding of the webbing, (see Fig. 6.22).

Pretensioner on buckle assembly with electronic sensor

Also this case, Fig. 6.23 highlights how the pretensioner is an integral part of the buckle assembly, creating a single component that is fixed to the seat of the vehicle.

As previously seen, the gas generates a pressure on the piston P that, in this case, is pushed along the tube T; the piston P, linked to the buckle Fb by a steel rope, can pull down the buckle Fb a few centimeters.

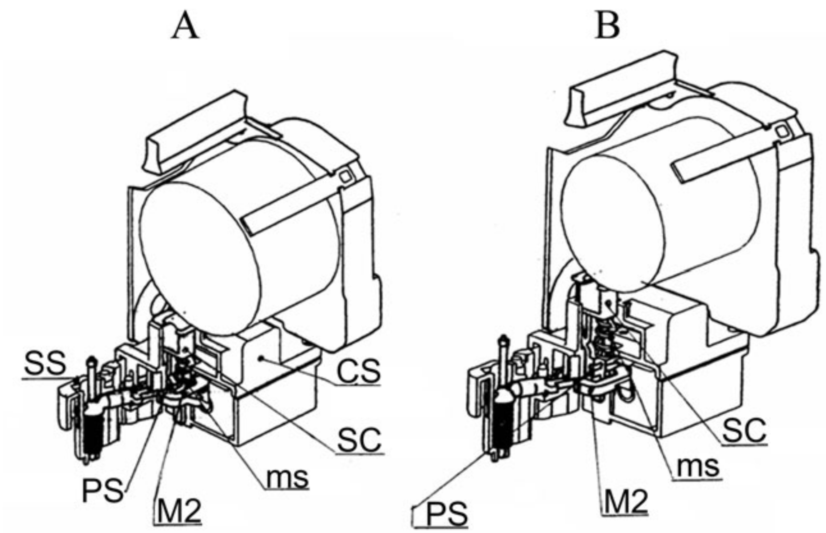


Fig. 6.21. Device to inhibit pretensioner's activation when the seat belt is not fastened (A), and when the seat belt fastened (B). Components: SS sensor housing, PS protuberance, M_2 mass; ms spring; SC sliding; CS cover sensor.

To conclude this explanation on pretensioners, and before initiating the explanation on air-bags, it is important to note how these two tools for car occupant passive safety are integrated into one system: The car passive system, as shown in Fig. 6.24.

Considering what it is mentioned before, it is easily understood why the pretensioners with the mechanical sensors have been abandoned, except for rare cases in which the air-bag is not present.

Finally, it should be noted that the use of pyrotechnic charges for pretensioners and air-bags requires knowledge and application of specific safety standards. Some of these are listed below.

The components with pyrotechnic charges require that their handling and storage are carried out in accordance with specific rules in order to avoid damage or injury.

The components with pyrotechnic charges must be protected from exposure to temperatures above 100°C, from sparks and blazes.

At temperatures above 150°C the self-ignition of the pyrotechnic charges is possible.

The components with pyrotechnic charges must be protected from stresses and falls.

The components which have suffered falls or crashes cannot be used and must be returned to the suppliers.

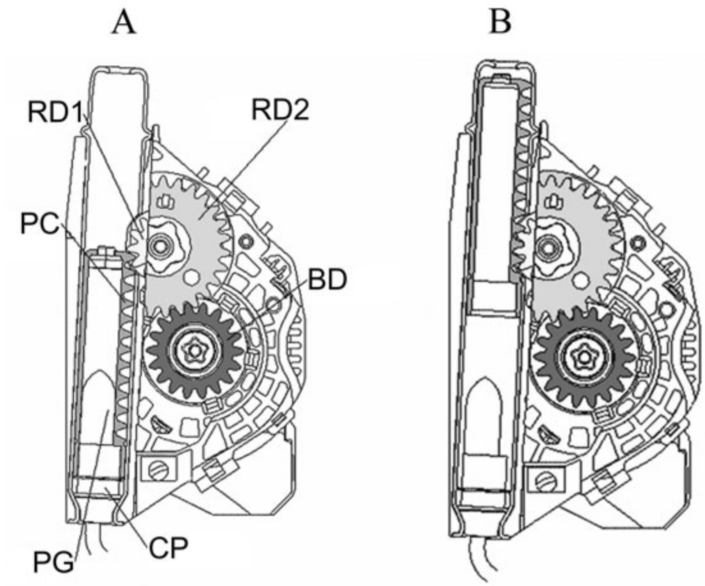


Fig. 6.22. Pretensioner on the retractor with electric sensor: (A) before activation; (B) after activation. Components: RD_1, RD_2 and BD gear wheels, PC rack-piston, PG propellent, CP pyrotechnic charge.

The gas generators (see in details in the air-bag analysis) cannot come into contact with acids, water, grease or heavy metals. This contact can cause the formation of poisonous gases, dangerous or explosive compounds.

As the propellant of the gas generator which is non-burned is lightly flammable, the parts of the gas generator should never be broken, damaged or manipulated.

For teaching or advertising demonstrations, only inert components should be used. These components must report the INERT writing which must be well visible.

After the activation, the component becomes hot; therefore it is necessary to wait ten minutes before touching it.

It is forbidden to keep pyrotechnic components together with inflammable materials or fuels.

It is strictly forbidden to disassemble pretensioners and airbags into their constituent parts.

The active control retractor system (ACR)

The ACR system is a system in which the pretensioning can be considered a part of an active safety system, representing an evolution of the pretensioner that, as

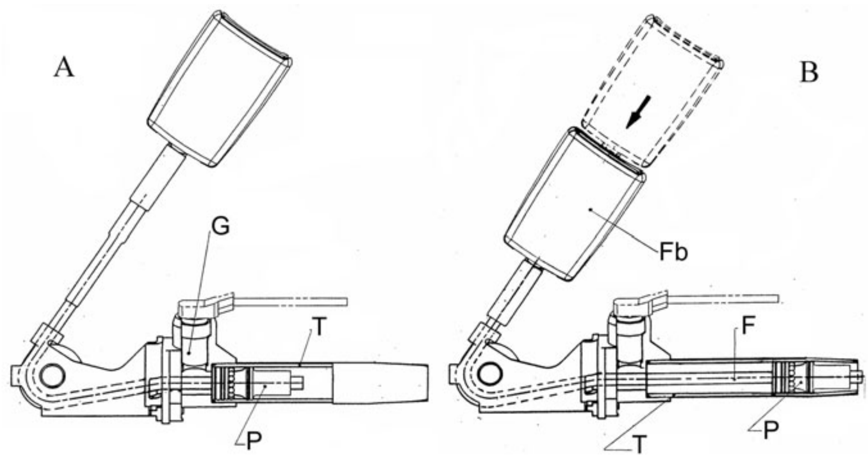


Fig. 6.23. Pretensioner on buckle assembly with electronic sensor: (A) before activation, (B) after activation. Components: G gas generator, T tube, P piston, Fb buckle F steel rope.

already seen, comes into action only in the case of a specific event, after which it must absolutely be replaced.

The ACR functions can be identified as follows:

- Restraining adequately the car occupants in case of different dynamic driving situations, increasing the drawing of the seat belts. When a non-usual condition is registered on the vehicle such as sport driving or emergency manoeuvres, the ACR system reduces the slack pretensioning in a reversible mode without activating the pretensioner when a collision does not occur. If the pretensioner does not become active, the ACR system reduces the drawing of the belts to the normal situation. The appropriate retention of the belts is particularly important for the driver, allowing better control of the vehicle in critical conditions and enabling the possible accident to be avoided (active safety).
- Providing a better comfort of occupants in normal conditions and less tension of the belts. In fact, when needed, the ACR system can increase the tension of the belts. To do this the ACR works in synergy with the active safety system such as ESP, ABS and body vehicle computer.

The ACR system comprises an electric motor connected to the spool of the retractor that allows the drawing of the seat belts to be increased when necessary, then returning to the original conditions when activation is completed (see Fig. 6.25).

The ACR system was initially powered at 42/48 V, relegating the use of this component to hybrids, electric and specific top-range cars. The possibility

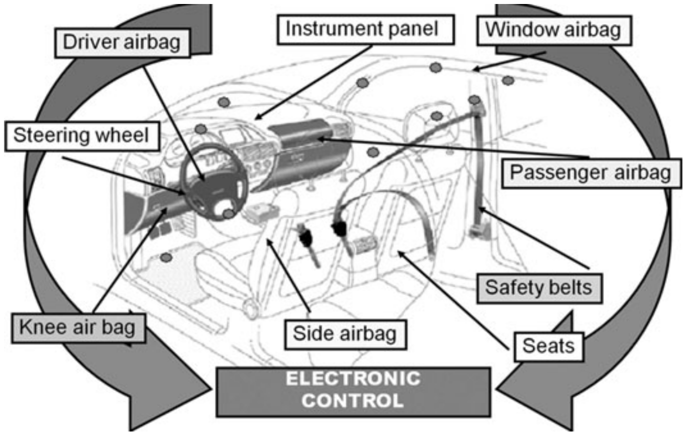


Fig. 6.24. Car passive system.

now to use the 12 V voltage in the car will offer a greater opportunity for market penetration in spite of the high price.

6.2 Restraint System – Air-Bag

6.2.1 General Issues

The air-bag is an additional restraint system which was conceived in Europe; it is used in the countries where the safety belts are compulsory, and is designed to be used in combination with the safety belt. In the case of an accident, within a certain impact speed range, it acts to limit the extent and the entity of injuries to the occupants of the vehicle. The USA are an exception because, even though the use of the safety belt is compulsory in almost all states, rules state that the occupants have only to be protected by an air-bag.

In the case of an accident, or if an action with certain force is exercised on the vehicle, one or more sensors, which are appropriately located on vehicle, send an electric signal to an electronic control unit. This unit establishes the type and magnitude of the impact and defines which ARS (additional restraint system) has to be put in action, sending an electric signal which primes the propellant activating the additional restraint system.

The air-bag has the function of interacting with the occupants and dissipate the kinetic energy together with the safety belts. The use of only a safety belt, even when it is well designed and mounted, enables the occupants to be restrained but, if certain deceleration levels are exceeded, can cause crushing of the thorax, giving rise to secondary injuries. For example, during a frontal impact, the driver wearing only a safety belt receives a very high load on the thorax, with a value near to 10 kN; instead, with an air-bag, this load is reduced by about 30%. Moreover the air-bag distributes its pressure on a larger body

Fig. 6.25. ACR system, active control retractor.

surface area and, at the end, enables an important reduction to the acceleration levels experienced by the head which are dangerous for the brain.

Today, as the safety is considered to be of fundamental importance, the presence of the air-bag facilitates the achieving of high scores in the rating tests proposed by organizations such as Euro NCAP.

The design and use of the air-bag are characterized by different technical aspects. The first regards the algorithm that has to recognize the impact, in terms of the variables used to characterize the impact and the limit curves.

Without entering into detail, which would be outside the scope of this book, there are generally four fundamental levels that have to be verified by the electronic control unit and which are important to distinguish logically:

- The algorithm decides if it is necessary to activate the air-bags or not at the correct time, compared with a series of defined impact (totally or in two steps if the module is dual stage);
- the control unit implements the impact recognition algorithm, considering also the tolerance on the components of the same control unit and of the vehicle;
- the control unit is capable of distinguishing the size and condition of occupant, considering also the tolerances of the sensors;
- for any dangerous impact, for example front impact (or rather an impact where there is risk of contact between the occupant's head and the steering wheel), the control unit will activate the air-bag system (totally or partially for the dual stage module).

The algorithm has to be capable of recognizing, with a very high precision level, all possible impacts for the occupants wearing safety belts.

Critical parameters, which have to be considered during the development of an air-bag system are:

- No fire limits;
- must fire limits;
- misuse events;
- biomechanics parameters relative to the occupants protection.

No fire limits

The no fire limits are defined as those impact conditions where the use of safety belt is sufficient to avoid injuries. For example when there is no risk of contact between the steering wheel or instrument panel and the heads of the occupants wearing safety belts. To understand the importance of this level, it is possible to consider the recovery cost, which has to be paid by the owner of the vehicle after air-bag deployment.

Must fire limits

The air-bag system must always activate in every type of impact where just the safety belt is not sufficient to ensure the biomechanics limits.

Misuse events

These events come from situations due to an improper use of the vehicle (low-level impact during parking operations) or due to the real use of car (i.e. bouncing due to bumps in the road, manhole covers, rail, etc., or impact against small animals).

To catalog these possible events, each manufacturer defines a set of experimental rules, so that the vehicles aim only at these experimental tests.

Biomechanics parameters relative to occupant protection

Ultimately, the air-bag must respect homologative and rating tests (pursued by car manufacturers with increasing determination). The reference biomechanics parameters in these tests are defined by expert groups and legislators after years of analysis, tests, simulations and discussions.

6.2.2 Components of the Air-Bag System

The main components of the air-bag system are:

- Sensors,
- control unit,

- cables,
- air-bag modulus.

In this section, which is dedicated to interior components of vehicle, attention focuses mainly on air-bag modulus, but few words will be also spent about sensors.

For the air-bag, sensors have to be electronic due to the position that they have on the vehicle and the information to be analyzed. The sensors can be divided in:

- Sensors for impact (front and side);
- sensors for the occupants of vehicle (presence of occupants, weight of occupants and the position of the occupants on the seats).

These sensors enable the air-bag system to be managed while avoiding, for example, activating the passenger air-bag if there is no passenger on that seat or, if there is a dual stage air-bag, allow pilot filling as a function of the weight and position of the passenger on the seat.

The main components of an air-bag modulus are:

- Gas inflator,
- bag,
- housing,
- cover.

Gas inflator

The gas inflator is the basic component of the air bag module and, for this reason, usually the name of the inflator defines also the name of the different air-bag modules.

The mission of the inflator is to produce the gas mixture in the quantity and time specified; this gas fills and inflates the bag. The gas inflator is composed by an igniter, comprising a little metal housing, which contains a small quantity of explosive charge (usually black powder), and an electric trigger; the trigger is piloted by the control unit and makes a little explosion that, in turn, triggers the solid propellant (explosive charge based on guanidine nitrate GuNi). Explosion generates a non toxic gas mixture (nitrogen and particulates).

The gas mixture is very hot, with temperature of about 800/1,000°C and before reaching the bag flows through a filter which has the task of retaining the solid waste of explosion and decreasing the temperature of the gas mixture. The filter is made with a mesh of metallic wires.

This type of gas generator is defined pyrotechnic due to the way in which the gas is generated. This type is mainly used to protect the driver and the passengers in the front seats from injury due to front impact, as described subsequently. Figs. 6.26 and 6.27 illustrate the inflators used for the driver and the passenger respectively.

Also hybrid inflators have been introduced on the market, so called because the igniter triggers a little pyrotechnic charge which, instead of being used to fill the bag, is mainly required to cause an instantaneous increase of temperature of an inert gas. This gas, which is contained in pressure in a housing, increases its volume and, in a specified time, fills the bag. This gas does not need to be filtered because it is not obtained from combustion. (Fig. 6.28)

These types of gas inflators, which constitute the hybrid air-bag modules, are heavier and more expensive but have been increasingly applied for the following reasons:

- They need a lower quantity of explosive charge than pyrotechnic inflator (about 10%), an increasingly important factor due to the increase in the number of air-bag devices used on a car;
- as already mentioned, the gas which fills the bag is not produced by an explosion, so it is less hot than a gas mixture generated by explosion of a pyrotechnic charge (less than half); therefore there is less risk of burning to the uncovered parts of the occupants (such as the face) when they go in contact with the air-bag;
- the gas (about 75% Argon, 20% Oxygen, 5% Helium) is less pollutant because it does not contain residuals from a combustion process;
- the bag filling speed, which is due to expansion of a pressured gas, is higher than that of a pyrotechnic inflator and thus is more suitable for those air-bags which need lower filling time.

Fig. 6.26. Gas inflator for the driver air-bag.

Fig. 6.27. Gas inflator for the passenger air-bag.

Fig. 6.28. Hybrid gas inflator.

Usually used for the driver and passenger air-bag are hybrid or, alternatively, pyrotechnic air-bags, while hybrid air-bags are used in all applications for knee protection and against side impacts.

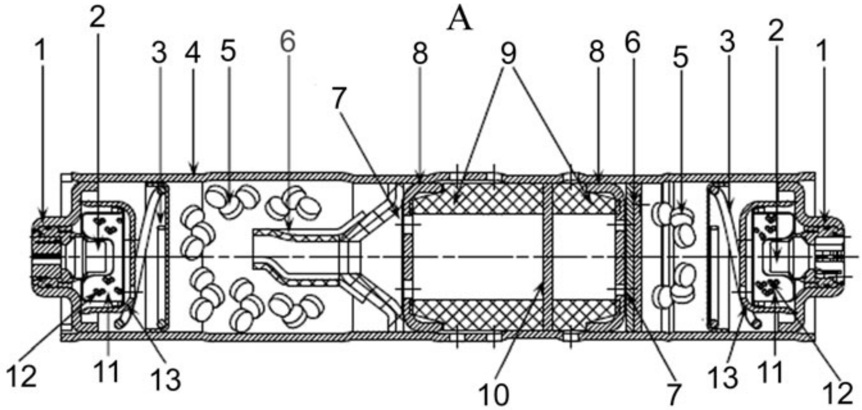
To conclude this overview of gas inflators, the dual stage inflators are examined; these are essentially double gas inflators which comprise two igniters and two hybrid or pyrotechnic devices, and usually have two different capacities of gas generation combined in the same bag. Fig. 6.29 shows the section of a pyrotechnic dual stage gas inflator.

Both the two igniters and the two devices for the gas generation can be managed separately; they can be activated simultaneously, as in a single stage inflator for example, or only a single stage can be activated. Usually the stage is activated that can create the required gas volume. Both inflators can be activated also at different times (separated by few milliseconds), so that the filling of the bag can be controlled. For example, if a sensor located on seat measures the presence of an occupant with very low weight, only the inflator which can ensure a quantity of gas sufficient to reach the appropriate biomechanics target is activated. In this way the restraint action is limited and secondary injuries to the occupants are avoided.

A similar example can be made considering the type of impact and, thus, measuring the action of the air-bag.

During the design of gas inflator, an important characteristic is the temperature range of the cockpit within which the air-bag has to ensure the demanded

A



B

N°	Quantity		
1	2	End cover	Steel
2	2	Spark unit	
3	2	Spring	Steel
4	1	Pipes	Steel
5	2	Propellent unit	
6	2	Filtering part	Steel
7	2	Diaphragm	Aluminium
8	2	Filter disc	Steel
9	2	End filter	Steel
10	1	Separator disc	Steel
11	2	Combustion chamber housing	Aluminium
12	2	Reinforced charge	
13	2	Cap of reinforced charge	Steel

Fig. 6.29. Pyrotechnic dual stage gas inflator: A: cross-section, B: table of parts.

performance. In fact the volume of a gas mixture strictly depends on the temperature. Fig. 6.30 shows the pressure of gas mixture made by the gas inflator, at different temperatures -35, +23 and +85°C as a function of time.

Bag

Usually the bag is made of a polyamide fibre fabric with a specific weave. It has not to tear or to ignite when filled with the gas mixture during the filling phase. The shape and volume of the bags depends on the space between the occupant and the interior of the car, and on the type of protection that the module has to ensure (driver front impact, rather than head protection for side impact).

The folding of the bag is very important in terms of minimizing risk of injury during deployment; for example, the steering wheel air-bag is star folded (see Fig. 6.31). To optimize performance during the opening phase, tear seams or strips (tethers) can be used to optimize the position of the bag in comparison to the occupant.

Finally the bags have vent holes located on the rear of the bag to assist gas release and control reduction of bag volume after the impact. Vent holes are not oriented towards occupants.

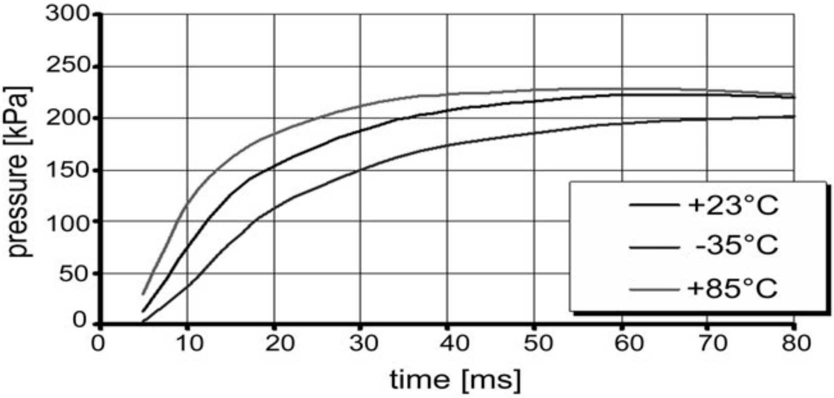


Fig. 6.30. Gas pressure as a function of time for different cockpit temperature.

Housing

Evidently the housing has the task of containing all or part of the components of the air-bag module. The main functions of the housing are to ensure an adequate protection for the fabric of folded bag and allow, by means of appropriate brackets, the fastening of the air-bag module to the cross beam of the instrument panel modulus and/or directly to the instrument panel. Usually the housing is made of metal (steel or aluminium) or of thermoplastics; its shape mainly depends on the type of the air-bag and the application.

Cover

The cover is the only component of the air-bag module which can be seen inside the car. A more detailed description is provided subsequently. The cover can be separated or integrated: It is separated when it appears as a cap which closes the space where the bag crosses the instrument panel during deployment (Fig. 6.94); it is integrated when the component cannot be distinguished from the dashboard. In both cases, the presence of the air-bag has to be always identified with the writing AIR-BAG (or equivalent words) on the cover. This indication has to be made directly on the same cover, and stickers are not allowed.

The main item for the cover has to be underlined: During deployment, the cover has not to cause any type of injuries to the occupants.

6.2.3 Air-Bag Typologies

Historically the first produced air-bag were developed to protect the front occupant, and in particular the driver, during front impact. Then, to optimize the restraint system, other types of air-bag were introduced. These can be divided into the following categories:

- Air-bag for protection against front impact, which can be further subdivided into:
  - Driver air-bag,
  - passenger air-bag,
  - knee air-bag.
- Air-bag for protection against side impact (called also Side-Bag), which can be further subdivided into:
  - Thoracic side-bag,
  - pelvic or pelvic/thoracic side-bag,
  - head side-bag.
- Air-Bag for the protection against rollover.

Driver air-bag (DAB)

Today this air-bag is a standard on all cars, being located in the centre of steering wheel with the task of avoiding direct contact between the steering wheel and its crown, the head, face and thorax of driver (Fig. 6.31).

Fig. 6.32 shows, by means of multi-body simulation model, an example of the simulation of a 48 km/h front impact with the driver wearing a pretension safety belt and of a driver without a safety belt.

Fig. 6.31 shows instead, from left to right, the cover, the bag with a star folding and different parts of gas inflator. Finally, Fig. 6.33 shows the frame of an inflated bag showing the exit of gas from the vent holes.

The driver air-bag can have a hybrid or pyrotechnic gas inflator and one or two energy stages. The DAB can integrate an acoustic signal device and is fixed on the steering wheel with screws or by means of a specific snap-in system which facilitates line assembly. The volume of the bag is around 55÷60 liters, usually with a circular shape; star folding is most commonly used.

Recently a particular type of DAB has been adopted in some cases. These devices have a bag with an asymmetric design featuring a protuberance towards the A-pillar in order to avoid a possible contact between the head of the driver and the pillar. This type of air-bag is used in particular for vehicles which have a highly sloped windshield.

Evidently the design of the bag needs specific attention because it could be activated at any angular position being on a rotating steering wheel.

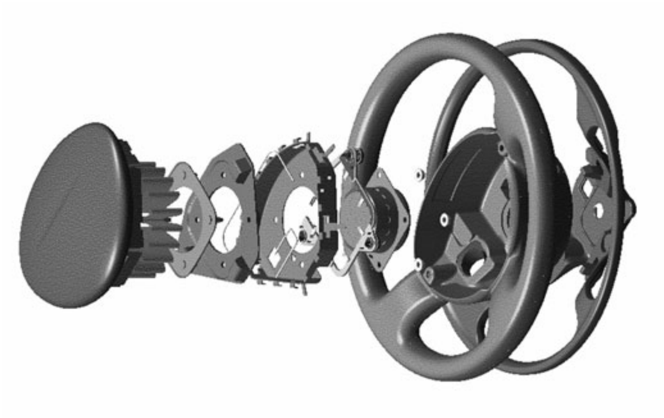


Fig. 6.31. Exploded view of a driver air-bag.

Passenger air-bag (PAB)

The use of passenger air-bag today is becoming almost standard. The volume of this bag is the highest of those used in a car, with a volume of about 120÷130 liters. Its function is to avoid contact between the dashboard and the passenger seated on the front seat. The gas inflator can be both pyrotechnic or hybrid with single or dual stage configuration. The PAB can be located on the instrument panel in three different positions: Front position, middle position and top position. In the first configuration the bag comes out from a part of dashboard oriented towards the passenger. The third configuration features the exit of bag on the top part of instrument panel, towards the windshield. This position is less aggressive for the occupant. Instead, the second configuration is in an intermediate position.

Today the top position is recommended because it is the least aggressive for the occupant, and because represents the best position to ensure the protection even when the passenger is not seated in the correct way (out of position OOP).

Fig. 6.34 shows an installation study for a PAB in the top position; it is possible to observe the lack of contact between the cover of opened air-bag and the windshield. In particular there is no contact between the cover and the head of a dummy which represents children of 3 and 6 years in a non correct position (OOP).

The position of the air-bag module in the top position and with an appropriate definition of the shape and folding of bag, enables deployment of the bag before in a vertically upwards direction, then horizontally and finally towards the abdomen of occupant. In this way the restraining forces are distributed in a less aggressive way on the passenger; see Fig. 6.34.

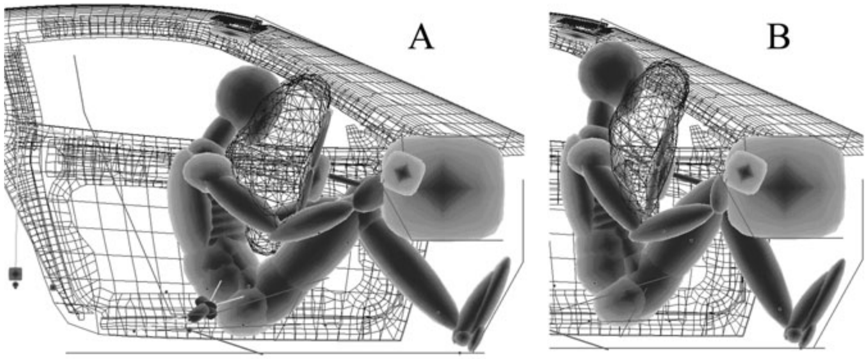


Fig. 6.32. Example of front impact simulation: (A) shows the driver wearing a safety belt; (B) driver without safety belt.

In Fig. 6.35 a passenger air-bag module is shown, highlighting the main components, in particular, from left to right side: The cover, the folded bag, a fixing plate, the gas inflator and the housing.

Knee air-bag

This type of air-bag enables braking of the forward movement of leg and pelvis of the occupants of the front seats in the case of front impact. This air-bag restrains the knee zone from which it takes its name. The knee-bag uses a hybrid gas generator and a bag with a volume of about 12÷16 liters, the smallest used on a car today. It is located on the dashboard at approximately the height of knees, and can be used either for just the driver or for both the occupants of front seats, as shown in Fig 6.36.

The installation on the vehicle is quite difficult because that zone of the dashboard is usually already occupied by important components such as the steering column or body computer (Fig. 6.37).

The knee air-bag exits between the instrument panel and the knees of occupant within a few milliseconds, thus enabling injury to lower limbs to be limited, contributing to an appropriate distribution of stress on the body.

Fig. 6.38 shows a graphic representation, demonstrating the optimization of the load during a front high speed impact with the knee-bag. A minimization of the force on femurs, a reduction of the sliding forward of the knees, a minimization of the compression on tibia and fibula and a reduction of the pelvis acceleration are obtained.

The knee-bag was invented to improve the protection of occupants that do not wear safety belts, with particular reference to the American market. The knee-bag (Fig. 6.39), has demonstrated excellent results also for occupants wearing safety belts, often contributing significantly to the achievement of five stars in the Euro NCAP rating.

Fig. 6.33. Deployment of bag and exit of gas from vent holes.

Side-bag

The side-bag has the task of protecting occupants from side impact. This is a very important task because, due to the low space between the occupants and the lateral car parts, the impact absorption of the vehicle system is very limited. For this reason, the task of absorbing side impact is attributed in a highly significant way to the air-bag for side protection.

In this type of impacts, the time of intervention for the restraint system is very short and the space in which the bag can deploy is highly limited. Moreover this type of side impacts include also passengers seated on rear seats. For these occupants, the possibility of OOP is very high, in particular when there are children.

Fig. 6.40 shows an elaboration of a mathematical model where the directions of the loads applied to occupant in the case of side impact are reported. More precisely F represents the load transmitted by activation of side-bag for head protection and of a thoracic side-bag, while I indicates the directions of pelvic and thoracic intrusion derived from the door.

The installation of the side-bag for pelvic and thoracic protection can be on the seats (backrest) or on the door (door panel) while the air-bags for head protection are mounted under the peripheral part of headliners.

Side-bag for pelvis-thoracic protection

Suppliers of air-bag and car manufacturers have each developed its own side protection strategies. Some prefer to install the side-bag on the door, while others prefer to install it on the seat, as shown in Fig. 6.41.

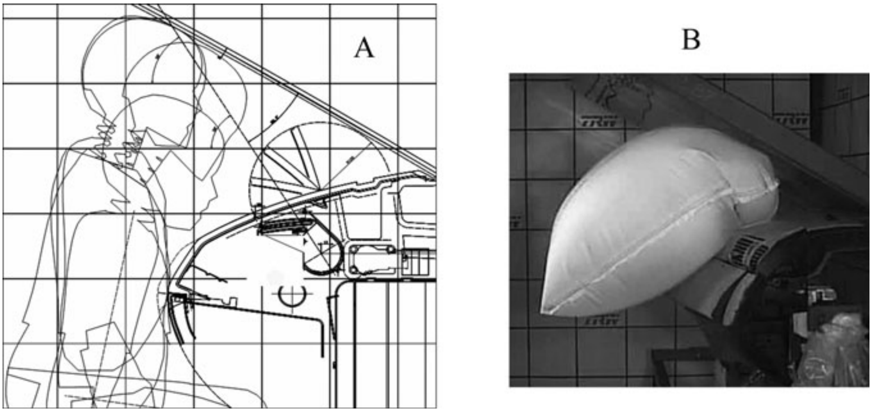


Fig. 6.34. A: passenger air-bag in top position (it is possible to note the effect on configuration OOP); B: frame on a deployed PAB in top position.

Nowadays, both for front and rear seat occupants, the most common protection for side impact uses an installation on the seat backrests.

The side-bag modulus, in Fig. 6.42, comprises the folded bag, the gas inflator and the plastic housing. In the figure the cover is not represented because it is integrated with the cover of seat, as described in the dedicated section.

The volume of the bag can vary between 12 to 18 liters depending on whether it is only a thoracic or a pelvic-thoracic bag.

Side-bag for head protection (window head-bag)

The task of these air-bags is to protect the head of occupants from impact against interior parts of the cockpit and can fall into two categories:

- Tubular side-bag, (Fig. 6.43);
- window side-bag, (Fig. 6.44).

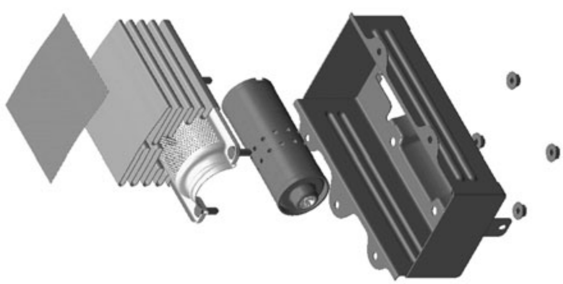


Fig. 6.35. Exploded view of passenger air-bag modulus.

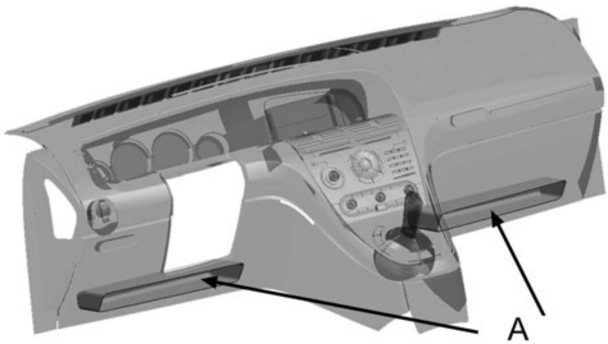


Fig. 6.36. Arrangement of knee-bag (A) on instrument panel.

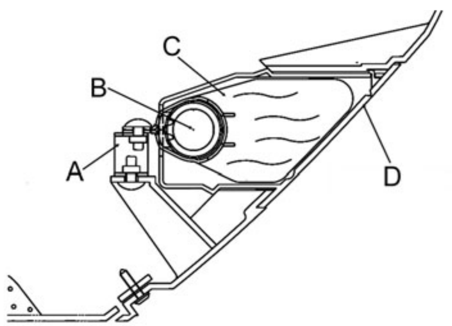


Fig. 6.37. Position of knee-bag under instrument panel. Components: A: fastening bracket for the modulus, B: gas inflator, C: bag, D: plastic cover.

Both types have the same denomination and are recognizable by the shape of bag. Nowadays window side-bag are mainly used.

It is possible to have a further subdivision, taking into account which occupants the side-bag should protect: Both front and rear, or only the front occupants.

The first ones are also called ABC head-bags because they protect the zone between the three pillars. The second are also called AB head-bags because they protect only zone between central and front pillar.

The volume of the bag for the window solution is about 25÷35 liters, whereas the tubular solution is 15÷25 liters. For these bags, a hybrid single stage gas inflator is used, which can be located at the end of the module or in the middle. In the latter case, faster deployment of the bag can be obtained as shown in Fig. 6.45.

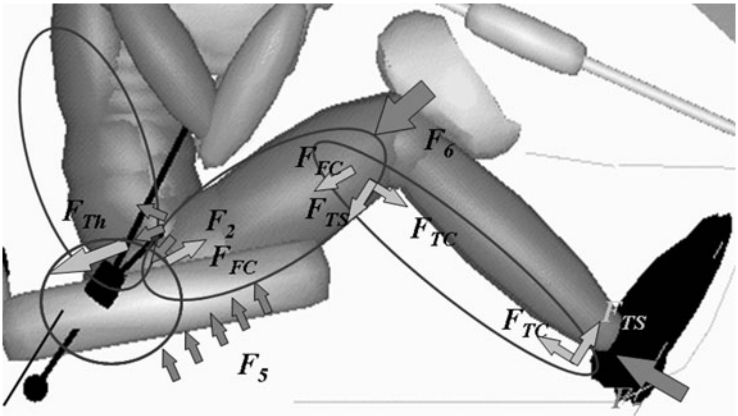


Fig. 6.38. Distribution of loads created by the knee-bag action.

A solution characterized by a tubular side-bag combined with a pyrotechnic single stage gas inflator is used when the principal aim is low cost and where there is little space for the installation of the air-bag module, such as in a small car.

Due to the oblong shape of the module, the gas inflator uses a spread tube to diffuse the gas mixture in an appropriate way in the long and narrow bags.

Air-bar for rollover protection

The protection to rollover can be achieved using a particularly complicated system, requiring complex electronic sensors and a specific control algorithm.

The targets of rollover air-bags are:

- To protect the head of occupant from impact against internal parts of cockpit;
- to protect the head of occupant from impact against the ground during rollover;
- to restrain occupants without safety belts.

The bag has a window shape and is made of a polyamide fabric with a layer of silicone. The thickness of bag is higher than a traditional air-bag and its volume is higher than 40 liters. Moreover, the design of the bag is characterized by a series of bubbles in order to obtain a stiffer and stronger bag in case of impact against the ground during rollover (Fig. 6.46).

Also the hybrid gas inflator has a specific design for this application, being more powerful and capable of creating a cooler helium based gas mixture. This feature is quite important because, during rollover, the bag needs to maintain pressure for a longer time, usually at least 4 seconds.

Fig. 6.39. Frame of an front impact test where the knee-bag deployment can be seen.

At this point, having overviewed the restraint systems, air-bags and safety belts, to better understand the action times which characterize these systems and the interaction between air-bag system and pretensioners of safety belts, it is possible to consider the scheme shown in Fig. 6.47 where on the x-axis there is time measured in ms, the origin being the time of impact. In particular it is possible to note three different times to fire, instants when the control unit emits activation signals. Starting from the origin, first there is activation of the first pretensioner, then that of the second pretensioners and of the first stage of air-bags, and finally the second stage of air-bags.

6.2.4 Simulation Model

The functioning of the air-bag system can be simulated numerically. Indeed the use of predictive simulation models is essential during the design of car body. Concluding this treatise on air-bag, it is useful to spend some words on the Madymo® software, since it has assumed relevant importance during the development of air-bags and due to high level of results which can be obtained.

Considering the physics of restraint system, to define the operation of the air-bag system in a correct way, it is necessary to simulate correctly all the building blocks which represent the different elements essential for operation of the system, such as characteristics of the inflator and its matching with air-bag volume.

For the bag strength and permeability characteristics, optimized folding forms and geometric elements of the vehicle are defined.

Fig. 6.48 shows a schematic representation of building blocks.

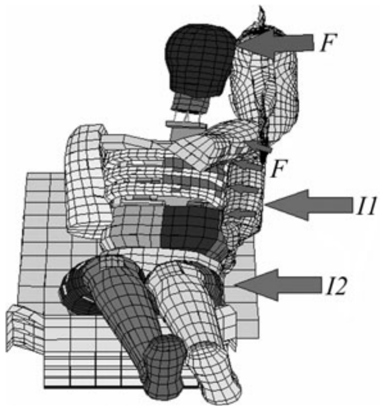


Fig. 6.40. Direction of primary load in case of side impact.

Fig. 6.41. Different typologies of side-bag.

The preventive optimization of the system needs appropriate planning of the geometry of vehicle, which has to consider the free flight and ride down distance. At the end of the simulations, accurate predictive performance can be attained. Fig. 6.49 shows the simulation of slide testing for a driver air-bag.

6.3 Dashboard Cockpit – Dashboard – Console

Before starting this section, to avoid confusion between dashboard and dashboard cockpit, it is necessary to specify the meaning of: Component, function and cockpit.

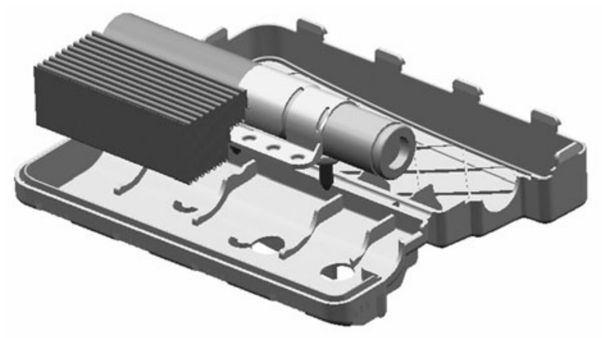


Fig. 6.42. Side-bag modulus.

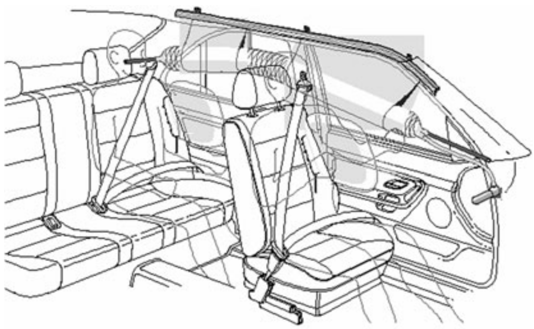


Fig. 6.43. Tubular side-bag.

- Component is an element which alone or assembled with other elements, is part of a vehicle such as the steering wheel.
- Function is represented by a set of components that allows one to implement a function; for example the function steering/driving is the set of more components that allow one to drive a car (steering wheel, steering column, steering box, etc.).
- Cockpit is a set of components, also belonging to different functions which make up an assembly overall; for example the dashboard cockpit (dashboard, crossbeam, climate group, etc.).

6.3.1 Cockpit

The main targets of cockpit design are to reduce cost, improve quality and reduce the space required for the vehicle assembly line. Cost reduction is possible

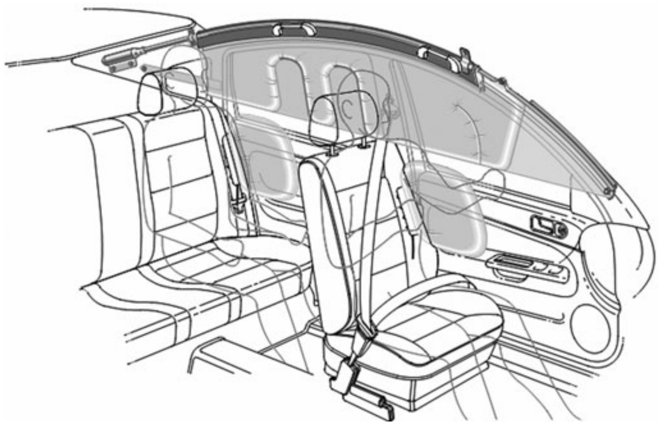


Fig. 6.44. Window side-bag.

Fig. 6.45. Side-bag modulus for head impacts.

through the simplification of the assembly of the components and to the possible integration between the components of the cockpit. The quality improvement is also due to an easier assembling and to the possibility to check, on the cockpit, the functionality of the components before the assembling on the car such as all the electrical connections of wiring.

Conventionally two dashboard cockpit families can be defined: The non-structural cockpit and the structural cockpit

Non-structural cockpit

The main components (Fig. 6.50) of this cockpit are:

- Overall dashboard;
- instrument board;
- switches;
- car radio set;
- body-computer;
- wiring and electrical connections;
- passenger air-bag.

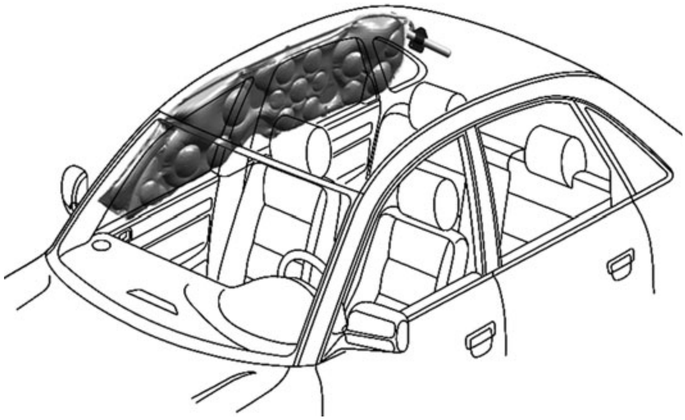


Fig. 6.46. Air-bag for rollover protection.

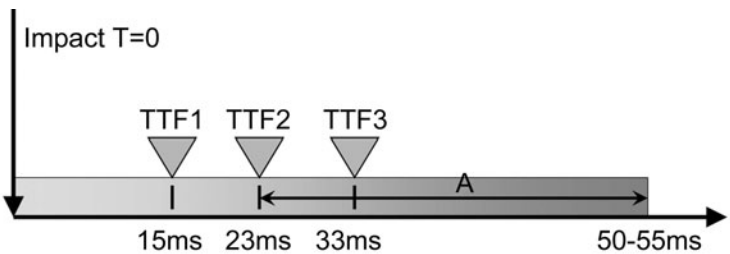


Fig. 6.47. Development of actions of different safety devices in case of impact. TTF1: time to fire of first pretensioner, TTF2 time to fire of second pretensioner and of first stage of air-bag, TTF3 time to fire of second stage of air-bag. The inflating time of bag of air-bag is put in evidence (A).

Structural cockpit

This cockpit is used on cars that do not have the car body under the windshield integrated into the body structure, but it is replaced by a crossbeam screwed to the body, which in addition to the specific structural function of the car body, has the function of a carrier on which to assemble the components of the dashboard cockpit. The main components (Fig. 6.51) of this cockpit are:

- Overall dashboard;
- instrument board;

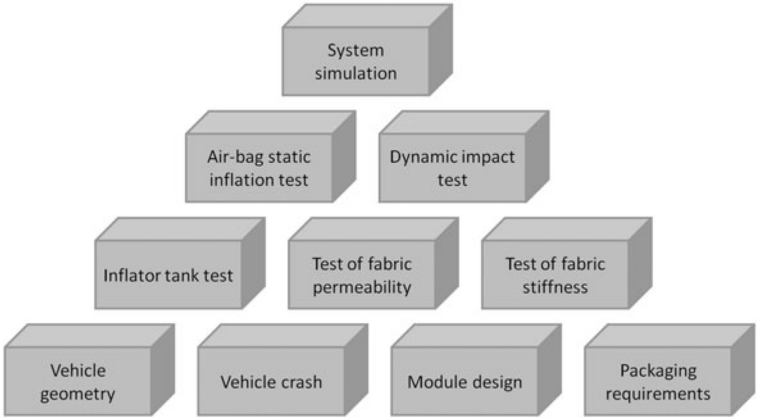


Fig. 6.48. Building blocks representation.

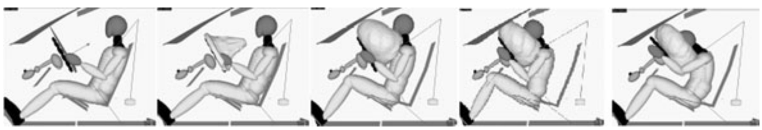


Fig. 6.49. Example of slide test simulation for driver air-bag.

- switches;
- car radio set or Info-Telematic Node (ITN);
- body-computer;
- wiring and electrical connections;
- passenger air-bag;
- steering column;
- pedal box (in some cases);
- gearshift (in some cases);
- climate group/HVAC (Heating Ventilation Air Conditioning);
- firewall (in some cases);
- crossbeam.

It is important to remember that, actually, the cockpits are characterized by intermediate compositions compared to the two cockpit families mentioned before, for example, there are some cases of cockpits that do not include the

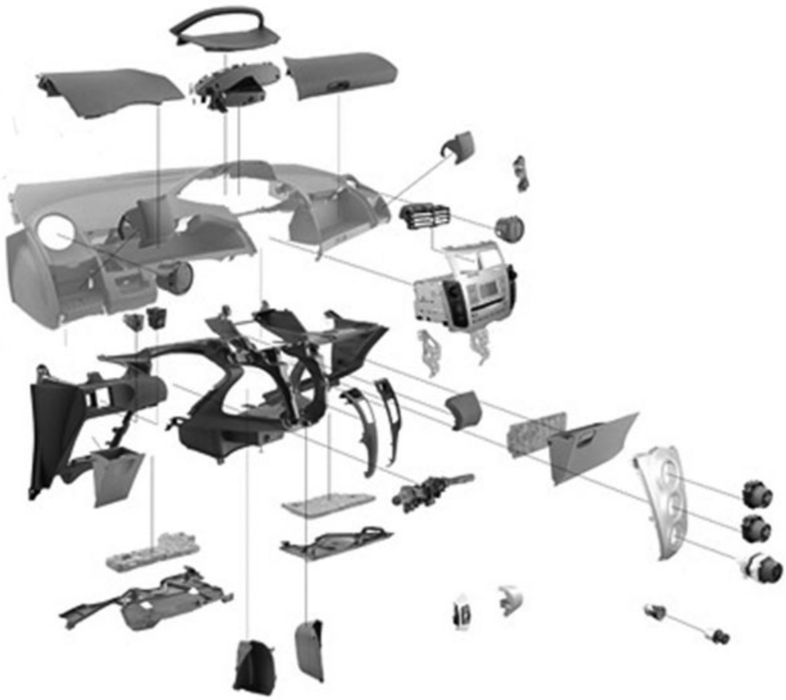


Fig. 6.50. Non structural cockpit.

firewall for practical difficulties in loading the cockpit in the vehicle or do not include the gearshift because it is on the console.

The cockpit has a specific value in the assembly cost, in fact, if it is properly designed, it can certainly provide economic benefits for the adjacent components that can be, at least, partially integrated.

6.3.2 Dashboard

The dashboard is defined as that component, or rather that group of components, which makes up the front passengers compartment. The dashboard of today, (Fig. 6.52) is very different from that seen on the first cars.

At the beginning of the last century, the vehicle had a structural wall under the windshield which was used to contain gages, instruments, switches, the hole for the ignition key and some warning lights; in luxury cars a wood frame and a glove box were added (Fig. 6.53).

Over time the instruments, some switches and warning lights were grouped together into one panel and protected by an anti-reflection visor in front of the driver to improve visibility and for assembly and service requirements; afterwards air vents and various other controls, glove compartments etc., were added until

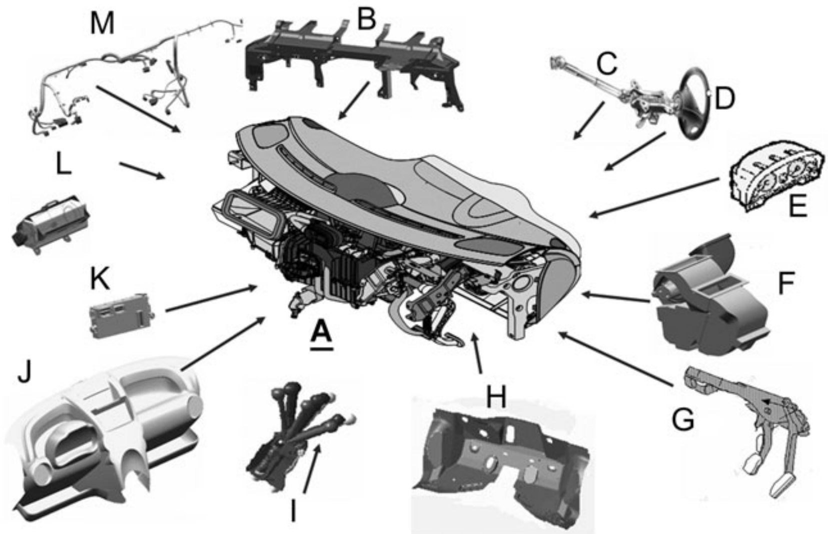


Fig. 6.51. Structural cockpit A, cross beam B, steering column C, steering wheel D, cluster/instrument board E, climate group (HVAC) F, pedal box G, fire wall H, gearshift I, overall dashboard J, body computer K, passenger air-bag L, wiring and electrical connection M.

a single self-supporting component evolved, enabling all the elements mentioned above to be incorporated: Today this component is called the dashboard and is represented in Fig. 6.54.

The dashboard is a very important component of the passenger compartment of a car because it contributes to some of the most important functions of the vehicle such as:

- Aesthetic function: Since the dashboard is noticed immediately after opening the door and entering the car, it becomes the key element in the aesthetic judgement, important in determining the rating of the vehicle; furthermore, while driving, the dashboard is the primary interface between the driver and the vehicle;
- safety function, for both active and passive safety.

Active safety, since it is possible to correctly distribute the air on the windshield and on the glass front door, and thus obtain a high level of visibility through the appropriate apertures (defroster/demister) which are present on the dashboard,

Passive safety, since in situations of impact of the head against the dashboard, the criteria of biomechanical performance required must be respected, as well as ensuring the absence of dashboard breaks that could injure the occupants.

Fig. 6.52. Dashboard.

Besides, the dashboard acts as a support to the passenger air-bag and to the knee air-bags when present.

In the case of passenger air-bag with cover integrated into the dashboard, the dashboard itself is part of the safety system, and as such it is subject to traceability.

Additional functions are:

- Ergonomic function, consisting, for instance, in the easy operation of the controls located on the dashboard and, to see correctly the instruments on the dashboard;
- comfort climate function, contributing to a proper distribution of the air in the passenger compartment, through air-vents located on the dashboard;
- objects containment function, with specific areas (drawers) on the dashboard, with appropriate sizes, in which to place objects.

Type of dashboard

The dashboards, according to their main characteristics and respective production technologies (table of Fig. 6.55), may be classified into:

- Stiff;
- covered;
- foamed.

This classification refers to the most important part of the dashboard, i.e. the dashboard body.

Fig. 6.53. Dashboard: How it was in a car of 1930.

Fig. 6.54. Body dashboard: How it is now.

Stiff dashboards

Stiff dashboards are those which, for their economy and lightness, and for the freedom in the design of their shapes and therefore for the stylistic versatility, represent the best solution for the lower segment cars.

The technology used is the injection moulding of thermoplastic materials, mainly belonging to the family of Polyolefin (Polypropylene) by adding mineral (talc) and elastomeric fillers or, mixtures of ABS and Polycarbonate. The desired appearance is achieved by coloring the polymer in mass and by embossing.

Before continuing the examination of the dashboard, it is necessary to spend some time on the embossing process because it is a process widely used to characterize the appearance of elements made by plastic materials.

What exists in nature has its own roughness or texture which give to the various objects a distinctive feature and makes them more perceptible to our senses.

DASHBOARD TECHNOLOGICAL FAMILY

		CHARACTERISTICS						NOTES	
TYPES	VARIANTS	Aesthetics	Touch	Freedom of style	Weight	Cost	Recycling	Problems	Segment
STIFF (injection moulding, embossed)	not painting	2	1	4	5	5	5	scratching	Lows
	painting	3.5	1	4	5	4.5	5		Lows Middle/Lows
	soft touch painting	3	2	4	5	4	5	embossing design less defined	Middle/Lows Lows
COVERED		3	3	2	3	3	5	only simple shapes	Middles
FOAMED	thermoformed covering	4	4.5	4	1	2	2/3	covering stretching	Highs Middle/Highs Middle/Lows
	slush or PU spray covering	5	5	5	1	1	2/3		Highs Middle/Highs Middle

(5 = maximum satisfaction 1 = minimum satisfaction)

Fig. 6.55. Classification of different dashboard types and their main characteristics.

Plastic materials, in themselves do not possess any of these characteristics; simply by appropriate preparation and processing of the mould's surfaces, specific features can be given to the plastic material components. This process is called embossing.

Embossing enhances and embellishes the plastic components at zero cost, except for the cost of embossing the mould. In fact, as an embossing process is carried out directly on the mould, the products obtained by a moulding process have already their surface embossed.

Besides embellishing the plastic components (including the rubber components), embossing allows:

- To mask the defects in the injection moulding process and reduce the production waste;
- to make the surfaces of the plastic components more resistant to scratches and abrasion;
- to make the plastic objects more functional (for example less slippery).

The topography of an embossed surface is identified by a measurement of roughness parameters (mean and maximum) and consists of a scale of roughness ranging from 12 K to 45 K corresponding to the average values of roughness expressed in micron, (K 12 = 0,4 μm and K 45 = 18 μm).

The type of embossing, i.e. the pattern to be made on the surface, should be defined in the early stages of the component design, as each embossing identifies the roughness which, in turn, defines the draft angle which is necessary for correct extraction of the component out of the mould. In fact, an embossed vertical wall, must have a draft angle which allows one to strip of the element from the mould. For example for a deep embossing (K$\geqslant$40), the draft angle must be not less than 10°, while for a less deep embossing the draft angle could be less than 5°.

There are two embossing processes:

- The texture;
- the spark-erosion.

Texturing. Texturing is the most used embossing process, expertise in which is jealously guarded by a few specialized companies.

After having defined and protected the areas of the mould not to be embossed, the area which must be embossed is covered by a film that reproduces the embossing design to be reproduced. With the use of a special chemical solution it is possible to engrave the mould surface which is not protected by the film through the corrosion, so as to obtain the embossing depth and the look of embossing design required.

An important feature of this embossing process is the possibility to choose from thousands of existing designs or to create new designs.

The steel blocks used to make moulds for which this type of embossing is required, should be free from any defects, such as inclusion and porosity. Besides, any repairs or modifications of the moulds must be made trying to avoid welding in the areas that should be embossed, because the welds causing changes in the chemical structure of the mould steel may give rise to defects resulting from non-homogeneous corrosion with respect to the areas of the mould surface which are not affected by welding (spots with halos).

The spark-erosion. This embossing process, unlike the texturing, is a well-known process which is also used to make moulds, generally of small sizes or for particular operations. The spark-erosion is a physical phenomenon performing a material removal as a result of electric shock. If the removal of material is limited to the surface area of the mould to be embossed, it is possible to achieve a similar removal of material like in the texture.

This type of embossing is used for the aesthetic treatment of small-sized moulds the design of which is performed using spark-erosion.

A fundamental difference with the texture is that the design which can be obtained is only one (like sandblasting), for which the only manageable variable is the depth that makes the embossing more or less engraved.

To conclude these brief notes on embossing, it should be noted that in order to achieve the same aesthetic effect on various plastic components with the same embossing and moulded with the same material, it is essential that the moulds are all made with the same type of steel (chemical composition). In fact, as already seen, the embossing is obtained by chemical incision or removal of the mould material and therefore different materials give different depth of embossing, i.e. different aesthetic results.

Characteristics	Polyolefin base polypropylene					
	Copolymer base	Copolymer 25/30 % talc	Copolymer for dashboard	Copolymer glass reinforced	PC + ABS	ABS thermo-resistant glass reinforced
Specific weight (g/cm^3)	0.89÷0.92	1.11÷1.17	0.97÷1.00	1.10÷1.13	1.11÷1.14	1.15÷1.18
Coefficient of expansion (10^{-6}/°C)	110	50÷70	50÷60	40÷70	75÷85	40÷50
Moulding shrinkage %	1.5÷2.0	0.8÷1.1	0.8÷1.2	0.4÷0.8	0.6÷0.7	0.2÷0.3
Residual calx %	/	23÷32	10÷12	28÷32	/	15÷17
Modulus of elasticity (N/mm^2)						
a 23 °C	1000	2500	1650	4500	1900	5000
a -30°C	/	5300	/	7300	2500	5300
a 80°C	/	750	550	2700	1600	3600
Izod impact strength (KJ/m^2)						
a 23 °C	6	4÷7	13	12	45	0.65
a -30°C	/	2.5	3.5	3.5	3.5	0.4
Distorsion temperature under load (1.8 Mpa) °C	50	65	50	140	100	105
			mineral filler + anti scratching	only for non esthetic components		non aesthetical components
Opacity	+	+	+	/	-	/
Aphonity	+	+	+	+	-	-
Not scratching	+	-	+	/	++	/
Moulding	++	+	+	o	--	-
Low cost	++	++	+	++	--	-

Fig. 6.56. Main characteristics of some plastic type.

Another factor affecting the aesthetics of a moulded plastic component is the gloss which influences the effect of the embossing, especially when the design is less marked. The gloss is measured by using a simple instrument: The glossmeter.

If the gloss is low (dull), the embossing may appear less pronounced and, on the contrary, if the gloss is high (bright), the embossing may seem deeper than it is in reality.

It is possible to change the brightness of the embossed plastic surface through the dulling, chemical and mechanical treatments (sandblasting and shot peening); the duration of these treatments is limited in time and therefore it is necessary to remake them.

Returning to the dashboard and in particular to the stiff dashboard-body, which is the basic element of the dashboard, it is appropriate to understand why the most used plastic material is Polypropylene with mineral and elastomeric fillers (see the table of Fig. 6.56).

Firstly Polypropylene is certainly a low-cost material with good characteristics, easily moulding, good opacity and aphonicity. Furthermore, by adopting the mineral filler (talc), properly treated with a process of sizing, it is possible to decrease the scratching effect, making any scratching less clear because talc is white.

Moreover, in the table of Fig. 6.56, it can be seen that the material for the stiff dashboard, in addition to esthetical characteristics, guarantees the best possible compromise between the structural features due to the minerals fillers (flexural modulus), the necessity not to have brittle break and a good energy absorption capacity as a result of collision, even at low temperatures (impact strength), due to elastomeric fillers (thermoplastic rubber, EPDM). Such compromise is obtained by using Copolymers.

Better features with regard to heat resistance could be only achieved with other materials which cannot be used because of their values for impact strength and aesthetic performance (Copolymer with glass fibres fillers) or because these materials are too expensive (blend between ABS and Polycarbonate).

It is the designer's task, if these types of materials are to be used, to agree with the stylist on shapes and geometries, allowing appropriate solutions so as to guarantee the values of flexural modulus and the resistance to temperature that can reach 110÷120°C.

ABS and Polycarbonate blend-based materials which, for their nature, can already be classified as engineering resins, as seen in Fig. 6.56, have characteristics that do not require the use of fillers and, for their high costs, they are mainly used for the dashboard having a design which can create problems of thermal resistance and impact strength, especially at low or high temperature. Their use is more frequent in technical components which are present on the dashboard, such as the air vents, for which is not thinkable, for example, to guarantee the resistance to the impact, especially at low temperatures, by using Polypropylene materials.

To summarize the behavior of thermoplastic materials it can be seen that the flexural modulus decreases by increasing the temperature, the impact strength decreases by decreasing the temperature. The mineral filler increases the flexural modulus and decreases the impact strength while the elastomeric filler creates the opposite situation. The shrinkage decreases with the presence of fillers.

In Fig. 6.57 a stiff injection moulded dashboard is shown, while in Fig. 6.58 a characteristic section (passenger side) of the stiff dashboard is visible.

Returning now to the table of Fig. 6.55, it can be observed that the aesthetics and the touch are the two major weaknesses of the stiff dashboard. The moulding process optimization and the embossing can improve the aesthetics, but cannot remove the plastic effect, which is inherent to plastic moulding injection process.

The way to really remove the plastic effect is the painting. The result that is achieved is such that it is used to apply the same component (painted or not), on different cars, giving a significant difference.

The painting process of plastic components is absolutely specific and different from the one which is used for other materials, such as the preparation of the surface of components to be painted and the painting temperature is very often much lower. Some plastic materials (polyolefin-based materials such as Polypropylene) cannot be painted due to the total adhesion absence of the paint, if the surface, which must be coated, is not firstly subject to flaming and/or treated with primers or plasma-treated in open space.

These processes are briefly described when the plastic materials used for the foaming dashboard support are discussed.

Fig. 6.57. Stiff injection moulding dashboard.

Other plastic materials, such as the polycarbonate and ABS blend, can be painted only by using an adhesion promoter.

Finally, by increasing the thickness and with a specific paint formulation, it is possible to obtain a particular painting that allows getting the soft touch feeling. This type of painting, due to its thickness (a normal painting has an average thickness of about 15 μm, the soft touch painting has an average thickness of about 40 μm), has a slightly negative effect on the embossing, as it levels its ridges and valleys.

Besides painting, there are other processes which characterize the surfaces of plastic components. One of these processes, started in the automotive industry, is the cubic-printing system. The element that must be treated is immersed in a tank containing water on whose surface floats a gelatinous film reproducing the design that you want to reproduce. During the emergence the element is covered by the film. Then, after the drying, the surface on which the film is deposited, is protected with a finishing paint coat.

With this process it is possible to reproduce the most varied types of finishes such as: Wood, textile materials, carbon fibers, etc.

Last but not least, the characteristic to be considered for the stiff dashboards is the recycling because, being moulded almost entirely with thermoplastic materials these are, by definition, recyclable. The recycleability is complete if in the development phase it is possible to adopt, for the various dashboard components, the same thermoplastic materials and if, especially for the non-plastic parts, it is possible to adopt assembly solutions which are easily dismountable.

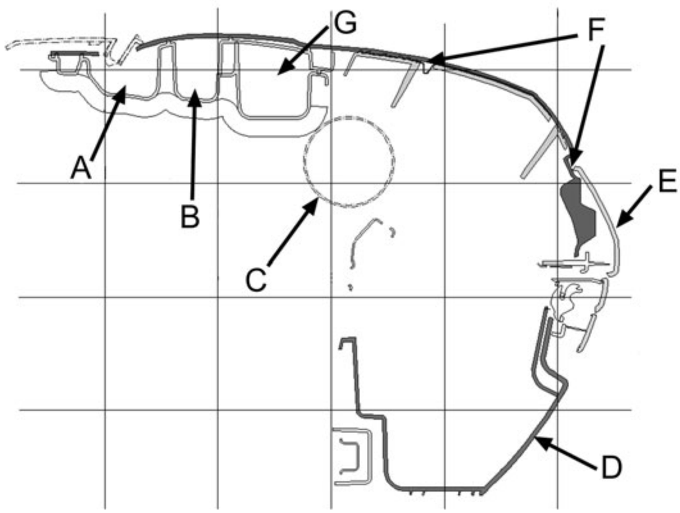


Fig. 6.58. Characteristic section of a stiff injection moulding dashboard: Defroster air duct A, demister air duct B, cross beam C, tilting glove box compartment D, aesthetic cover E, body dashboard F, vents air duct G.

Covered dashboard

This type of dashboard represents an intermediate solution between stiff and foamed dashboards (Fig. table 6.55), and being such, it tries to recover the aesthetic and tactile performance without penalizing too much weight and cost.

The covered dashboard is, in fact, a stiff dashboard on which a covering consisting of an embossed laminated plastic plus an expanded plastic layer having a thickness of about two millimeters is joined by bonding. This covering, with its color and embossing has an esthetical function and, with its expanded part, even a tactile function (Fig. 6.59).

Covering material. Initially the material used was the laminated PVC (polyvinylchloride), now the most widely material used is the TPO (polyolefin based material).

The adoption of the TPO was made possible thanks to the technical evolution of bonding processes and preparation processes of the surface to be bonded (flaming and plasma treatment in open environment).

The elimination of PVC, besides the ecological benefits resulting from the non-use of chlorides, has also enabled the reduction of the fogging (deposition of volatile compounds present in PVC that, by condensing on the windshield, cause an effect of fogging). It has also improved the resistance to the prolonged sunlight exposure by improving the tactile sense and eliminating the feeling of greasiness, typical of PVC.

Support materials. In parallel to the TPO adoption, instead of using PVC for the covering and instead of using PC (polycarbonate) and ABS

Fig. 6.59. Covered dashboard.

(acrylic-butadiene-styrene) blend for the support material, PP (Polypropylene) materials have been recently used.

The use, in the past, of the PC-ABS blend was due to the impossibility to have the adhesion when using PP materials.

Moreover, the covered dashboard, just for the covering that characterizes it, has a better ability to absorb energy and to resist to the impact compared with a stiff dashboard. Therefore it is possible to use PP with more filler talc (25÷30%) and without EPDM (elastomeric filler) with a consequent increase of the flexural modulus and cost reduction. The impact strength reduction is compensated by the presence of an expanded covering which is glued on the support.

It is also not necessary to have the support material with the not-scratching material for the simple reason that the support is covered.

Covering process. The process used to apply the covering on the support is the Vacuum Thermo-forming process and, for this reason, the covered dashboard is also known as Vacuum Thermo-formed Dashboard.

The support is drilled with holes which, towards the surface being covered, have normally a diameter of 1.5 mm. A greater diameter could generate a laminated impressing, during the thermo-forming operation; the holes should always be obtained directly from the mould although, in some cases, it may be complex or even impossible in consequence of the mould draw line, which would require to realize the holes by recovery operations.

The vacuum thermo-forming process, represented in Fig. 6.60, may be identified in three phases:

- Phase 1: Positioning of the support on the thermo-forming mould and application of a thermal bi-component adhesive, through a robot. The use of a robot is important in order to ensure that the repeatability of the

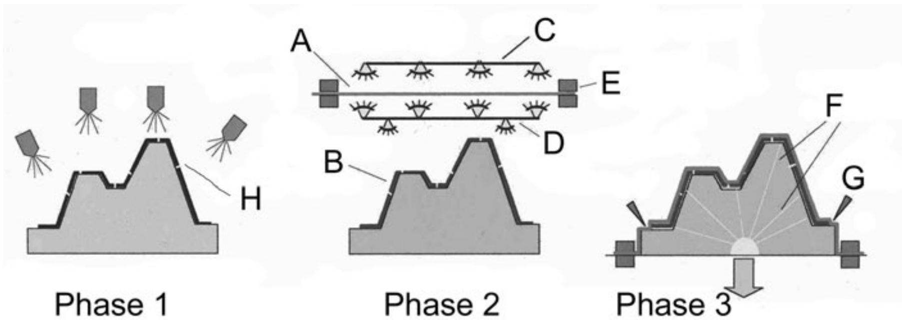


Fig. 6.60. Vacuum thermoforming process: Phase 1, positioning on the support and adhesive application; phase 2, thermo-heating of the covering; phase 3, vacuum thermoforming. Parts: A covering (PVC exp. / TPO exp.), B support with adhesive, C heating upper park lamps, D heating lower park lamps, E frame detention, F vacuum channels, G cutting device, H insert holes.

adhesive application is correct both in terms of distribution on the support surface and in terms of quantity.

- Phase 2: Thermo-heating of the covering material and thermo-heating of the adhesive applied on the dashboard support.
- Phase 3: Vacuum thermo-forming that, by sucking the covering material on the support, through the vacuum channels of the thermo-forming mould, enables the adhesion between the dashboard support and the covering.

It is just this process that determines the shape limits which represent one of the most important critical point of this dashboard type. It is clear that the concave-shaped covering with respect to a convex- shaped one, especially by the heat effect, puts the adhesive in condition to work in traction with the possible detachment, if during the bonding process occurs even only a slight anomaly.

External radius limits are another critical point. The radii that define, for example, the air vent locations and which cannot be less than the covering thickness of about 2 mm, see Fig. 6.61.

Finishing process. This is an important process for the covered and foamed dashboards. It consists in trimming and finishing on the perimeter and in the parts that need to be opened such as the locations for the air vents (see Fig. 6.61).

These kinds of operations can be done by means of punching, water jet, laser or, quite frequently, by manual milling.

With the adoption of TPO in the covering and PP (Polypropylene) supports, now there are good conditions for recycleability as for the stiff dashboard.

To conclude the examination of the covered dashboard, which represents the type of least used dashboard, it should be remembered that this technology

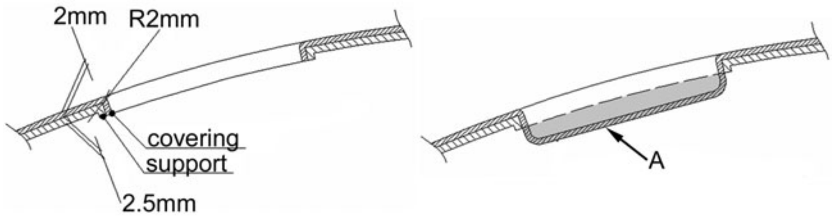


Fig. 6.61. Left: example of external radius; right: finishing of part to be removed.

is also used on foamed dashboard components such as door glove compartment, in order to guarantee the same foamed dashboard finish, but with less cost and weight. In these cases laminated materials with expanded part are not used, but the normal laminated materials whose thickness is about 0.8÷1.0 mm and which, in any case, guarantee the aesthetic performances.

It can also be employed on stiff dashboard where the use of covered parts makes possible to aesthetically enrich a stiff dashboard.

Foamed dashboard

It is certainly the dashboard type that, more than the other two that were considered above, contributes in a fundamental way, with the seats and the door panel, to the car passenger compartment furnishing. In fact, from the table in Fig. 6.55, it is possible to see that this solution ensures the best design freedom for style and form, and then also, achieves the best performances in aesthetics and touch (see Figs. 6.62 and 6.63).

The dashboard importance in characterizing the vehicle passenger compartment is also evident by the fact that, since the 1990s, the use of the foamed dashboards has become more and more extended. Today they are also used on economy cars.

While the covered dashboard is made up on a stiff support, in the foamed dashboard between the support and the covering, there is a soft layer with about 5÷10 mm of thickness. The process with which this soft layer is made, is called foaming.

The three most important parts of the foamed dashboard are: The support, the foam and the covering.

The support. It is the structural part of the foamed dashboard which is put into the foaming mould. The first characteristic of the support is that, in this case, unlike stiff dashboards, is much more simple: It must not have an esthetical function, it must not guarantees impact strength and resilience as well as a good absorption energy capacity as a result of collision, because the set of the support, the foaming layer and the covering guarantee the performance required.

Moreover, the support not having to reproduce the shape of the dashboard design as in the case of the covered dashboard and within the limits resulting

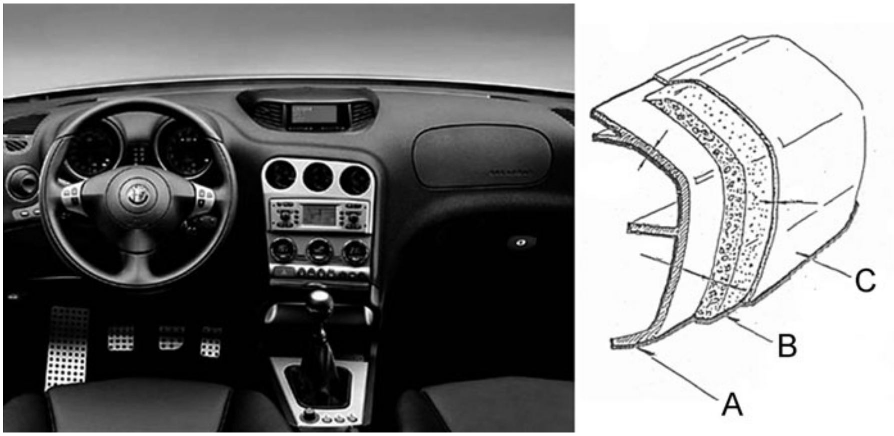


Fig. 6.62. Foamed dashboard: Support A, foam B, covering C.

from the foam thickness, can be designed with a more suitable shape in order to optimize the structure.

The material used is always an injection-moulded thermoplastic, but as said before, it is possible to adopt materials with a better structural performance like higher flexural modulus and high temperature resistance. These materials could be the following: Heat-resistant ABS reinforced with glass fibres or Polypropylene copolymer with mineral filler (talc), as shown in the table of Fig. 6.56.

While for an ABS support there are no adhesion problems, between the support and the foam, as already has been seen for the covered dashboard, it is impossible to have adhesion by utilizing polypropylene. Only the flaming or the plasma treatment, causing the double bonds rupture between the carbon atoms in the polyolefin molecular chains, enable the adhesion between the polypropylene support and the foam.

The flaming is a process through which, with a flame usually generated by a Bunsen burner and manoeuvred by a robot, the support surface to be joined with the foam, is treated.

The recent possibility to use the plasma in open environment has created a valid alternative to the flaming. In fact, the cold flame of the plasma enables a better surface treatment without damaging the same. This would happen with the normal flame if, due to the surface tortuousness, it were necessary to stop for a long time in a specific surface part with its consequent overheating and therefore deterioration of the plastic material characteristics.

For dashboards to be assembled on low-production vehicles like buses or heavy trucks, in order to limit the investments, other technologies can be used such us low-pressure moulding processes, which use thermosetting resins or vacuum thermo-forming process and thermoplastic plates having a thickness of 3÷5 mm.

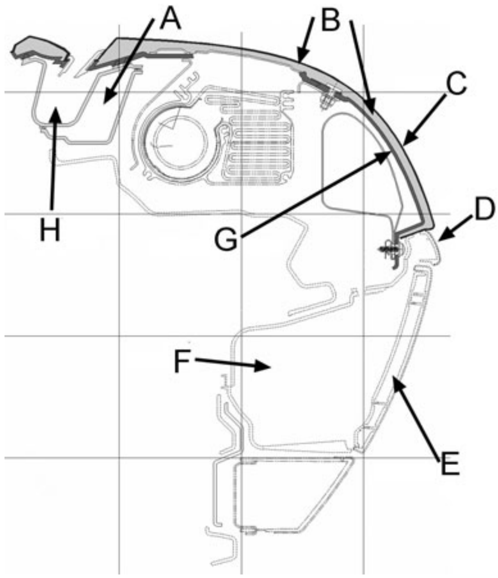


Fig. 6.63. Tipical section of the foamed dashboard: Demister duct A, foam B, covering C, cover D, door glove box compartment E, drawer F, support G, defroster duct H.

The covering. The covering is the dashboard skin. One of the technologies which is currently most used is the vacuum thermo-forming, already seen with respect to the covered dashboard.

The covering consists of an embossed laminated material obtained by calendaring in compact TPO. Normally the thickness is about one millimeter (the thickness depends on the dashboard geometry), but it does not exceed 1.2 mm. In the past a laminated material made from PVC/ABS blend was used (having already mentioned the main reasons for which it has been decided to replace the PVC/ABS with TPO, to which the improvement of the touch consequently to the ABS elimination must be added).

The vacuum thermo-forming process represented in Fig. 6.64 may be classified into five phases:

- Phase 1: Heating the laminated material top and bottom through two heating lamp panels.
- Phase 2: Supporting the warm laminated material through the air, in order to prevent, as a heating result, the softening and deforming downward of the laminated material, coming into contact with the mould forming and generating a localized pre-stretched.

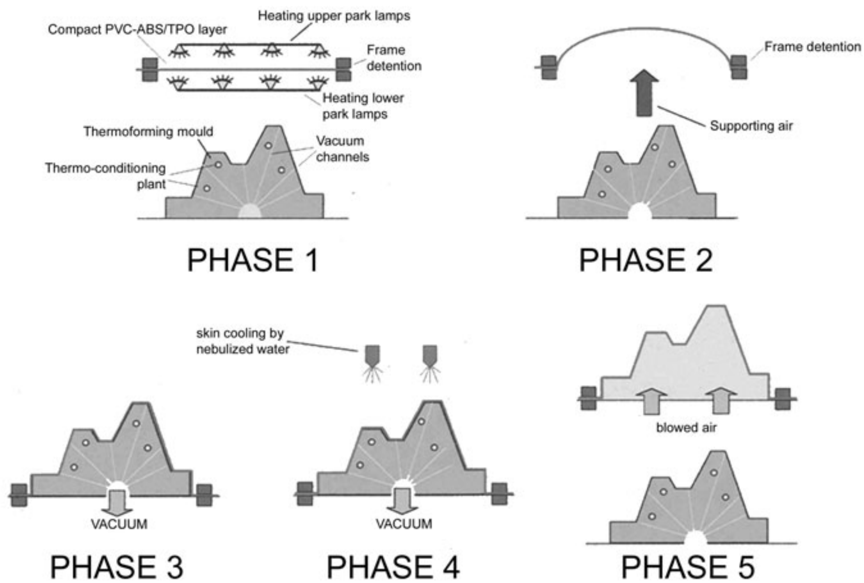


Fig. 6.64. Vacuum thermoforming process: Phase 1 heating the covering material. Phase 2 pre-stretching and supporting covering material. Phase 3 thermoforming. Phase 4 cooling. Phase 5 demoulding.

- Phase 3: Vacuum thermo-forming; by means, of vacuum application through appropriate channels obtained in the thermo-forming mould, the laminated material is sucked on the same mould.
- Phase 4: Cooling by spraying atomized water on the thermo-formed covering; even the mould forming, with cold water, participates in the covering cooling.
- Phase 5: De-moulding by means of blown air; the laminated material, which has now taken the new three-dimensional conformation, is detached from the forming mould and is ready to be put into the foaming mould.

The vacuum thermo-forming is a process that allows one to have the laminated material transformation in the three-dimension skin and that represents the shape of the foamed dashboard. This happens through the stretching of the flat embossed laminated material. If the stretching exceeds certain limits, it will damage the laminated material embossing, and a gloss variation by damaging the dashboard aesthetic.

Recently, with the availability of second-generation TPO and thanks to the introduction in its formulation of new elastomeric fillers and a new reticulation process of the laminated material after the embossing, it has been possible to reduce the effect of the stretching, which however exists.

Fig. 6.65. Laminated grid to evalute the stretching.

Practically, the depth of the embossing engraving does not change because, thanks to the reticulation of the embossed surface, the stretching generates only a widening of the embossing valleys without lowering the ridges of the embossing and therefore the stretching effect becomes less visible.

It is necessary to value the stretching of the laminated material which is consequent to the dashboard geometry (a dashboard with important drawings is more stretched) and its aesthetic acceptability; in fact, the embossing design has an influence on aesthetics (a less carved embossing and with not neutral designs, makes the stretching more clear).

After stretching simulation, during the car development process, it is possible to produce, very quickly, by means of the CAS, the vacuum forming mould, to get immediately the real situation (Fig. 6.65).

Another technology to produce the foamed dashboard skin which, compared to the previous one has the advantage to eliminate the stretching, is the slush molding. This technology is born in the Sixties in the US and has also extended to Europe in the last two decades.

It consists in obtaining the skin by using forming moulds made only with the female part, embossed and heated, which is filled up with PVC powder.

Researches to use polyolefin (polypropylene) powders are in advanced development, even if, in this moment, unfortunately, their industrial use is not yet possible. The use of thermoplastic polyurethane (TPU) powders, although they have tactile and aesthetic advantages, has been abandoned for economic reasons.

The moulds to make slush coverings are obtained from the saddled model with the chosen skin (natural, synthetic, etc.). From this model, through next silicone and resin castings, the resin master model is obtained. This model is similar to the saddle model, from which, through following steps it is possible to obtain a nickel shell, which represents, in negative, the original saddled model.

This shell embedded in a structure, is the mould for the slush (Fig. 6.66). The nickel shell during the slush process, undergoes a deterioration and after about 20,000 skins produced, it should be replaced.

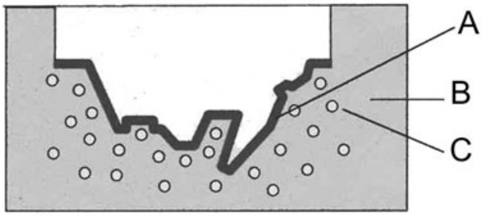


Fig. 6.66. Moulding for slush skins: Nickel shell A, mould structure B, thermostatation mould C.

Besides eliminating the stretching, which is a characteristic of the thermoformed laminated material, the slush technology allows:

- To obtain skins with designs that are not feasible through the vacuum thermoforming;
- to have a faithful reproduction of any embossing kind;
- to have a great freedom in design; for example in getting radii less than 0.5 mm;
- to obtain writings directly from the mould or false seams.

The skin production cycle is represented in Fig. 6.67, from which it is possible to see that the process is based on the powder transfer from its container to the pre-heated slush mould. Through the rotation of the container and mould (phase 3), the powder, which is in contact with the heated shell, adheres to the shell itself, which is emptied, again by rotation (phase 4).

A following heating and cooling allows one at the end, to de-mould the formed skin (phase 7).

An alternative to the skin manufacturing process, just described, is represented by the spraying. By using a mould, similar to the one of Fig. 6.66, instead of filling this last with PVC powder, on the embossed mould surface, a thermoplastic polyurethane compound is sprayed.

By measuring the amount of sprayed material, the time of permanency on the embossed surface of the sprayed material and the mould temperature, after a suitable cooling, it is possible to extract from the mould a skin which is similar to the slush skin but with much better tactile quality.

This process, more expensive than the previous one, is used only for cars at the top of the range.

The foaming. Through the foaming it is possible to obtain the expanded material that characterizes the foamed dashboard. The foam is the material that, by interposing between the support and the covering, provides the required softness.

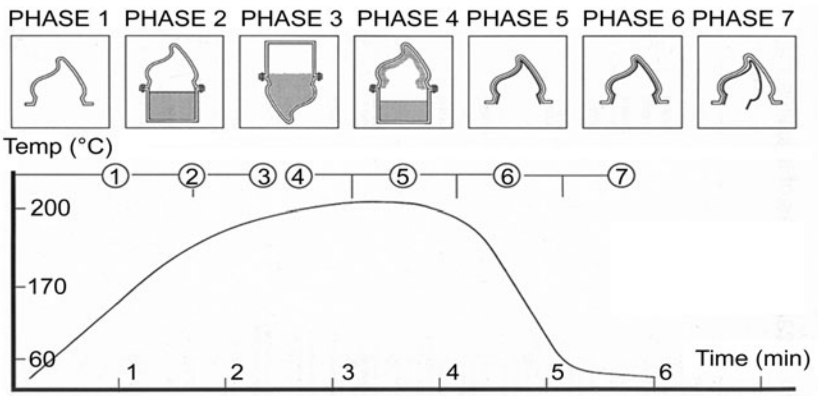


Fig. 6.67. Covering production cycle by slush technology. Phase 1: mould heating. Phase 2: starting rotation ($170 \div 180°C$), fixing to the mould of the powders container. Phase 3: rotation, mould filling with the PVC powders. Phase 4: rotation with return to initial position and PVC sticking on the mould walls. Phase 5: sintering, separation of the mould from the powders container. Phase 6: cooling. Phase 7: demoulding.

The material used is a thermosetting (polyurethane), obtained by mixing in the mould, at low-pressure, polyol and isocyanate. The attempts to use thermoplastic materials (polypropylene), because the polyurethane is not recyclable, have not given encouraging results.

The foaming mould, due to the low pressures used, is composed of an aluminium male and of a thermostatically controlled resin female, with possible aluminium spacer block.

The support is usually placed on the male, while the covering is placed in the female, where it is held in position by the vacuum created through the suction channels (phase 1).

After the mould closure, a pre-heated polyurethane is injected (phase 2); in some cases the polyurethane is poured into the mould when it is still open. After a suitable reaction time and formation of the foam, it is possible to de-mould the dashboard (phase 3), as shown in Fig. 6.68.

In the table of Fig.6.69, there are some parameters characterizing the injection moulding and the foaming of the dashboard body which confirm that stiff dashboards (injection moulding) are less expensive but with higher investments then foamed dashboards.

Finishing process. The process is similar to the one described for the covered dashboards with the addition of the need to remove the foam that, during the foaming, may have infiltrated on the support part that should be released for the subsequent assembly operations (e.g. welding).

The removal of the foam is facilitated by a preventive process of waxing, consisting in the application of a wax layer on the support surface that must be free of foam.

In these recent years, in order to avoid the waxing and the foam removal, a process called run-off has been consolidated. This process consists in avoiding that the foam is seeped inside the support through the seal between the support and the covering.

The recycleability of the foamed dashboards is more complex than the stiff and covered dashboards, as the polyurethane foam, being a thermosetting material, is not recyclable.

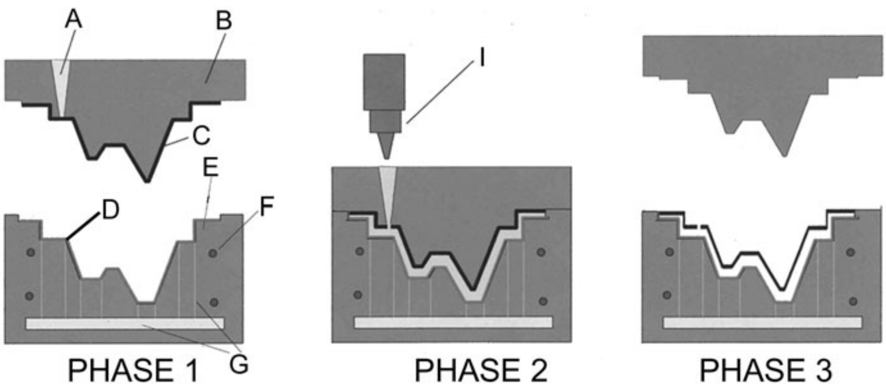


Fig. 6.68. Foaming cycle: Foam injection channel A, mould male B, support C, covering D, mould female E, mould thermostatation F, vacuum G, head of polyurethane foaming I.

Monolithic and non-monolithic dashboards

After having examined the dashboard classification in terms of technologies and characteristics and before starting the examination of the most important dashboard components as well as the assembling technologies, it is necessary to remember that the dashboard design can be:

- Monolithic (Fig. 6.70), when the dashboard body is made up of a single piece;
- decomposed (Fig. 6.71), when the dashboard body is made up of more than one piece.

	FOAMING	INJECTION MOULDING
Pressure inside mould (kg/cm^2)	25	250 – 300
Mould temperature (°C)	40 – 50	60 – 70
Parts stamped for shift	50 – 60	250 – 280
Mould cost (%)	100	400 – 500

Fig. 6.69. Some characterizing parameters for injection moulding and foaming.

Fig. 6.70. Monolithic dashboard.

The monolithic solution, being composed of a low number of pieces, is certainly cheaper and more reliable (no noise problems resulting from the presence of more parts) and with less problems resulting from aesthetics (no need for constant clearances and profiles between the different dashboard parts).

On the other hand, the freedom to get any kind of design and therefore the style freedom is significantly reduced, as a result of the constraints of the injection moulding process, such as the draw line. In other cases, for instance, it is necessary to disassemble parts of the dashboard for assembly requirements, as the chassis hardware may be in the shadow of dashboard parts.

Another limitation of the monolithic dashboards is represented by the request to have different colors, without the use of painting.

Fig. 6.71. Decomposed dashboard.

Today it is difficult to find monolithic solutions because hybrid dashboard solutions having foamed upper part and stiff lower part are frequently required.

Dashboard assembling

The assembling of the various dashboard components, as in general for the plastic elements, can be done in many ways, such as:

- Snap fasteners;
- mechanical fasteners (screws, rivets, etc.);
- welding;
- gluing.

Snap fastener

It is the classic clamping type for plastics components, even though, in the automotive sector, this type of clamping is almost never used alone. It is integrated with mechanical fasteners such as screws or used to produce plastic/metal hybrid solutions.

The definition of profiles for the coupling teeth and their branches, depending on the use (frequent coupling and release, irreversible coupling, etc.) and the different plastic materials, can be easily found in the documentation available on the market.

Mechanical fasteners

Also for this type of clamping there is a wide range of products, but the use in the automotive sector of screws and rivet is increasingly going down also considering the noise problems encountered with the discontinuous coupling of plastic parts. (Fig. 6.72).

MATERIALS	PP	PE	PA	ACE	ABS & ST	POF	ABS/ PC
Polypropylene	■	○	○	○	○	○	○
Polyethylene	○	○	○	○	○	○	○
Polyamide	○	○	■	○	○	○	○
Acetalic	○	○	○	■	○	○	○
ABS & Styrene	○	○	○	○	■	■	■
Polyossifenil	○	○	○	○	■	■	■
ABS/Polycarbonate	○	○	○	○	■	■	■

Fig. 6.72. Compatibility between different materials for the noise due to contact.

Welding

They represent the most common type of clamping which is used to assemble the dashboard parts, also because, only through the welding, it is possible to get assemblies which are able to significantly contribute to the structural characteristics. They also ensure, where necessary, the air seal (air ducts).

It is essential that the parts to be welded are moulded with the same thermoplastic material. Only variations of the material fillers can be accepted, but in any case they must be analyzed every time.

The most important welding processes for the dashboard components are:

- Vibration;
- hot-blade;
- ultrasonic;
- laser.

Vibration welding. The heat is generated by the friction due to the rubbing between the two surfaces to be welded and which are placed into contact with a specific pressure (Fig. 6.73).

The two components, placed in special containment cradles, must have a geometry enabling a relative movement of about $3.5 \div 4.0$ mm, while the inclination of the surfaces to be welded, compared to the horizontal direction, shall not exceed $15°$. Moreover, it is important that the components to be welded, have geometric conditions (flatness) such as to guarantee a homogeneous contact pressure of the two surfaces to be welded.

This welding is normally used for high-production volumes, the cycle time is about 30 seconds and the vibration welding, being a continuous welding, has very good structural and seal characteristics.

The welding of parts with circular geometry is optimal for this technology. Fig. 6.74 shows some examples of typical geometries which are used for the welding areas.

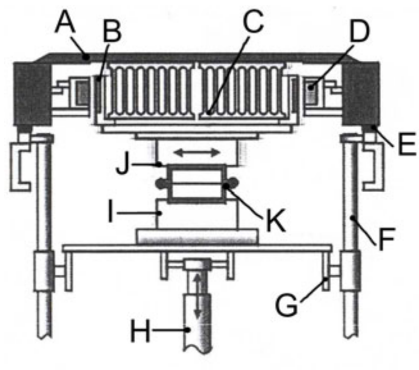


Fig. 6.73. Scheme of linear vibration welding: Bridge A, driver box B, spring C, electromagnetic bobbin D, anti-vibration E, colum guide F, lifting table G, hydraulic/pneumatic cylinder H, lower cradles I, upper cradles J, parts to be welded K.

Hot-blade welding. The heat is transmitted to the surfaces to be welded by a hot retractable blade, interposed between the two surfaces. Even in this case the two components to be joined are placed in containment cradles. The surfaces to be welded must not have inclined parts that do not guarantee such a pressure to ensure enough permeation between the two parts (Fig. 6.75).

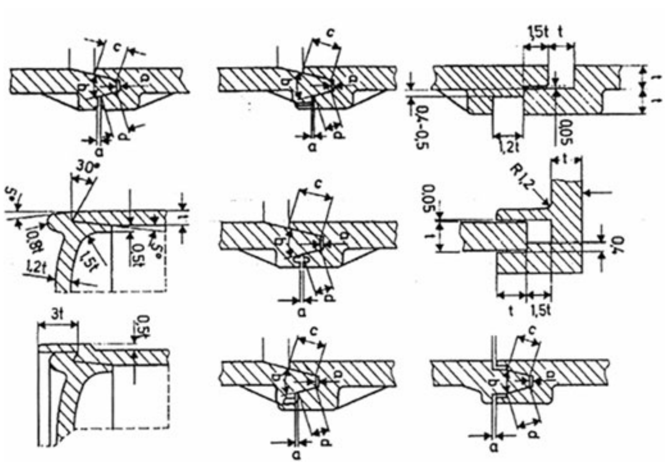


Fig. 6.74. Conformation of welding bead in the roto-welding.

A particularity of this welding technology is the upsetting which is produced by the plastic material softened by the heat as a result of pressure. Should the welding have aesthetic characteristics, it would be necessary to identify the welding joints as those shown in Fig. 6.76, which mask the upsetting.

Even in this case, during the planning phase, it is necessary to define the tolerances of mutual flatness that the two welding surfaces must have for a correct welding.

The welding cycle time is about 45 seconds. The welding obtained has structural characteristics and can guarantee seal performances.

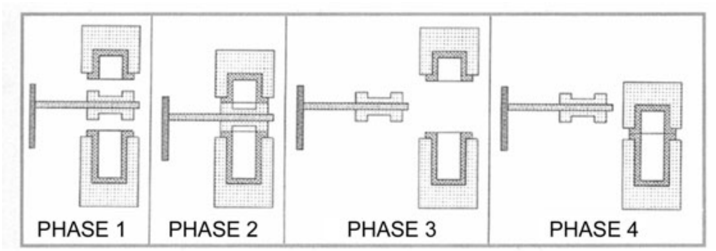


Fig. 6.75. Sequence of the hot blade welding phases.

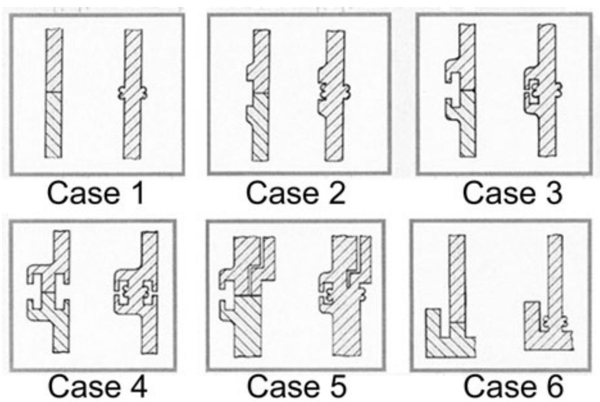


Fig. 6.76. Typical examples of hot blade welding joints.

Ultrasonic welding. A device converts the electrical vibrations, received by a generator at a given frequency, into mechanical vibrations. Then, it sends them to a sonotrode/horn which increases and transmits them by increasing their amplitude, to the parts to be welded. The transformation of the vibration into heat determines the heating which enables the welding (Fig. 6.77).

Between the two surfaces to be welded, in order to increase the effectiveness of the welding, an energy director is provided (Fig. 6.78). It concentrates the heat and is completely melted during welding.

By its nature, this welding is discontinuous and therefore not suitable for the sealing, unless an element with sealing function is fitted in. The structural features depend on the number of welding points and on the sonotrodes which are used.

The ultrasonic technique allows one to make other operations such as the upsetting or the riveting illustrated in Fig. 6.78, which is achieved by fusion of the plastic material shaped like the rivet head. By this way it is also possible to join different plastic types or plastic and metal.

Finally it should be noted that not all the plastics have the same weldability characteristics. For example polypropylene and ABS are easily weldable, while the acetalic resins or polyamides are not easily weldable. In general plastic materials having a broad melting range can be easily welded.

Laser welding

This type of welding, recently applied in the field of plastic materials, is also a consequence of the use of lasers for the dashboard when it also becomes the cover of the passenger air-bag.

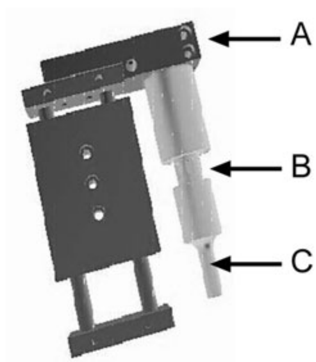


Fig. 6.77. Unit for ultrasonic welding: Support bracket A, converter B, sonotrode C.

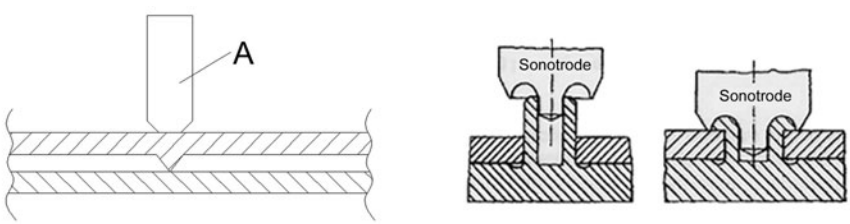


Fig. 6.78. Left: Detail of the energy director, sonotrode A; right: Ultrasonic riveting upsetting.

This process, which is finding application in the shoot channel (see the air bag cover section) welding on stiff dashboards, enables the same structural characteristics of vibration welding to be achieved with the advantage of avoiding damage (upsetting) to the aesthetic surface of the dashboard. Since smoke is not generated, good control of the welding process is ensured together with effective integration in the traceability process for a safety-critical component, as is the case of the dashboard when the passenger air-bag cover function in integrated.

Bonding

The adoption of adhesives in the assembling process for vehicle plastics components has not seen significant application to date because plastics are not among the easiest materials to bond.

Today, however, the use of hot melt has made it possible to overcome the characteristic weaknesses associated with traditional adhesives, and adhesion values can now be reached to guarantee performances not inferior to welding.

Hot melts are thermoplastic adhesives applied melted on the surfaces to be bonded (110÷200°C) which are solid at room temperature when they exhibit their adhesive characteristics.

The adoption of bonding technology, apart from enabling the union of elements produced with different plastic materials and providing sealed joints, permits significant reduction in investments with respect to welding since the specific equipment required is limited to simple cradles in which the parts to be bonded are placed. The robot which is needed to correctly apply the adhesive is not a specific equipment.

Having analyzed the dashboard body and described the dashboard functions, the different types of dashboards, together with the main technologies and their assembling techniques, it is now appropriate to analyze the most important dashboard components.

Dashboard components

The main components of the dashboard are:

- Air ducts;
- blower/air vents;
- glove compartment/drawer;
- instrument cover;
- passenger air-bag cover;
- controls.

Air ducts

The air ducts will be described in detail subsequently in relation to the air conditioning system; here it is appropriate to mentioned these components in terms of being dashboard parts.

Air ducts are divided into:

- Defroster/demister air ducts. These ducts are responsible for the transport of the air for defrosting and demisting by the HVAC (Heating Ventilation Air Conditioning) to the windscreen and to the glass front doors;
- ventilation (vent) air ducts. These ducts are responsible for the transport of the air by the HVAC to the air vents, normally located on the dashboard.

Defroster/Demister air ducts. Defroster/demister air ducts are usually manufactured via injection moulding and welded to the dashboard body, contributing significantly in terms of stiffening of the coupling between the dashboard and the windscreen frame, creating a box structure as shown in Figs. 6.79, 6.58 and 6.63.

The material used is a thermoplastic, similar to that used for the dashboard body to which air ducts must be welded. If, for example, the dashboard is made of polypropylene with mineral and elastomeric fillers, the duct will be moulded in loaded polypropylene. Thus there is no need to use the elastomeric filler for impact strength performance or mineral filler with non-scratch performances.

Ventilation air duct. Also the ventilation air duct is generally produced by injection moulding but, unlike the previous duct, is moulded in two parts and welded together. In fact it is not convenient to use the direct welding on the dashboard body because the air in the duct could be heated by the sun. This would result in a longer cool down because it is through this duct that cool air comes to the passenger compartment.

Fig. 6.80 illustrates the differences between the two types of ducts. Occasionally vent ducts are made using blow moulding technology. In this case the material used belongs to the polyolefin family, but with specific formulations. appropriately created for the blow moulding process as shown in Fig. 6.81. Figs 6.58 and 6.63 illustrate these ducts in cross-sections of the dashboard.

Fig. 6.79. Defroster and demister air duct.

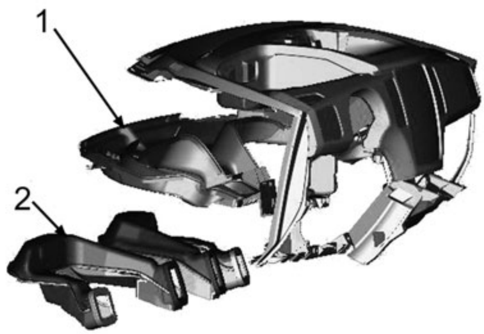


Fig. 6.80. Example of air vent duct and defroster/demister air duct.

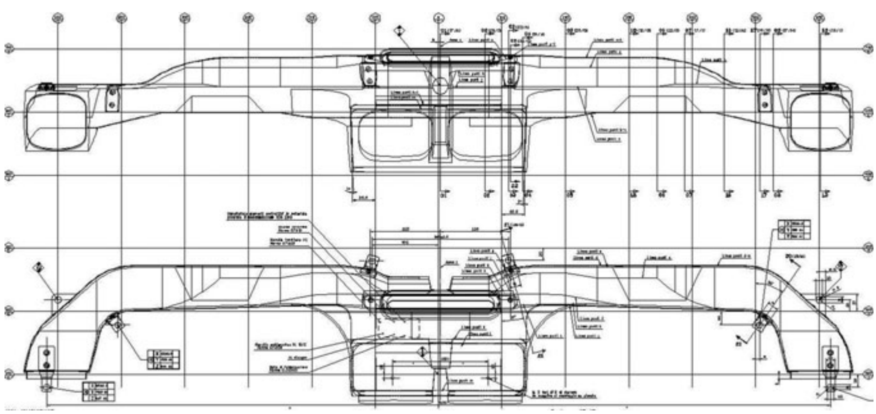


Fig. 6.81. Blow moulded air duct.

Blow moulding uses specific machines that extrude the material in cylindrical form, when the cylinder has crossed the mould. The mould, made up of two parts, closes by pinching the plastic tube at both ends. At a later stage, an inert gas is blown inside the cylinder by means of a special injector which, making the plastic adhere to the two walls of the two cooled parts of the mould, produces a hollow body which constitutes the duct required.

Subsequent recovery operations enable the necessary openings for the duct to be made.

This technology is the same as that used to make conventional plastic bottles.

Air vents

The air vents are the terminal ring of the distribution chain through which air, appropriately treated, enters into the passengers compartment.

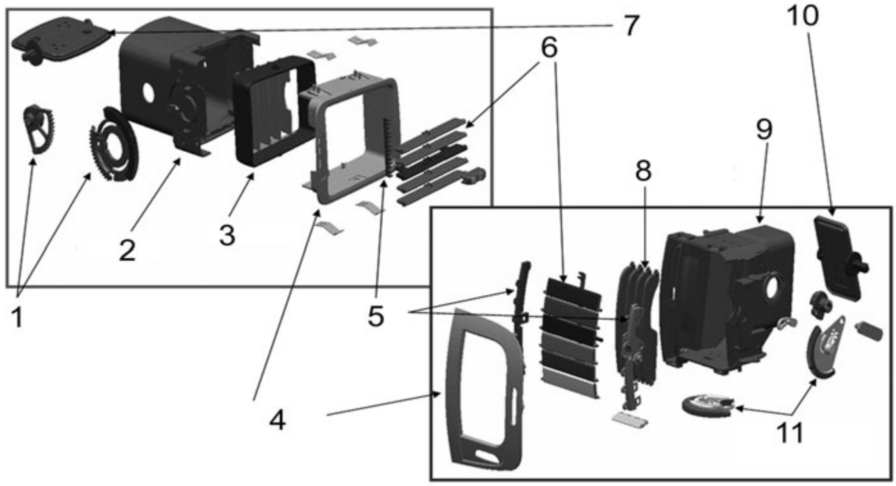


Fig. 6.82. Exploded view of two air vent types and their components: Control wheel 1 and 11, body 2 and 9, rotor 3, stack 4, combs 5, fins 6, close door/shutter 7 and 10, baffle 8.

In many vehicles air vents are placed only on the dashboard (low and medium/low segments), but their application is increasingly extending also to other components of the passenger compartment such as the console.

The function of the air vent is to allow the occupants of the car to adjust the direction and, in part, the amount of air released by the climate group, in order to achieve the best comfort climate conditions. As with the air ducts, the description of air vents will be continued subsequently when the air conditioning system is examined.

The main components of an air vent are (Fig. 6.82):

- The body, through which the connection with air ducts is produced and on which air vent components are assembled;
- the fin and rotor, which are necessary to manage the airflow direction;
- the leverages, gear wheels, combs and controls, to drive the vent functions;
- the door locking, to stop the air getting in the frame.

The air vents can be classified into three families, the origin of which relates to the tradition of OEM brands, aesthetics, patents and costs:

- Fin air vents;
- rotor air vents;
- round air vents.

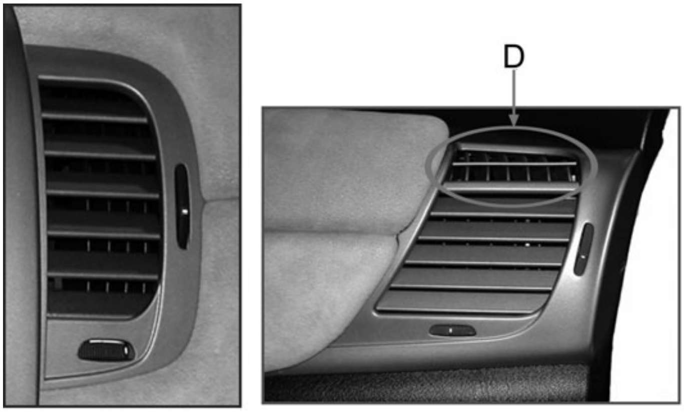


Fig. 6.83. Fins air vents; demister area D.

This classification determines the way the air vent kinematics is designed.

Fin air vents. In this solution, fins are mounted separately on the air vent body and are located in two rows, one external (toward the car occupant), the other internal. The two fin rows, through the combs that connect them, allow one to manage the air-flow direction, for example the external row in the high/low direction and the internal row in right/left direction; see Fig. 6.83.

The external row of blades can be completely closed, thus creating a continuous closed surface that integrates with the component design on which the air vent is mounted, generally the dashboard.

The increasing use of this kind of air vent has led to the elimination of the locking door, allowing one to recover part of the higher costs of this type of air vent. It should be noted, however, that the removal of the locking door has required the revision of the values of admitted air blow-by, since the seal which can be achieved when the fins are closed is not comparable to that of a door equipped with gaskets.

Rotor air vents. The main feature of this solution consists in the external row fins, which are integrated into a frame/rotor which, when rotated around a horizontal axis for example, enables the air-flow to be directed upwards and downwards.

The row of inner fins are mounted separately on the air vent body (as in the fins air vent) or on the rotor. By means of a comb, these fins manage the air-flow in the right/left direction, as shown in Fig. 6.84.

Also this type of air vent enables the possibility to eliminate the locking door, thus leaving to the inner fins row not only the task of directing the air-flow but also to lock it. Clearly the consequences are the same as those described above with regard to the fin air vent.

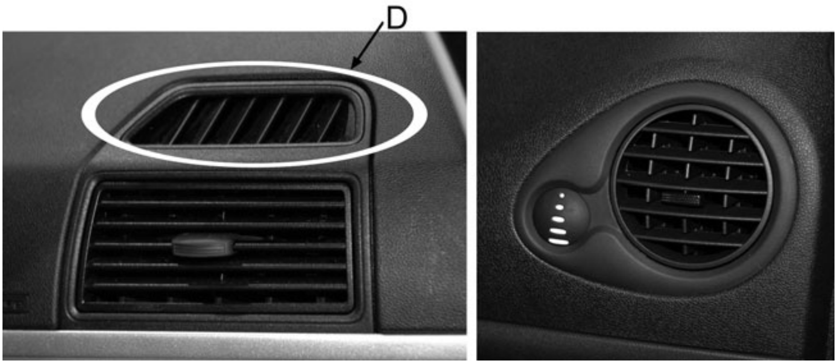


Fig. 6.84. Rotor air vents; demister area D.

The rotor air vent is more economical and reliable if compared with the previous one, because it comprises a smaller number of parts, but does not permit the same stylistic freedom as fin air vents do.

It should be remembered that the air vents may incorporate the demister, which is the air outlet used to defrost and demist the glass front doors, as shown in Figs. 6.83 and 6.84.

The size and orientation of the fins determining the air-flow direction, are fixed and defined during the design phase in order to ensure the performance levels defined in the type approval.

Round air vents. This solution, due to its geometry, enables both a cylindrical rotor equipped with suitably shaped and manoeuvrable fins, and a spherical rotor with integral fins. With simple rotation and without specific leverage, this solution enables four air-flow directions to be selected and air closing to be managed; see Fig. 6.85.

Characterized by its simplicity and low cost, the round air vent, which was fitted originally on sport cars, is now also used on many different types of cars, also thanks to the application of different finishing, such as chromium plating.

Materials and common technologies. All the air vent components are produced by injection moulding of thermoplastic materials.

Air vent bodies, rotors and fins, in order to ensure a good dimensional stability which is essential to guarantee correct operation, good impact resistance even at low temperature and good aesthetics, are moulded using technopolymers such as the ABS and PC (polycarbonate) blend. The leverages and the gear wheels, which enable long-term functionality and resistance to stress, are also moulded by technopolymers such as polyamides or acetalic resins.

When the air vents design is particularly simple, as some cases of rotor air vents and round air vents, the air vent bodies and the rotors can be moulded by polypropylene-based materials with suitably loaded fillers. This choice is used

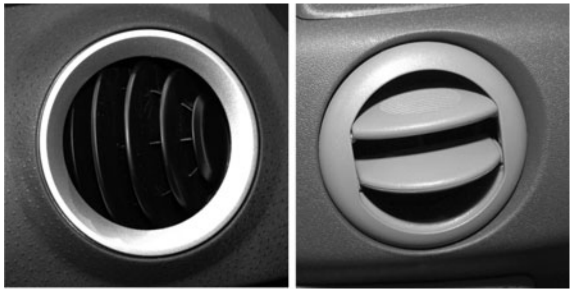


Fig. 6.85. Round air vents.

in order to reduce costs and, especially for stiff dashboards, in order to simplify recycling.

Design criteria and rules. Besides guaranteeing the fluodynamic specifications which will be discussed subsequently, the air vents must ensure safety features in the same way as the dashboards, and offer highly ergonomic characteristics such as manoeuvrability and the prehensility of the controls. They must also meet a series of functional requirements such as the load manipulation of the controls and the general absence of noise.

Finally, it is important to remember that the air vents, like the other types of similar components, must be designed following the robust design techniques, not only for the intrinsic quality of the product but also to reduce times and costs with respect to production and assembly.

Glove box compartment/drawer. The function of the dashboard to contain objects is generally met using storage spaces. The most important storage space is the glove box compartment, usually placed in front of the passenger, the version with a door, shown in Figs. 6.86 and 6.87, becoming increasingly common.

The glove box compartments can be classified into:

- Fixed glove box compartments with door;
- tilting glove box compartments.

The second solution is used mainly when insufficient space is available in the x direction for the size of glove box compartment required (Fig. 6.88).

This solution has the disadvantage of hosting the objects in the mobile part of the glove box compartment; thus the weight of the objects is felt during drawer closing, while during the opening, the drawer should be retained or be equipped with appropriate systems to slow its opening.

Fixed glove box compartment with door. This component consists of:

- Drawer;

Fig. 6.86. Glove box compartments.

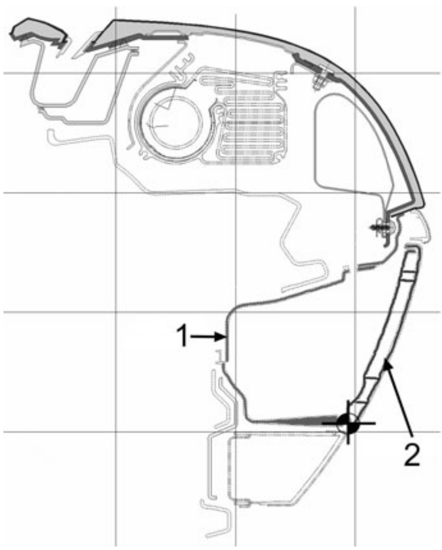


Fig. 6.87. Typical section of a dashboard, highlighted the parts that make up the fixed glove compartment: Fixed drawer 1, and doors 2.

- door;
- closing system.

Drawer. In theory, when the design and assembling condition permit it, the drawer can be integrated with the dashboard body, especially in the case of the monolithic stiff dashboard. Usually, however, the drawer is a separate injection moulded part assembled on the dashboard body.

Predominantly the material used is Polypropylene with mineral filler. This choice does not only arise due to economical reasons, but from technical reasons as well; in fact the sound absorption characteristic of polypropylene is taken into account since in this application it is particularly important to attenuate possible noises caused by the objects contained in the drawer.

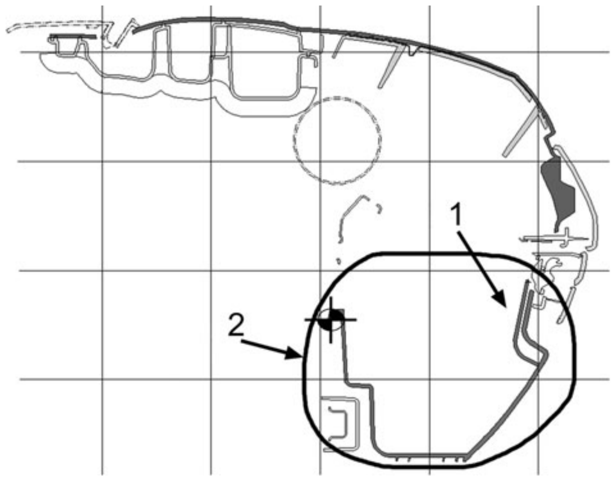


Fig. 6.88. Typical section of dashboard, highlighting the parts that make up the tilting glove box compartment.

For applications on higher segments vehicles, the drawer can be enriched by flocking.

Door. In stiff, covered or foamed non monolithic dashboards, of which the lower stiff part is injection moulded, the door is made up of two moulded parts, door and door reinforcement. These two parts are first moulded using the same plastic material as the dashboard, with which they must match aesthetically and then welded to one another to provide the door with an appropriate structural strength. Door reinforcements are also used for containing spaces, as shown in Fig. 6.89.

If the door is to be coupled aesthetically with a covered dashboard, it is also coated using the same technique as that used for the dashboard. The same

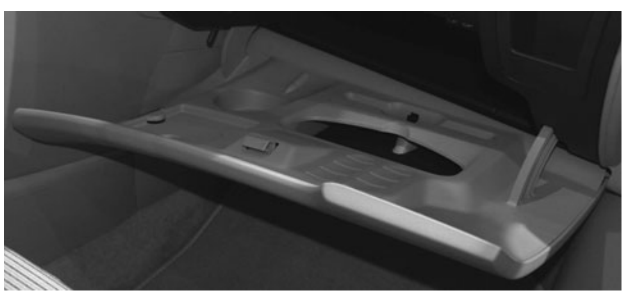


Fig. 6.89. Door reinforcement with containing spaces.

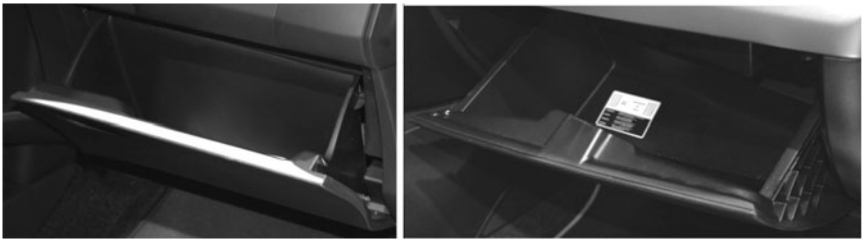


Fig. 6.90. Tilting glove box compartment.

type of technique could be used, for economical reasons; in the case of coupling with foamed dashboards because, the aesthetic matching is guaranteed in any case, although tactile matching is not guaranteed in this way. Fig. 6.87 shows an example of such a situation.

The totally foamed door is obtained by making the door with the foaming technique (injection moulded support, thermo-formed coating or slush skin and polyurethane foam). The door reinforcement is made using injection moulding and assembled to the foamed door.

The door is fixed to the drawer or dashboard body via a hinged system; the hinges can be integrated in the door reinforces (mobile hinge) or drawer (fixed hinge), or can be independent to enable possible adjustment to optimize the geometric coupling between the glove compartment and the dashboard.

For the most simple and economical solutions, some examples of film-hinges exist.

The glove compartment should be completed in two top corners by small rubber blocks that avoid possible contact which would generate noise.

Closing system. The closing system comprises a gear located on the door external part (button, door-handle, etc.) and a closing device located inside the glove box compartment (striker plate).

The gear can be located at the door centre, in which case the closing system is in the middle, or sideways, oriented towards the driver in order to make operation easier from the driver seat; in this case it is necessary to have a doubled closing system with two lateral hooks.

Tilting glove box compartment. As shown in Figs. 6.88 and 6.90, the tilting glove box compartment is composed of:

- Drawer, which functions as container and door;
- reinforcement;
- closing system.

The drawer is a movable element hinged to the dashboard body usually using the same technology and material as the previous solution. In order to provide sufficient structural consistency, a reinforcement is welded inside the drawer which also contains the closing system, for which what mentioned before is still valid. The hinges and the closing system are the most critical points of this solution because they must support the weight of whatever is contained in the drawer.

Dimensioning criteria and design rules. To perform its function, the glove box compartment must have a minimum capacity defined in terms of volume (6÷10 liters) and by the three dimensions x, y, z that are necessary to contain the objects defined by the rules.

To conclude matters relating to the glove compartment, which are also largely valid for many other dashboard parts, it is important to remember that in the design activities it is essential to define the gaps and flushes which are stylistically acceptable and, at the same time, technologically feasible. For example, Fig. 6.91 indicates how the gaps can be managed, by replacing the adjacent parts sharp edges with an appropriate radius, thus rendering less evident possible skewing (not constant gaps).

Similarly, by deliberately misaligning one part with respect to another adjacent part, it is possible to reduce the effect of casual misalignments in the case that perfectly aligned parts are not required.

Additional contents. In addition to flocking, previously mentioned for higher segments cars, the closing system can have a lock with key; lighting inside the drawer is often provided.

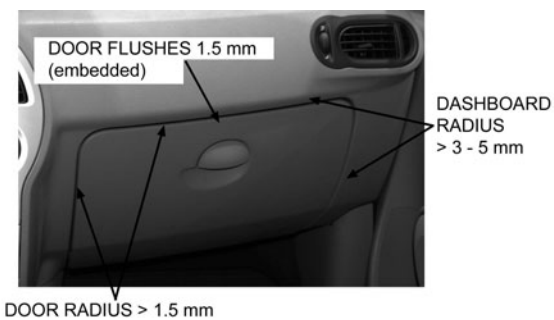


Fig. 6.91. Example of gaps and flushes inherent coupling between the glove box compartment door and the dashboard.

The cooled glove compartment is becoming increasingly commonplace, which is achieved by sending a cool air-flow into the drawer, by deriving and channelling air from the ventilation system.

Instrument cover/cluster

This is a component that can be either integrated into the dashboard body, as shown in Fig. 6.92, or separate as shown in Fig. 6.93. Integration, although always possible in theory for stiff and foamed dashboards, is only really feasible in certain cases depending on the geometry and on the possibility of dismantling the instrument board. For the technological limitations already seen, the covered dashboard less frequently has integrated cluster.

As well as being very important for the stylistic definition of the dashboard, the basic function of the cluster is to ensure the absence of reflection of the instrument board on the windscreen and thus to improve visibility for the driver (active safety).

When the cluster is separate, it is normally made up of two injection moulded parts, the exterior one providing aesthetic performance and the inner part acting as a reinforcement.

Fig. 6.92. Instrument covers/clusters.

Fig. 6.93. Separate instrument cover.

The two parts are welded together (normally using the ultrasound technique) in order to ensure adequate dimensional stability, high structural consistency and good heat resistance.

The cluster should not generally pass the shock test because it cannot be contacted by the driver in the case of a collision, being located in an area protected by the steering wheel.

The plastic materials can be Polypropylene with mineral fillers (not necessarily elastomeric fillers) or ABS/PC (polycarbonate) blend, when the geometry is particularly critical in terms of heat resistance.

Passenger air-bag

As already seen while considering air-bags, the air-bag cover can be separate or integrated. Here it is appropriate to examine how these two cover types have a very different impact with respect to the dashboard design.

Separate cover for stiff dashboard. In case of a separate cover, the dashboard has simply the task of hosting the air-bag module, the cover of which must close the dashboard opening through which the bag deploys, as shown in Fig. 6.94.

Fig. 6.95 shows a cross-section of an air-bag module with a separate cover fixed by means of the housing. The cover is obtained using injection moulding of the thermoplastic elastomeric materials.

In the case of Fig. 6.95, as a result of the bag deployment, the cover opening has the H conformation. This denomination results from the shape of the predefined breaking lines (tear- line) obtained directly by the mould. This conformation is similar to opening a door with two swings.

There are also other types of tear lines such as C, as already seen in the section on air-bags.

However it should be realized that it is crucial for the cover to open without any risk of generating possible lesions for the car occupants. These lesions may be caused by tear lines with aggressive profiles or due to the possible detachment of cover parts following air-bag deployment.

For the dashboard designer, in addition to the installation issues, the air-bag with separate cover also creates the possibility that the bag in his opening generates breakage of the dashboard and/or its components in areas close to the

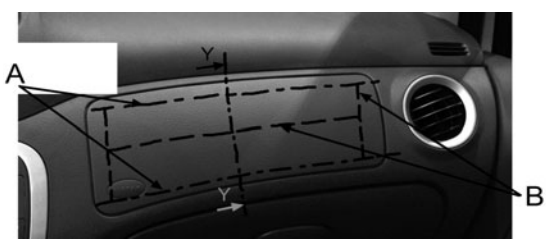


Fig. 6.94. Typical example of reported cover with H opening, showing the thinning zones with hinge function A and the tear- lines B.

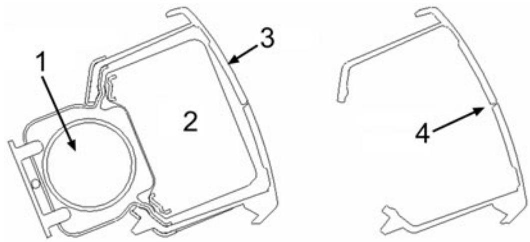


Fig. 6.95. Cross section of an air-bag module with separate cover. Components: Gas generator 1, bag 2, cover 3, tear line 4.

air-bag module and aesthetic problems in the management of couplings between the cover and dashboard.

Other design issues arise from the difficulty of achieving acceptable finishing (color matching) of the cover with regard to the dashboard, being realized with different materials. Last but not least, the imprinting that the default tear lines transmit on the aesthetic surface of the cover.

With the increasingly widespread use of the passenger air-bag, today almost standard, the separate cover has been replaced by a cover integrated in the dashboard. Today, in fact, there are no longer traces of the air-bag on the dashboard apart from the obligatory inscription.

The adoption of the integrated cover has not only resulted in an improvement in dashboard aesthetics, but has also enabled new design concepts. As a consequence, the dashboard itself has become an integral part of the safety system. For this reason the dashboard is subject to specific safety regulations, of which the most important is surely component traceability.

There are several ways to implement a dashboard with integrated cover. Here the two most important solutions are considered, one for stiff dashboards and the other for foamed dashboards.

Integrated cover for stiff dashboards. Unfortunately it is not possible to obtain the tear-lines directly by the cover mould, as in the previous case, due to its complexity, because in this case the cover is part of the dashboard itself. Therefore the opening lines are obtained by recovery operations, usually using a laser driven by a robot following a defined route, perforating the dashboard with a very large number of blind holes with a diameter of a few tenths of a millimeter and a pitch just exceeding the hole diameter.

A slightly conical section is given to the hole, while the residue thickness, which is not perforated, is approximately the 15÷20% of the dashboard thickness. Thanks to the system versatility, it is possible to change easily the number of the holes, the depth of the holes, and the pitch, to optimize the cover opening.

In addition to the need to create the opening lines with a recovery operation, there is another key feature that differentiates this cover from the separated cover; namely the plastic material of which it is moulded cannot be chosen at will but must necessarily be the material of the dashboard. It has already been seen that the selection of the thermoplastic material for the stiff dashboard body is a compromise between stiffness and impact strength. This material is very different from the material which is necessary to use for the cover since its most important characteristic is strength.

Therefore it is not really feasible that the dashboard body, in its role as cover, exhibits the strength characteristics to enable, during the bag deployment, conditions which are similar to the separate cover; consequently it is necessary to:

- Define a tear- line which does not constrain the cover to the dashboard body, i.e. an opening line that completely contours the air bag deployment;

- connect the dashboard body part, that during the bag deployment would be projected inside the passenger compartment, to the dashboard itself using an appropriate component that retains the separate part while preventing brittle fracture. This device is termed the dashboard shoot channel.

The dashboard shoot channel (Fig. 6.97) consists of two injection moulded parts in plastic material, connected by a structural fabric.

The exterior part, which is fixed, also has the task of correctly orienting the bag in its deployment and has the structural role to retain the body part that is separated by deployment of the air-bag. For this reason it is moulded in Polypropylene with glass filler (see table in Fig. 6.56).

The internal mobile part is injection moulded with thermoplastic rubber, which is the same material used for the separate cover.

The fabric is made using interwowen warp and weft, usually in polyamide fibres with appropriate properties.

The link between the external and the internal part is made using co-injection of the two materials on the fabric, by a press that has two different injection groups. Finally the dashboard shoot channel is welded by vibration on the inside of the dashboard body placing the tear line between the fixed and mobile parts. The welding of the fixed part, does not present particular problems because the two plastic materials are compatible (Polypropylene family). The welding of the mobile part is more difficult because two different materials need to be joined, polypropylene with thermoplastic rubber; see Fig. 6.96.

In this way the fixed part (external), remains integral to the dashboard body, while the mobile part (internal), is integral with the dashboard body part which is detached during air-bag deployment but cannot harm occupants being retained by the fabric.

Fig. 6.98 shows the dashboard shoot channel detached from the dashboard following air-bag deployment and the part that has been opened, part of the dashboard; it is firmly anchored to the movable part of the dashboard shoot channel.

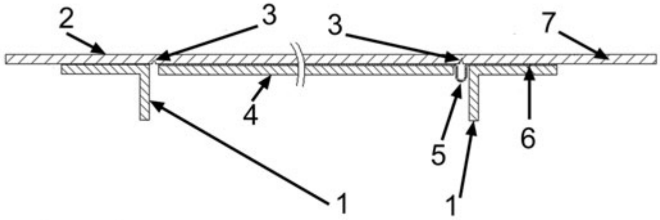


Fig. 6.96. Section of a stiff dashboard with integrated cover: Dashboard shoot channel 1, embossed surface 2, tear-line 3, shoot channel movable part 4, fabric 5, shoot channel fixed part welding with the dashboard 6, dashboard 7.

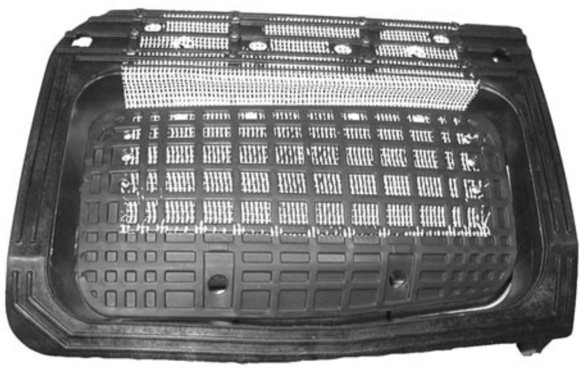


Fig. 6.97. Dashboard shoot channel.

An evolution of this solution, currently under development with the first cases of application, is the replacement of the fabric with the same thermoplastic rubber as used for the mobile part, enabling considerable savings.

Integrated cover for foamed dashboard. One solution, which is currently employed, is shown in Figs. 6.99 and 6.100 where, it is possible to see a pressed sheet element that is fixed to the dashboard support in the position of the opening through which the air-bag deployment takes place. This sheet element has the same function previously performed by the dashboard shoot channel.

The inflating bag deforms the sheet part, already prearranged to open, by lacerating the foam and exiting through the laminated part, the break being determined by an incision made with a hot blade that penetrates into the laminated part with a depth of approx. 50÷60% of the total thickness. Fig. 6.101 shows the air-bag after deployment.

Fig. 6.98. Shoot channel movable part 1 joined to the body dashboard 3 and the dashboard shoot channel 4 through the fabric 2.

The increased use of foamed dashboards and passenger air-bags is pushing the research centres, car manufacturers and air-bag suppliers towards identifying innovative solutions.

Controls

The image of Fig. 6.102, is intended to provide an idea regarding the number of controls in the passenger compartment, a number which tends to grow as vehicle functions increase.

These controls, being prevalently allocated on the dashboard and on the console, are treated in this section.

While designing the location of the control devices, the following criteria should be taken into account:

- Accessibility;
- visibility;
- ease for use.

Since the accessibility and visibility of the controls shall be treated in the second volume, in this section only the feasibility for use of the controls is considered.

The placement of the controls within a space that can be reached by the driver and the passenger must take into account the correlation between the

Fig. 6.99. Sheet metal element used for the air-bag deployment in the case of foamed dashboard.

priority index given to the execution of a definite control and the level of feasibility for use of the controls in the operating space.

The priority index takes into account the importance, frequency, unpredictably and rapidity that may be required in the control execution:

- Importance, the level of indispensability for driving (safety);
- frequency, the average number of operations performed in the unit of time;
- unpredictably, the level of randomness with which the need to activate the control itself occurs;
- rapidity which may be required for the execution of the control.

Fig. 6.103 shows the distribution of the auxiliary driving controls divided into priority levels: High, medium and low.

Since the feasibility for use of a control is not uniform within the operating space, it is possible to locate spaces that are more accessible with respect the muscular use and to the articular load of the limbs which make the movement. These zones are confined around the extremities of the limbs, in a position of rest or semi-flexure. Outside these zones, the feasibility for use decreases until it reaches the minimum at the limit surface of accessibility.

Based on these considerations, it should be noted that:

- The controls of the functions for emergency actions must be placed in the zone which can be instinctively reached as quickly and accurately as possible;
- the location of the controls must also follow the criterion of functional analogy, i.e. the grouping of all controls in relation to the accomplishment

Fig. 6.100. Sheet metal element used for the air-bag deployment after the bag opening.

of functions aimed at the same principal goal (for example exterior lighting, cleaning windows, etc.);

- the location of each control must also take into account whether activated with the car stopped or in motion (for example, the change of the wheel position steering may be made with a control to be handled only when the car is stopped).

Finally the controls can be allocated in three main positions:

- On the dashboard, steering column switch, steering wheel and console, controls, must be placed related to driving and environmental conditions, and usually safety functions, i.e. such controls must be visible without significant distractions with respect to watching the road and operated with as limited hand movements as possible from the steering wheel;
- the controls for the seat adjustment are placed on the seats;
- in other parts of the passengers compartment (i.e. rear-view mirrors adjusters, window regulators, etc.).

Dashboards: criteria for design and verification

The dashboard body must first respect all primary requirements including strength, stiffness, resilience, resistance to vibration and thermal stress (fatigue). The structural calculation with finite elements and the static and dynamic tests at the bench and in the vehicle are normally used to design and verify the design.

In the collision tests with the impactor, shown in Fig. 6.104, robustness and resilience are important to verify the absence of fragile breakages with splinters and the achievement of the required HIC objectives.

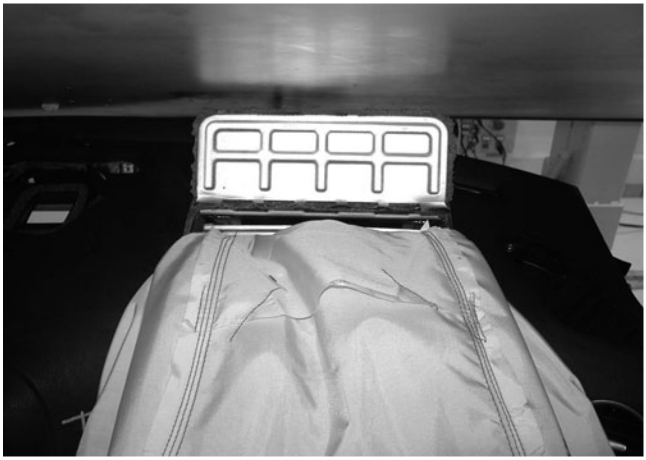


Fig. 6.101. Sheet metal element used for the air-bag deployment after the bag opening.

As concerns stiffness, levels are expected which exceed the required target in the various reference positions and in the three Cartesian directions. In addition, the achievement of the expected dynamic stiffness performances, which are evaluated by the analysis of the vibration modes of the dashboard, complete with all the components provided, must be guaranteed.

Usually the first resonance frequency should not be less than 35 Hz. Today there is the tendency to increase this frequency to above 40 Hz in order to avoid dynamic coupling with the resonance frequencies of the unsuspended masses, which have been found to help creaking.

As regards fatigue and ageing, test modes exist which are standardized by each car maker, combining both vibrations and thermal cycles with different humidity conditions, conducted in special climatic chambers. The accelerated fatigue cycles must reproduce the decay exhibited by the car on the road, after at least two years of average mileage covered in the most severe conditions of route and climate.

A series of tests also exists to check the appearance, reliability, packageability and functionality, relating to which it is important to consider:

- The dimensional stability at high temperatures for a definite period of time;
- the residual deformation due to imposed thermal cycles;
- noise tests on the new dashboard and after fatigue tests;
- vertical settlements;

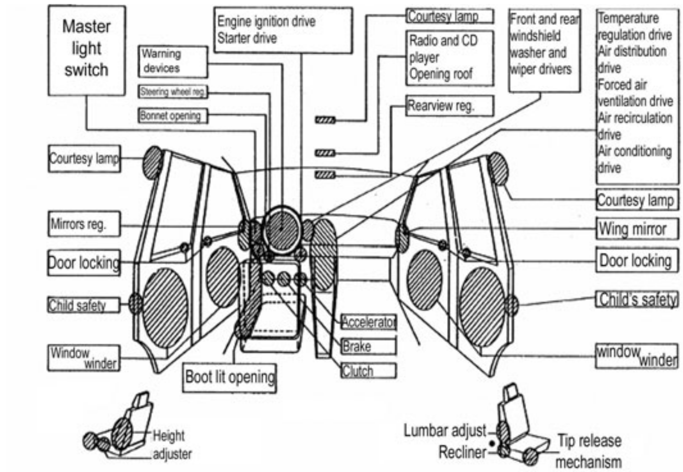


Fig. 6.102. Arrangement of controls inside the vehicle.

- the decay of tightening torques;
- the resistance to chemical agents and light;
- misuse, such as an excessive load placed in the glove compartment;
- static and movement interferences of mobile elements;
- easy replacement of the dashboard components;
- aesthetics checks.

Finally it is important to emphasize the selection and dimensioning of the elements fixing the dashboard to the dashboard cockpit and the dashboard cockpit to the body. Any loosening due to vibrations must be avoided; plastic parts must not be permanently deformed; squeaks and rattles between the parts must not occur.

Normally self-threading screws are not used as fixing elements being less effective than metric screws.

6.3.3 Console

This component arises from the opportunity to use the space above the central tunnel, as an area equipped for containing objects while creating a finishing element to cover the clutch of the gear shift lever and contributing to the attenuation of floor noise; see Fig. 6.105.

Furthermore the console has an aesthetic function, as noted previously, especially on higher segments cars, contributing to the climate comfort since it hosts the air vents for the ventilation of the rear seats.

DRIVES WITH HIGH INDEX OF PRIORITY (GROUP I)	DRIVES WITH MEDIUM INDEX OF PRIORITY (GROUP II)	DRIVES WITH LOW INDEX OF PRIORITY (GROUP III)
- Master light switch	- Rear windshield wiper drive	- Engine ignition drive
- Lights selector	- Rear windshield washer drive	- Starter drive
- Selector switch main-beams / dipped-beam headlight	- Backlight drive	- Parking lights drive
- Direction indicator drive	- Headlamp cleaning drive	- Radio and CD player drives
- Warning device	- Temperature regulating drive	- Window winder drive
- Visual signal	- Air flow regulating drive	- Seat drive
- Front windshield wiper drive	- Air distribution drive	- Door-locking drives
- Front windshield washer drive	- Forced air ventilation drive	- Wing mirrors regulation drive
- Front fog light drive	- Air recirculation drive	- Courtesy lamps and spot drives
- Rear fog light drive	- Air conditioning drive	- Clock drives
	- Board computer drive	-Check control and instrumentation drives
	- Duplication of radio and CD player drives	- Electric lighter drive
	- Anti crash light drive	
	- Buffers, antiskid, interlocked 4WD drives	

Fig. 6.103. Table with the auxiliary driving controls divided according to the level of priority.

The different console types may be classified, as with the dashboard, as follows:

- Stiff;
- covered;
- foamed.

In many cases, in contrast to the dashboard, the placement of the console on the car is not highly visible to the occupants; so the aesthetic and tactile functions are less important. For this reason the stiff solution is used more frequently than occurs with the dashboard, and can be enriched by painted and covered parts.

Stiff consoles are made by injection moulding; Polypropylene materials with anti-scratching characteristics are generally used.

Since the console is not subject to shocks concerning the occupants' safety, there is no need to use elastomeric fillers. In any case, the minimum radii specified must be guaranteed.

Covered or foamed consoles are only used in high segments cars. The hybrid solution is often used also: In this solution, the console is made up of several parts which must be assembled together. In these cases, it is normal that the least visible parts are stiff, while the others are covered or foamed.

Fig. 6.104. Some examples of impact test on dashboard through impacting.

Fig. 6.105. Console.

6.4 Interior Trims

6.4.1 Pillars and Interior Valence Panels

These components are generally made of plastic material with a traditional aesthetic function (the covering of the pillar plates and the relative joints, drilling, puckering and aesthetic deficiencies of plate pressing), and some functions recently acquired which tend to require changes with respect to the original technologies.

Among these new functions is safety, requiring energy absorption in the event of contact with the occupants due to a collision, the absence of fragile breakages, and comfort by improving the thermal absorption and insulation.

The function has been recently enriched by the presence on the front pillar (A pillar) of the demister for the front and side glasses. This solution allows to overcome the difficulty to position these vents correctly on the dashboard, as shown in the example of Fig. 6.106.

Compared to the front door panel, the demister on the A pillar has the advantage that the connection between the dashboard air duct and the pillar is made between two components that are both assembled on the body; in addition, it is assembled on a component from which it is easy to direct the air-flow toward the side glass. Instead, when the demister is located on the front door panel, the connection is between a fixed part, the dashboard and a mobile part, the door panel.

Fig. 6.106. A demister vent on the front A pillar.

As regards energy absorption in the event of a collision, biomechanical criteria are adopted, referring to the deceleration of semi-spherical elements impacting the pillars at a speed of 25 km/h.

Achieving the specified biomechanical values is enabled by including ribs in the rear part of the pillars appropriately or by incorporating structural foam between the body and the pillar in order to absorb energy.

In any case, the pillar coverings should allow sufficient deformation to ensure deceleration values of less than 80 g for 3 ms. These biomechanical values correspond to a compression which is less than 30 mm.

In the presence of the side air-bag, in order to protect the head in the case of side impact, as in Fig. 6.107, the pillar covering must be capable of deforming so as to enable the correct air-bag deployment, of course without any breakage. The deformation of the pillar may be allowed by its elasticity or by driven failure of one or more pillar fasteners.

The most important design aspects for this type of components are:

- The material and the relative moulding technology;
- the type of fasteners;
- the type of coupling with the adjacent components.

Fig. 6.107. Example of how the pillar covering (in this case the B pillar), must be able to deform itself for the correct air-bag deployment.

Pillar covers

This section focuses on the materials and technologies widely used for this type of component. The pillar covers can be grouped into two families:

- Embossed stiff;
- trimmed.

Embossed stiff pillar covers

Such pillar covers are obtained using thermoplastic injection moulding (Polypropylene) with the addition of mineral fillers with anti-scratching characteristics, and are normally used in vehicles belonging to lower segments.

Trimmed pillar covers

In the past, this solution was performed using the vacuum thermo-forming technology, examined previously while discussing covered dashboards. The trimming material was most often an embossed and calendared sheet based on PVC/ABS, not expanded because the tactile sensation on the pillars does not have the same importance as for the dashboard. The support was obtained using thermoplastic injection moulding (ABS); this material was adopted because the gluing process on ABS is much easier than on polypropylene.

Currently, the trimming solution that is used mainly is in-moulding or over-moulding, i.e. the injection of plastic material in one mould in which the fabric is placed; see Fig. 6.108.

This technology is applicable whenever the sample to be covered has a simple geometry, such that it does not involve stretching that would damage the fabric which must have mechanic and elastic characteristics that enable it to resist the stress in the mould during the plastic material injection.

The trimming and support materials should be chemically compatible so as to ensure good adhesion; furthermore the plastic material injection into the mould must be designed in such a way as to create the least possible tension on the fabric in order to avoid defects, for example wrinkles.

The adoption of moulding processes at low pressure has further contributed to the diffusion of covered interior trim components in general since it enables the use of a wider range of covering materials.

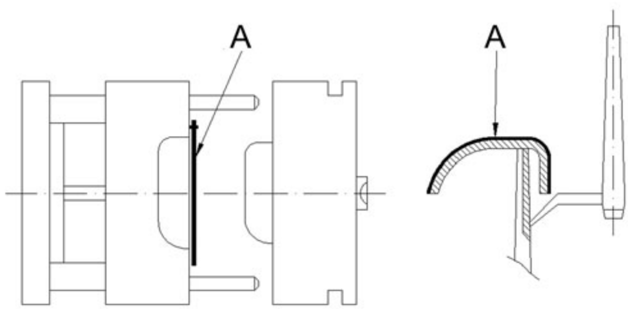


Fig. 6.108. Outline of the over-moulding process, highlighting the trimming material A.

Types of fasteners

Fasteners made through the use of screws, normally hidden by caps, have now been almost completely replaced by snap fasteners which represent, a more economical solution, now adopted even when, as previously mentioned, it is necessary to ensure the failure of one or more fasteners for correct air-bag deployment.

Figs. 6.109 and 6.110 illustrate a fastening snap adopted for an A pillar cover. The fastener is made by a coupler system obtained by mobile slides directly on the pillar. This coupler is inserted into a metal clip placed into a cavity cut in the metal sheet of the body.

Fig. 6.109. Front pillar cover rear view.

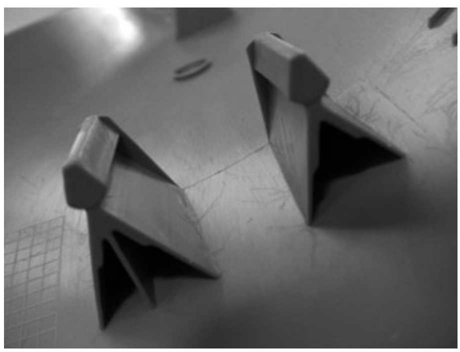


Fig. 6.110. Detail of a fastening snap shown in Fig.6.109.

Figs. 6.111 and 6.112 illustrate another solution, adopted for the central lower pillar (B pillar) cover. In this case, the fastener has a special coupler system (Fig. 6.113) placed as can be seen in Fig. 6.112.

In Figs. 6.110 and 6.112 it is possible to see clearly how essential it is to reduce the thickness of the ribs at the pillar joint to avoid the shrinkage, that is caused by the presence of the mobile slides in the mould.

Coupling with adjacent components

As previously discussed, the correct management of the couplings is critical to achieve high quality in terms of visual perception by the customer. For example

Fig. 6.111. Lower part of the central pillar (B pillar) cover (rear view).

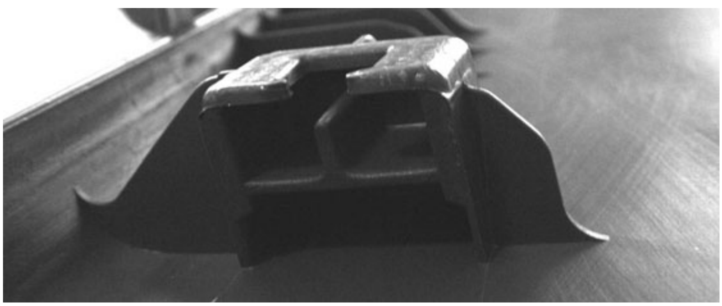


Fig. 6.112. Detail of the fastening snap shown in Fig. 6.112.

the upper coupling between the three pillars (front, central and rear) and the headliner is made by overlapping of the upper part of the pillars and the headliner, so that the eye has no reference to enable the identification of any flushing errors and irregular gaps (Fig. 6.114).

The vertical walls of the body, below the third window side or below the rear fixed glass in the three-door cars, are usually covered by elements called interior valence panels, the configuration of which is equivalent to the door panels reviewed shortly.

The common function and the aesthetic matching with the other covered body side parts, require that they are made by the same technologies and materials used for the pillars and the door panels.

When these covering parts are not visible by the occupants of the passenger compartment, but only from the hatchback door when it is open, they can be treated as the luggage compartment covering parts.

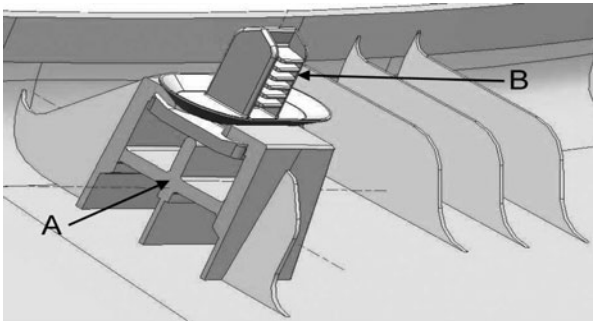


Fig. 6.113. Detail of the coupler system: A: snap support called dog house, B: snap called Christmas-tree

In all coupling types, the function to avoid squeaks and rattles should not be forgotten and then the rules of the coupling with compatible materials must be applied.

6.4.2 Door Panels

The door panels, along with those of the dashboards and the seats, are among the most important elements for the vehicle trim; correspondingly their aesthetic function is of primary importance (Fig. 6.115).

Other functions of the door panels are: Safety and containment of objects, often in addition to hosting some controls such as the adjustment of glass windows and external side mirrors.

In particular, as for the safety function, these components play a primary role in side impact protection. For this reason, foamed or honeycomb energy absorbers are often added to the armrests which must not be intrusive with respect to the abdomen and thorax (Fig. 6.116) and in some cases contain the side air-bags.

As already seen, there are also some examples in which the door panels contain the air duct terminal part and the demister for the side door windows.

Fig. 6.115 illustrates one door panel archetype, characterized by a set of aesthetic and functional elements: An upper part, which may contain some controls, a central part, normally covered by fabric or the same material used for the seats, an armrest and a lower end with a drawer and, possibly the rear reflector and courtesy light, all supported appropriately.

Types, technologies and materials

There are two main door panel types:

- Flat door panels;
- pre-formed, three-dimensional door panels.

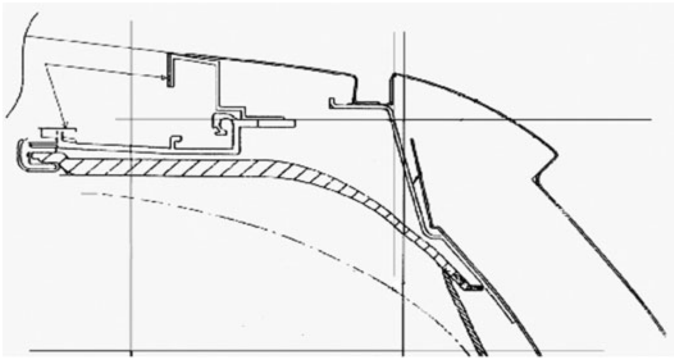


Fig. 6.114. Example of coupling between the upper part of the pillar cover and the headliner.

Flat door panels

These are made with a covered flat plate on which the upper fascia, the armrest, and the glove compartment are incorporated. This solution is still used today in some economic segments of cars and commercial vehicles (e.g. delivery vans), as shown in Fig. 6.117.

The panel comprises a support and a covering. The support is made of a flat slab, made with a pressed blend of wood fibres impregnated with thermosetting resins (of Masonite®). The covering is normally composed of an embossed laminated part in PVC, the padding effect being obtained by slabs of few millimeters' thickness of wadding electric welding. The laminated part and the padding are applied to the pre-blank Masonite® support, through high frequency electric welding. The covering material can also be fabric prepared for electric welding using a PVC film on the rear part (Fig. 6.118).

Assembly on the door is performed using visible fasteners and, whenever possible, by using the same fasteners that are used to assemble the other elements such as armrest, drawer, etc.

Pre-formed door panels

This solution enables the integration in the door panel of the upper fascia, the armrest partially or completely and the glove compartment.

To examine the various types of pre-formed door panels, it is convenient to distinguish between:

- Uncovered door panels;
- covered door panels.

Fig. 6.115. Typical example of a door panel.

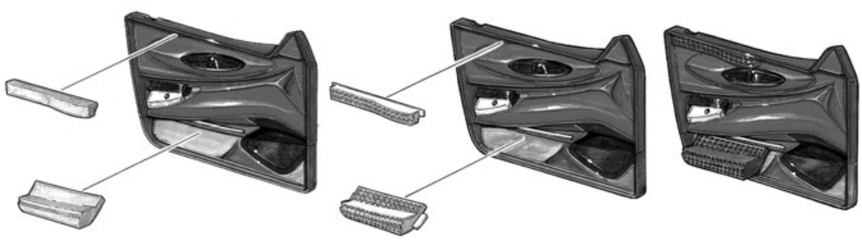


Fig. 6.116. Various types of energy absorbers located between the door panel and the door.

Uncovered door panels. Uncovered door panels are obtained using injection moulding technology, exactly as already seen for the stiff embossed dashboards. These panels have the same characteristics in terms of design freedom (stylistic versatility), weight, cost and recycleability and demonstrate the same aesthetic and tactile critical characteristics.

Generally the used material is of the polyolefin family (Polypropylene), with mineral fillers in the anti-scratching formulation and, when required for side impact needs, with elastomeric fillers.

In Fig. 6.119 (section 02-02), it is possible to see how the panel can be aesthetically enhanced using a central part covered with fabric. Such part is obtained using the same technology that will be examined while discussing the covered door panels. Also in this figure, it is possible to see how the external part of the door handle is integrated with the door panel itself. The outside part of the handle is moulded separately and then assembled to the panel by welding (point C of Fig. 6.119). This welding must be managed as shown in Fig. 6.120,

Fig. 6.117. A typical example of a flat door panel with a separate drawer.

to ensure an optimal aesthetic result and avoid, whilst gripping the handle, the perception of any edge that may arise from the junction of the two parts.

The door panel is clamped to the door frame by fastening systems which should not be visible, in a similar way as for pillar covers. These fasteners are completed by the mechanical clamping used to assemble the panel to the door like, for example, the fixing of the door handle.

The co-injection has been developed to improve the non-optimal tactile performance of this stiff door panel. This technology consists in injecting in the same mould two different compatible thermoplastic materials by using an injection press that has two separated thermal plasticization groups, as shown in Fig. 6.121.

Injected initially is the A material which in this case must have aesthetic and, as far as possible, tactile characteristics (it must have a perceptible soft feeling even though the thickness is limited to about 1.0÷1.5 mm). The B material, with only structural features, is injected immediately afterwards and, as shown in the previous figure, must be able to push the A material against the mould walls, by creating an outer layer which is sufficient to completely cover the A material with the appropriate thickness.

Besides the advantage of providing a minimum soft feeling, this solution is also capable of presenting an embossed surface with no scratching problems, because the covering material has no mineral fillers. Regarding the disadvantages of this solution, in addition to the weight and cost increase, due to the double moulding presence, it is important to consider the higher investments, but above all, a more complex process with a possible increase of scrap as a consequence.

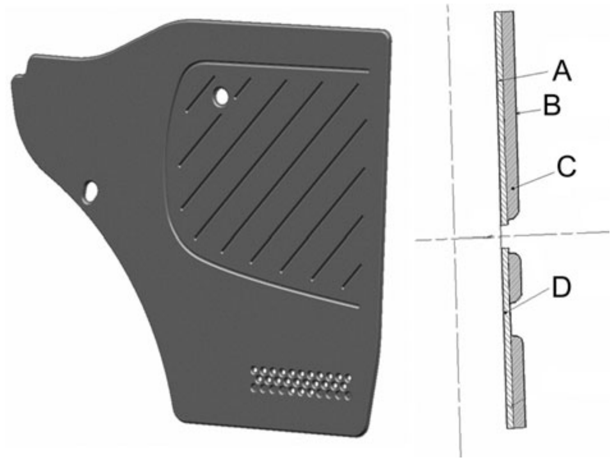


Fig. 6.118. Outline of a flat door panel: A and B laminated PVC, C wadding slab, D support.

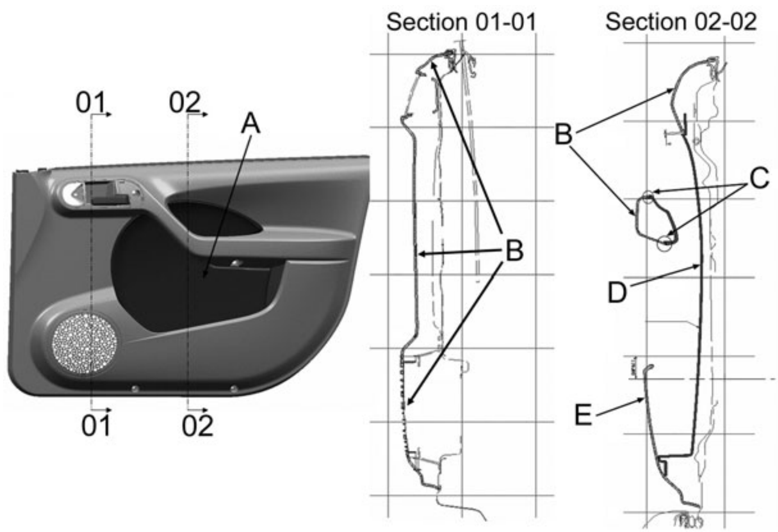


Fig. 6.119. Section of a monolithic panel of Polypropylene. Details: A and D central part, B and E Polypropylene door panel, C welding.

Covered door panels. The covered door panels can be divided into two categories, according to the manner in which the covering is applied:

- Panels with the covering applied during the moulding of the support;
- panels with the covering applied after the moulding of the support.

As regards the door panels with the covering applied during the moulding of the support, different technologies exist for their production. Here it is appropriate to just illustrate the two most used technologies: Compression moulding and injection-reaction (R-RIM, Reinforced-Reaction Injection Moulding); even though thermoplastic over-moulding technology at low pressure is increasingly beginning to spread (see the section on pillars).

Compression moulding consists in simultaneously moulding a pre-heated extruded sheet in Polypropylene based material with vegetable fillers and the covering (fabric or thermoplastic laminated).

During the compression phase, the covering anchors to the support which is heated and before the mould opens, a perimeter shearing system removes the surplus parts of the sheet and the covering, before then finishing the panel perimeter (Fig. 6.122).

In this way it is possible to obtain a covered panel in a single shot, certainly at a competitive cost; however it is necessary to take some important design aspects into account:

- The panel design must be such that its geometry (radius, drawing depth), does not cause tearing of the sheet during moulding;
- the covering material, in addition to its chemical compatibility with sheet support material, must have an elasticity to withstand the stretching that is generated during the compression;
- stiffening ribs, which are typical of the injection moulding, cannot be obtained;

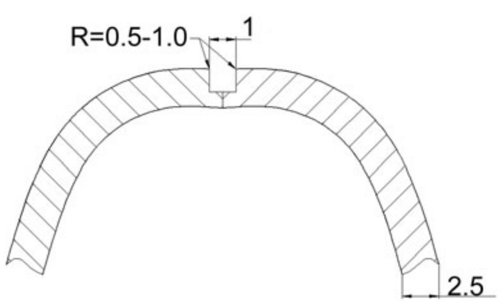


Fig. 6.120. Design for a concealed weld joint.

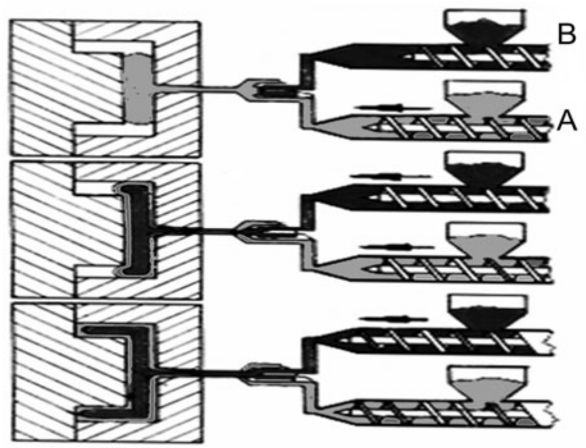


Fig. 6.121. Outline of the co-injection process.

- to obtain invisible fasteners, it is necessary to add, using ultrasonic welding, small injection moulded part (dog houses), because in the compression moulding it is not possible to use the mobile slides as in stiff pillars (Fig. 6.113).
- a possible weak point in the side crash exists, which may be limited by replacing the normal mineral or vegetal fillers with a mat made of long vegetal fibres impregnated with thermoplastic resins (polypropylene).

An interesting evolution of this technology consists in the combination of the compression and injection moulding processes.

During the compression of the sheet for the support and the covering, when the mould is still closed, some polypropylene is injected onto the rear part of the support by a thermoplastic injection group, thus enabling possible stiffening ribs and the small bridges to be obtained that otherwise, as already seen, should be added. This operation is made possible by appropriately modifying part of the male mould for the compression.

As for injection-reaction (R-RIM), this is nothing more than a foaming. As already mentioned with respect to the foamed dashboard, polyurethane loaded with glass fibres is injected into a foaming mould at low pressure, after having placed the thermo-formed covering into the female part of the mould and closed the mould.

Despite losing all smoothness, the foam thus obtained becomes self-supporting and therefore does not require any type of support. At the same time it is possible to integrate the housing for the fastener devices to assemble the panel on the door (Fig. 6.123).

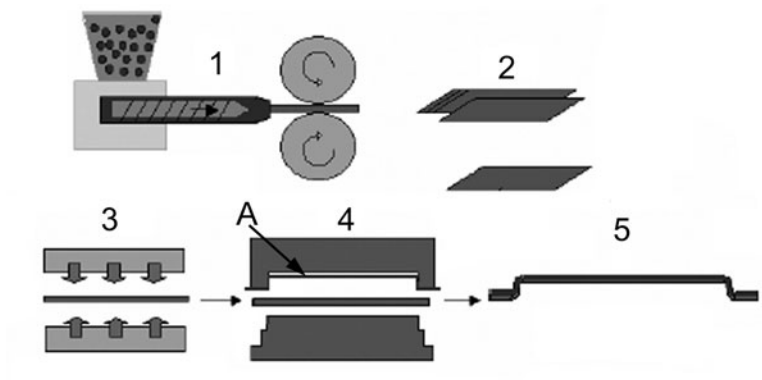


Fig. 6.122. Outline of the covered door panels production. Process steps: 1 Extrusion of Polypropylene with vegetable fibres, 2 extruded sheet, 3 heating of the sheet, 4 compression moulding, 5 moulded door panel.

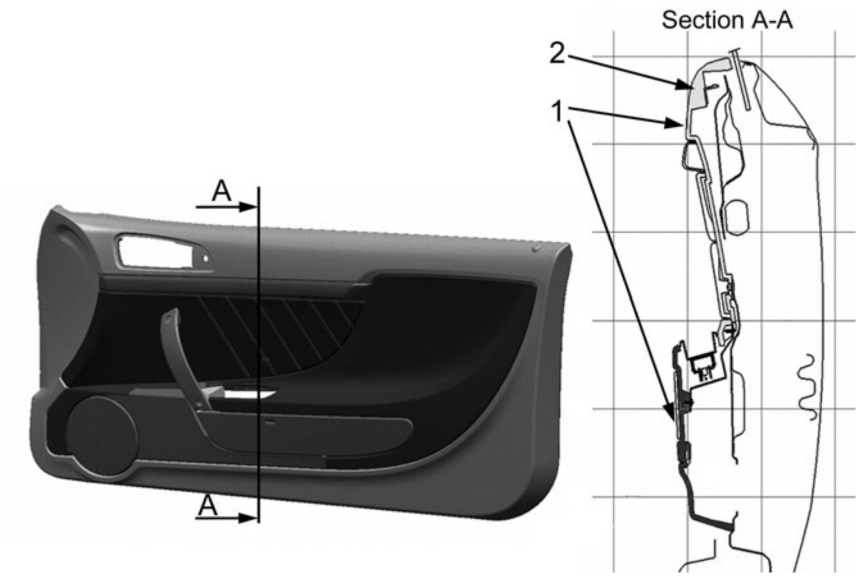


Fig. 6.123. Door panel made by R-RIM process. Details: 1 Covering, 2 R-RIM support.

For panels with simple geometries (bending radii not too small and indents not too deep), the covering material may be laminated, partially expanded and, with a thickness of about two millimeters, designed to give the panel a soft feeling. In this case the covering material, which can not be thermo-formed, as in the previous case, is placed into the female mould by means of vacuum suction through small holes in the mould, thus creating a so-called female thermo-forming.

Further important features of this solution include the possibility to manage different thicknesses due a need for space and the possibility of obtaining reinforced ribs, as shown in Fig. 6.124.

Regarding the disadvantages of this solution, it is important to remember the non-recycleability (polyurethanes, the family of plastics to which R-RIM belongs, are thermosetting) as well as the high cost of the panels, while investment costs are low: Correspondingly the R-RIM solution is predominantly used for applications on high segments or with low production volumes.

At this stage it is appropriate to also analyze the panels with the covering applied after the support moulding. Also in this case just those technological solutions which are most used for the support are considered, namely: Post-formed Masonite®, mats (Lignotoc®) and emulsions with vegetable fibres impregnated with thermosetting resins (Fibrit®).

As with the post-formed Masonite®, the post-forming is made by compression after softening by steam action. The possibility of post-forming is very limited anyway and therefore this solution is only used for panels with indents that are not deep.

The covering is applied as for flat panels, while the fasteners, which should not be visible in these applications, are obtained by using mostly bonded reported small bridges onto which the fastener systems already discussed above are fitted.

The Lignotoc® support is made through the compression moulding of a fibrous cellulosic mat with a binder based on thermosetting resins. The geometry constraints mentioned above do not apply and in the moulding the achievement of considerable indents is guaranteed, as is normally required for the armrests.

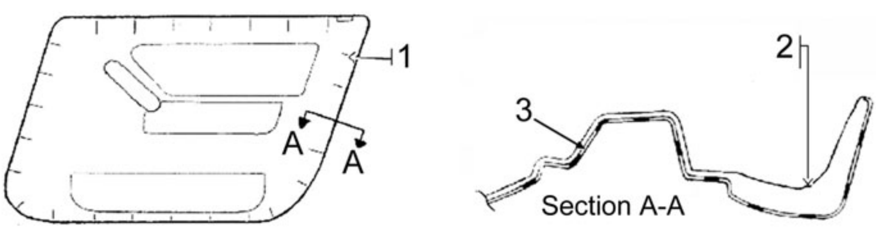


Fig. 6.124. Reinforced ribs obtained by the R-RIM process: 1 and 2 Rib, 3 expended covering material.

The use of thermosetting rather than thermoplastic resins, despite reducing recycling possibilities, gives the door panel a greater dimensional stability and higher structural consistency.

The covering process is the same as already seen for the covered dashboards and, since the geometry of the door panel is less complex than that of the dashboards, the shape constraints are not so important in this case, while for the fasteners the usual small reported dog house are used.

Finally, the Fibrit® supports are obtained using an emulsion of cellulose fibres with thermosetting resins and water, filtered through a filter with the shape of the inside part (as similar as possible to the support desired).

The impregnated resin fibres are deposited on the filter surface, thus generating a three-dimensional mat which will be compacted by subsequent squeezing before the final compression.

The typical characteristic of a support thus obtained is a good freedom of forms, the low specific weight (0.7 kg/dm^3) and an intrinsic micro-porosity which facilitates vacuum thermo-forming due to the bonding of the covering material on the support.

It is indispensable, during the design phase, to put reinforcement metal inserts, where for instance the use of screws is required for assembling requirements.

As for the covering and fasteners, the above considerations are still valid.

In summary, the different technologies are:

- Flat door panels; applications limited to the economic versions of low segment vehicles and commercial vehicles.
- Pre-formed uncovered door panels; constantly increasing use in low and middle segment vehicles.
- Pre-formed covered door panels; constantly increasing use in medium-high and high segment vehicles.

A pre-formed hybrid solution has become increasingly widespread, with the upper part covered and the lower part uncovered, but simply injection moulded and embossed; instead for the higher versions, the same solution has two types of coverings, as presented in Fig. **??**.

6.4.3 Parcel-Trays

The parcel-trays are components that provide a horizontal surface, used to cover the luggage compartment while creating a useful support surface for light objects.

They can be fixed on steel plates, or movable: Self-supporting (supported by side, can be moved or lifted), or skirt-shaped (rollable). Fixed parcel-trays are present on three volume cars while the movable solutions are normally present on hatchback vehicles.

Normally, the parcel-tray is not required to exhibit acoustic insulation characteristics, which could be achieved by adding an acoustic mat to the lower part.

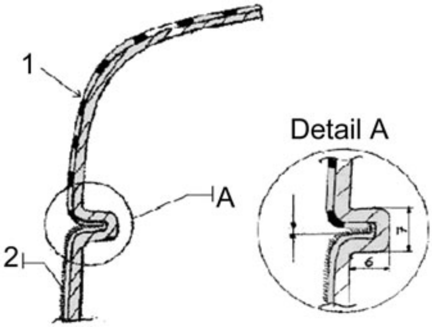


Fig. 6.125. Panel door section with two different types of covering: 1 Laminated, 2 fabric.

Movable self-supporting parcel-trays

These are parcel-trays supported by the side-shelves which are raised by means of ties connected to the hatchback door, thus allowing easier access to the luggage compartment (Fig. 6.126). Such parcel-trays can be divided into:

- Compression moulded parcel-trays;
- bi-sheet compression moulded parcel-trays;
- injection-reaction (R-RIM) parcel-trays.

Compression moulded parcel-trays

This technology, which is similar to that already analyzed for covered door panels, enables the covering application to be obtained during the compression moulding of the support, which consists of an extruded polypropylene sheet with mineral or vegetable fillers.

The covering, for low or middle-low segments, consists of a smooth needle-felt or, to a lesser extent, of a non-woven or stitch fabric.

The fundamental difference compared to door panels is the fact that, in the case of parcel-trays, which must support loads, one, or in some cases two, reinforcing metal bars are inserted during compression moulding, as shown in Fig. 6.127.

The load conditions required by different automobile manufactures may vary. For example, in a typical aging hot test under load, a cylindrical mass with a diameter of 160 mm and a weight of 4 kg is applied at a temperature of 80 °C for about 100 hours. The maximum defection admitted must be less or equal to 5 mm.

As an alternative to Polypropylene sheets with mineral and/or vegetal fillers (talc or sawdust), in order to obtain a material with higher mechanical properties,

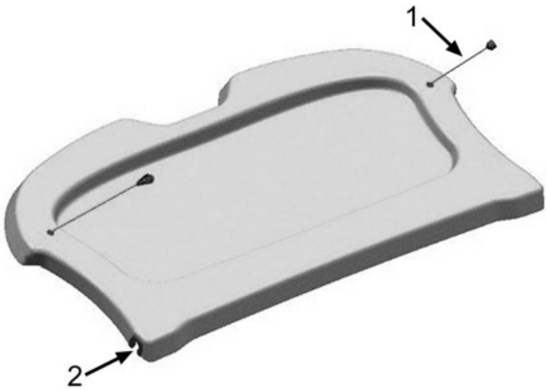


Fig. 6.126. Archetype of self-supporting parcel-tray, that can be moved and lifted. In particular: 1 lifting tie, 2 housing for the pin.

polypropylene sheets with glass fibres 15÷20 mm long are being used increasingly, in percentages that cannot exceed 20%. This solution, in addition to improving recycling possibilities, also enables significant weight saving by eliminating the metal bars.

Bi-sheet compression moulded parcel-trays

This is an evolution of the compression moulded one described previously, enabling a box-type structure with a consequent increase in rigidity, although not enough to permit the removal of the metallic reinforcement.

The manufacturing process requires the use of two extruded polypropylene sheets with vegetable and mineral fillers described above. The two sheets are heated at different times; the first sheet is positioned on the male part of the

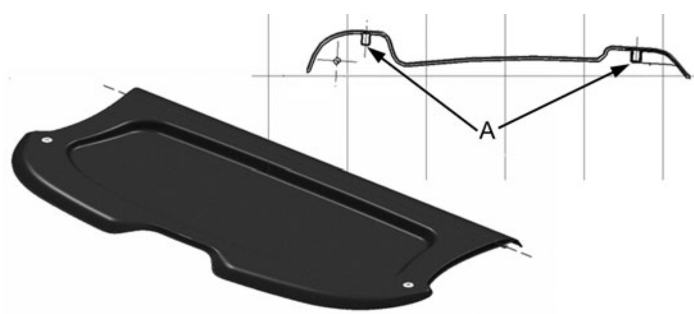


Fig. 6.127. Parcel-tray with metal reinforcing bars A.

mould, then the parts that must be co-injected (for example the reinforcing bar) are added, before the second sheet and the covering are positioned.

As soon as the mould is closed, air is injected under pressure between the two sheets which, via a process similar to the traditional blow moulding already examined in the section dedicated to dashboards, enables an empty covered piece to be obtained.

Injection-reaction (R-RIM) parcel-trays

This technique is absolutely identical to that of the door panels, which enables the elimination of the reinforcement bar due to the use of glass fibres, similar to those examined previously.

To conclude the matter of the self-supporting parcel-trays, it should be recalled that the appropriate selection of the geometry, as the example shown in Fig. 6.128, can improve the stiffness of this part.

Besides, hinged rotation can be made possible with the rolling pin placed on the parcel-tray or on the side-shelf (Fig. 6.129), which is usually an injection-moulded part like the pillar covers.

Elimination of the noise generated by the interaction between the parcel-tray and the hatchback door can be achieved by inserting small rubber blocks, as in Fig. 6.130.

For particular large vehicles, such as minibuses, specific solutions such as the one shown in Fig. 6.131 can be used to cover the luggage compartment.

This solution belongs to the family of compression moulded parcel-trays that in this case, because of their size, must be foldable so as to be more easily removed. This is ensured by creating special hinges (plastic and fabric film). In practice, as shown in the example of Fig. 6.131, this is like having three parcel-trays that can be folded together.

Rollable skirt-shaped parcel-trays

By their nature, the parcel-trays of this type are not self-supporting and only perform the covering function. They are mainly used in station wagons and minivans.

An anti-intrusion luggage net can be integrated into this parcel-tray to vertically separate the passenger's compartment from the luggage compartment.

This type of parcel-tray is represented in Fig. 6.132. The covering of the luggage compartment is made by two laminated sheets, in welded PVC, between which a cotton batting is interposed.

Rollable skirt-shaped parcel-trays also have different configurations and compositions depending on whether they are applied in combination with fixed or sliding rear seats, or with rear seats with different adjustment possibilities, as in Fig. 6.133.

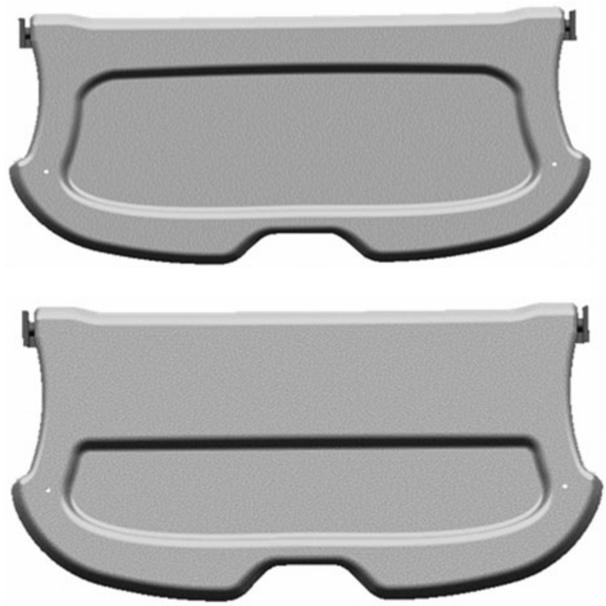


Fig. 6.128. Geometries that optimize the stiffness of the parcel-tray.

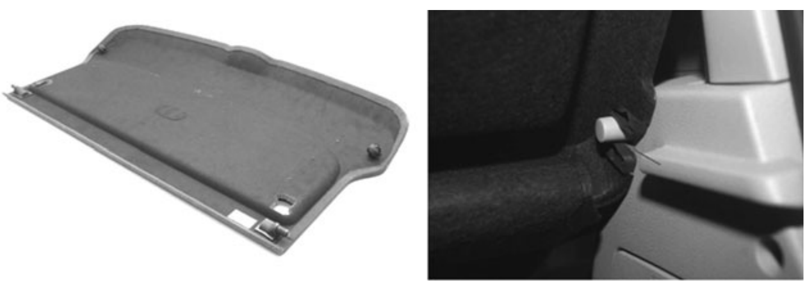


Fig. 6.129. Different types of hinged parcel-trays: Left: pin on the parcel-shelf; right: pin on the side.

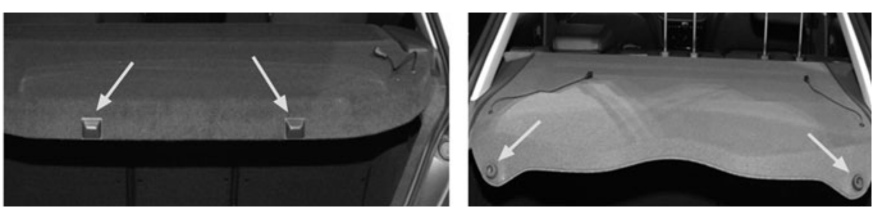


Fig. 6.130. Example of rubber blocks on the parcel-tray.

Fig. 6.131. Example of compression moulded and foldable parcel shelf.

Fixed parcel-trays

Fixed parcel-trays are essentially finishing elements, even though, with the passing of the time, other components have increasingly been assembled on to them, such as speakers and rear sunshades; see Fig. 6.134.

Generally fixed parcel-trays are made by compression moulding, which has already been examined while describing the movable ones. The fundamental difference consists in the fact that those of this type are not self-supporting and thus do not need to have structural characteristics; for example, metallic reinforcements are not necessary. In Figs. 6.135 and 6.136 it is possible to see how these parcel-trays are simply fixed mechanically to the sheet of the window shelf; in particular, Fig. 6.136 represents the solution adopted on a high segment car, in which a sound absorbing mat is present.

In conclusion, it must be remembered that there are still many parcel-trays made with a support in Fibrit® and subsequently covered (the technology has already been described).

Again in this case, as with other components which are present in the vehicle, it must be considered that the choice of one technology instead of another also depends on existing manufacturing facilities.

6.4.4 Headliners

Until the Seventies, the headliner was made of fabrics or thin imitation leather (usually PVC), sewed and linked to the inner roof vehicle structures through metallic wire rods, sometimes by interposing cotton batting or spongy materials to give a soft feeling.

Fig. 6.132. Example of skirt-shaped and rollable parcel-tray.

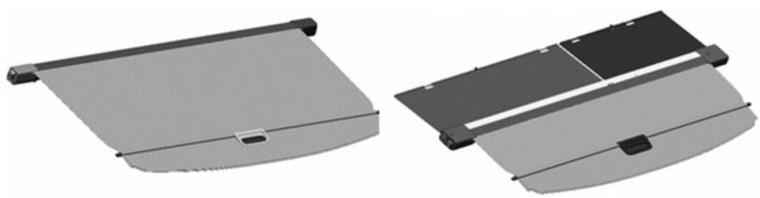


Fig. 6.133. Example of skirt shaped and rollable parcel-trays: Left: with a fixed rear seat; right: with a sliding and split rear seat.

The high cost resulting of the manual assembly, the absence of protection in case of head impact against the roof ribs in rollover case, the absence of any kind of isolation and the limited possibility of alternatives as for the covering materials, gave way to the so-called preformed headliners, now widely used (Fig. 6.137).

These components, designed to be self-supporting, are essentially made by using a support layer (stiff, foamed, stratified or other), covered with a fabric or laminated PVC, which are glued or over-moulded on the support. A layer of a few millimeters of soft material is often placed between the covering and the support.

The attachment of the preformed headliner to the inner roof metallic structures is made by using mechanical fasteners (screws), with which also other components are fixed to the body, such as handles, ceiling lamps and sunshades. Additional screws are also used, hidden by caps, or snap hooks with Velcro® in the central part of the roof; sometimes the same result is obtained by gluing the inner surface of the metal roof to the headliner support, generally using water-based adhesives.

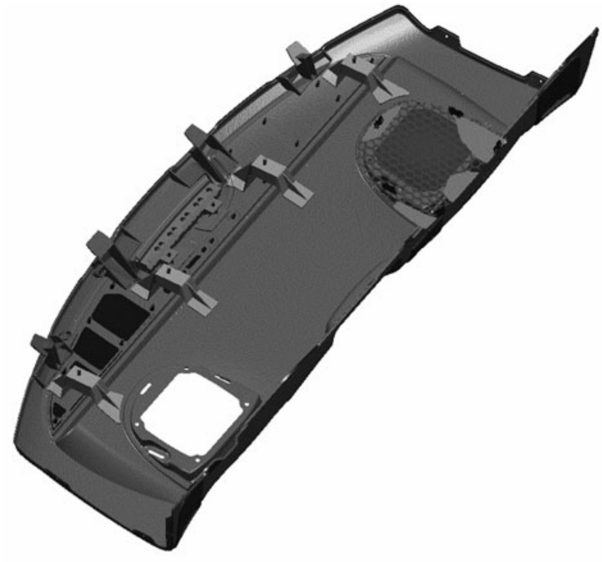


Fig. 6.134. Fixed parcel-tray integrating speakers mounts.

Besides the aesthetic function, and easier and economic assembly, the preformed headliner was also assigned a safety function which, as previously seen, consists in acting as a head air-bag cover for the side impact and, as will be seen later, a comfort function in terms of noise reduction.

The preformed headliner must be self-supporting even in the most severe thermal and moistness conditions; this requires an appropriate study of the structure that, in the most complex cases, as for example for the opening roofs, may require the adoption of reinforcing metal inserts. Moreover the headliner must provide a certain degree of softness because it may come into contact with the heads of the occupants. Its thickness and conformation must also provide protection in the event of a rollover or, in any case, of a possible head impact.

The numerous tests performed in the past have shown that the isolation and the sound absorption of the headliners produced until now are far less important than other components which are present in the passenger compartment, so that certain solutions, such as the bonding to the roof or the use of cardboard, were also judged to be acceptable despite being unsatisfactory from the acoustic point of view.

Only recently, as will be seen, a new solution enabled a significant contribution to the improvement of acoustic comfort to be achieved.

Many technologies have been used in the past to produce the preformed headliners, for example: Vegetable fibres impregnated with thermosetting resins (porous), various solutions based on reinforced polyurethane, cardboard,

Fig. 6.135. Fixed parcel-tray (seen from above).

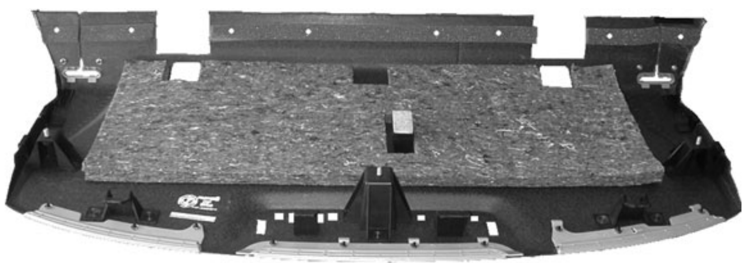


Fig. 6.136. Fixed parcel-tray (seen from below).

polystyrene foam and extruded polypropylene-based sheets with sawdust filler moulded by compression (Woodstock®).

Today, however, the most important and widely used technologies are the following:

- Porous;
- polyurethane reinforced with glass fibres (PU/GF);
- cardboard;
- reinforced non-woven fabric with a thermoplastic base.

Porous

This type of preformed headliners is perhaps the one that was most used, although today it has been superseded by a PU/GF solution.

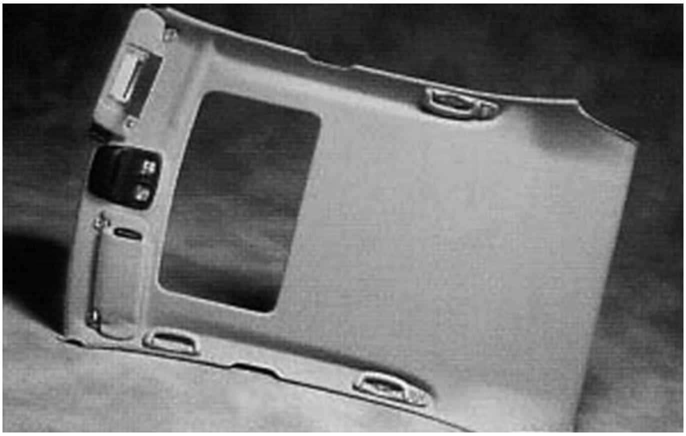


Fig. 6.137. Preformed headliner.

The bearing part (support) is a mat made of cotton impregnated with thermosetting resins (phenolic base) moulded by hot compression, the surface density of which can vary significantly, depending on the self-supporting performances to be achieved. This value can vary from about 1,400 kg/m^2 for cars to about 2,500 kg/m^2 for the truck cabins, by acting both on the mat composition and on the moulding.

The covering material can be applied during the support moulding if it is non-woven fabric, or by trimming after the support moulding for the other covering materials used such as non-woven fabric plus URL (layer of polyurethane material with open cells with a thickness of just a few millimeters).

The characteristics of this technology include excellent formability (it is possible to mould pieces with large drawing), good self-supporting, and low cost. Moreover it is the only solution of not recent application which, due to its porosity, can contribute to noise reduction given the possibility of changing its density. Nevertheless its weight is relatively high and it can cause environmental problems arising from the use of phenolic resins that emit formaldehyde.

Today the porous headliner solution is mainly used, as already indicated, for large applications (trucks), due above all to its good self-supporting capacity, as shown in Fig. 6.138.

Polyurethane reinforced with glass fibres (PU/GF)

This solution, which is the most widely used today, is based on the use of more layers of different materials, moulded by hot compression, which together form the preformed headliner, as shown in Fig. 6.139.

The covering may consist of different materials including the following:

- Non-woven fabric, with surface density generally included between 150 and 200 g/m^2;

Fig. 6.138. Porous preformed headliner.

- non-woven fabric plus URL, with surface density usually around 200 g/m^2;
- jersey plus URL; the jersey is normally elastic only in the longitudinal direction, or also in the transversal direction but is more expensive in this case.

The quantity of glass fibres, which provides the headliner with the required stiffness, is determined according to the specifications. For example, for a headliner with an opening roof, about 130 g/m^2 of fibres are required, while for a normal headliner the average amount falls to approx. 100 g/m^2.

The polyurethane layer which, together with the glass fibres, determines the structural characteristics of the headliner normally has a final thickness between 6 and 12 mm.

The most important characteristic of this solution is the smaller weight compared to the porous one, which on average is about 650 g/m^2, as well improved ecological performances since phenolic resins are not used. The formability is lower compared to the porous one, while the cost is higher. As for noise absorption characteristics, the PU/GF solution is significantly less performing than the porous one.

Essentially two production processes are used to make the PU/GF preformed headliners, namely:

- The wet process;
- the dry process.

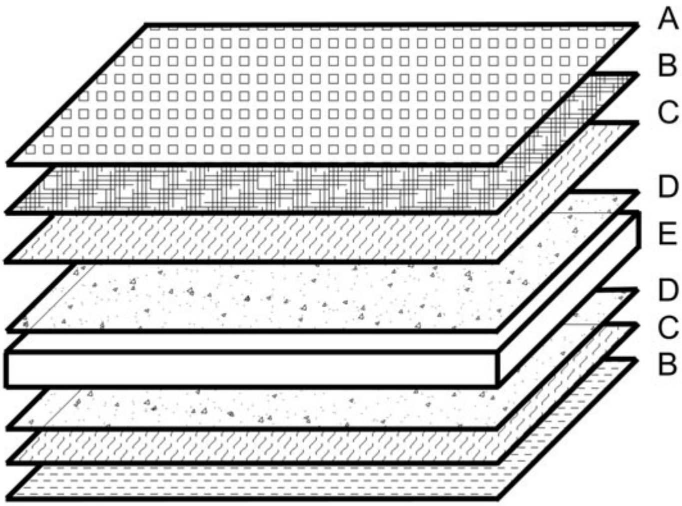


Fig. 6.139. Preformed headliner moulded by hot compression (PU/GF), made of various layers: A aesthetic surface (covering), B adhesive, C glass fibre, D blinder, E polyurethane foam.

The wet process

This is an ongoing process performed by a line that can match the various material layers seen in Fig. 6.139.

The polyurethane is supplied in rolls and dipped into a tank containing the binder and the chemical reagent, which impregnates the polyurethane layer on which long glass fibres are made to fall by gravity in the desired quantity per square meter. A film of adhesive, sealant and covering material runs continuously along the surface.

On the other side, the glass fibres are placed in the same way on the film of adhesive/sealant that moves under the polyurethane layer.

Once all the different layers are completed, it is all deposited in the open mould on a vertical press for the compression moulding. Subsequently the perimeter is finished by shearing using a specific press.

The dry process

Again referring to Fig. 6.139, the composition of the various layers is made by subsequent overlap of each layer, including the two that in the previous process are obtained by immersion of the polyurethane layer in the tank containing the binder and the chemical reagent.

The compression moulding and finishing operations are the same as described for the wet process.

Cardboard

This technology is used primarily for economic reasons; as seen in the previous dry process, essentially the polyurethane layer is replaced by a cardboard sheet (Fig. 6.140).

Compared with the previous solutions, it is cheaper both in terms of the costs of the components and the investment, but it accentuates the limitations of formability and acoustic characteristics.

Reinforced non-woven fabric with a thermoplastic base

This final solution, which is also the most recent one to have entered the market, basically aims to provide a significant improvement in terms of acoustic performances of the preformed headliner, even if this implies a not negligible increase in costs.

The objective of improving the sound absorption coefficient can be achieved by combining the headliner support, which must have good porosity characteristics, to an air space between the same headliner and the roof of the vehicle. This air space has a fundamental importance and should not be less than 25 mm.

In fact, when the air space increases, the frequency at which the sound-absorption peak is exhibited decreases and the absorption levels increase significantly; moreover, when the thickness of the porous support increases, the sound-absorption peak, in the same air space, moves toward lower frequencies and the sound-absorption bell tends to narrow. This fact is illustrated in Fig. 6.141.

Again, the preformed headliner is obtained by compression moulding of all the different material layers at room temperature. The covering material is usually made of the same materials described for the PU/GF solution. The non-woven fabric is often used in combination with URL to give the desired feeling of softness.

The fundamental feature of this solution is the use of felt as headliner support. The felt is made up of a layer of non-woven fibres, made to joint to each other, by milling and pressure. The fibres that make up the felt are not joined, being processed into a yarn and fabric, but through adhesion, without the use of bonding agents.

The felts are obtained by making a strip of fibres pass through a bath of boiling water in the presence of substances like acids and alkali and by beating it so that the fibres form a thick and compact stratum. For their characteristics, and in particular porosity, felts are used in industry as filters or in sound absorbing surfaces.

In this specific case, the fibres used are thermoplastic polypropylene-based fibres, polyester and glass fibres in order to achieve the self-supporting characteristics required, with a surface density that can vary from 800 to 2,000 g/m^2 according to the geometry of the component.

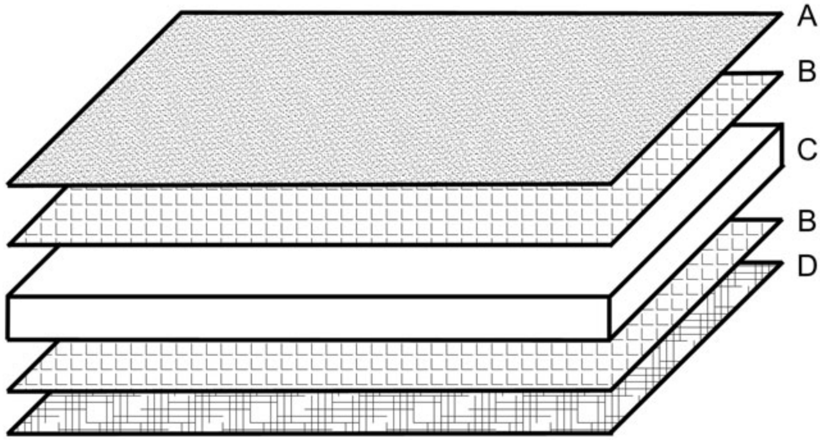


Fig. 6.140. Cardboard solution: A cardboard; B adhesive; C URL; D covering.

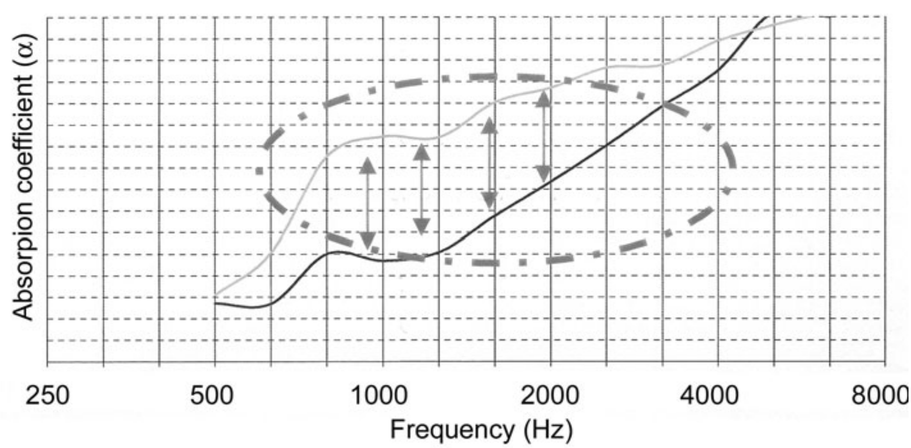


Fig. 6.141. Acoustic absorption test result for the headliner.

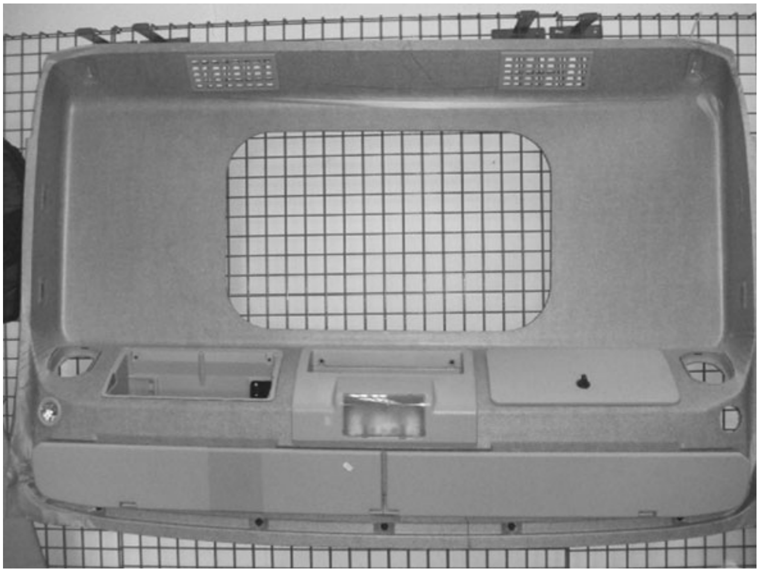


Fig. 6.142. Preformed headliner modulus.

Today, due to its high cost, this solution is used only for applications on vehicles that must achieve particularly high levels of acoustic comfort. Another positive feature is recycleability, although this is limited by the presence of glass fibres.

Finally it is important to bear in mind the larger vertical dimension of the preformed headliner because, in addition to its natural thickness, it needs an air space between the car roof and the inner part of the headline, in order to exhibit the required acoustic performance.

The preformed headliner module

Some examples exist of preformed headliner modules. The module is a set of different components, also with different functions, which are grouped for the assembly.

One of these is the headliner module assembled in the truck cab, shown in Fig. 6.142, on which the lighting system, electrical wiring, glove compartments, sunshades and air ducts for ventilation are all assembled.

6.5 Seats

The seats, together with the air conditioning system, represent the most important components from the perspective of comfort. In fact, by acting essentially as a filter which, as a function of frequency, can amplify or attenuate vibrations due to the road and the dynamics of other components, the occupant of a vehicle attributes principally to the seats responsibility for pleasure or discomfort and tiring whilst driving (Fig. 6.143).

Seats incorporate an elastic suspension system, usually non linear (due to the presence of foam with springs) with complex damping (due to the intrinsic properties of foams and friction). The capacity of this system to filter vibrations can be relatively low, particularly at certain frequencies; for this reason, in particular on heavy vehicles, seats have been conceived which use an additional suspension system that often can be adjusted depending on the weight of occupant. In this way, function of the seat is to isolate the occupants with respect to the vibrations that can cause discomfort.

In contrast, in particular for sport cars, situations exist in which drivers seek almost a direct link with the body of vehicle in order to improve feel, i.e. to be able to evaluate correctly, and without delay, each movement of the vehicle which can provide an important indication of vehicle handling and adhesion with the ground.

Fig. 6.143. The seats, together with the air conditioning system, represent the most important components from the perspective of comfort.

The design of a standard car seat often represents a compromise between of these two contrasting requirements. Its padding and spring system has to be able to provide a rigid link with the vehicle and at low frequencies (less than 3 Hz) but insolate the occupants increasingly at higher frequencies.

At the same time, the seat must ensure an appropriate postural function, i.e. the correct seated position for the occupants. In particular, as concerns the driver, a correct drive position has to be ensured (in terms of visibility, control operation, etc.); the importance of this aspect for active safety is clearly evident.

For the vehicle and seat designers, correct postural function translates into appropriate dimensioning of the seats which have to offer a wide range of adaptability to accommodate all possible occupants, covering as broadly as possible the needs of the population from 5%ile to 95%ile (and even up to 99%ile). Some requirements can be personalized by means of regulating devices and mechanisms (longitudinal movements in x direction, tilting of backrest, etc.).

Another fundamental function for seats is the safety. The contribution of seat to active safety has already been mentioned; most important is the behavior of seats for passive safety since side-bags are often fixed to seats, and nowadays both low attachments for safety belts are usually installed on the seat structure itself. Moreover, this structure has to ensure:

- Restraint of occupants, within the required limits, both for front and rear impact.
- Collapsibility at defined load levels.
- A significant contribution to avoid the submarining phenomenon.
- Limitation, as per specifications, of the intrusion of rear passenger or luggage with respect to the occupants of the front seats.
- Limitation, as per specifications, of the intrusion of luggage with respect to the passengers of rear seats.

In addition, the aesthetic function of the seats represent one of the most important aspects concerning the decoration of cockpit.

Automatism and additional functions are continuously being developed by designers, making the seat an increasingly complex system in terms of technology. Today it is of fundamental importance in the conception of a new car. In fact body design starts and is developed around the reference R point, the haunch joint of driver seated on seats.

All functional and legislative constraints utilize the R point as reference.

In the future, the driver seat may be considered to be control station of vehicle, with all controls integrated; furthermore there will be the possibility to move the seats to different positions within the vehicle.

6.5.1 Front Seats

Depending on the type of vehicle and its intended customer, in many cases the driver seat is evolving into a status seat for the owner, a specialized seat for high performance driving, and a multi functional seat with all possible ergonomic and electronic sophistications which allow to adapt it to different requirements.

The passenger seat tends to differ from the driver seat in terms of its functions; in general priorities are different from those of driver seat. For example, the passenger must be able to get in and out of the car easily, and in cases even when disabled (requiring, for example, the rotation and/or translation of the seat); the passenger does not have to use pedals for driving, and thus the position of his legs is different; the passenger can sleep (tilting backrest or tilting seat), work with a computer (equipped seat), and communicate or generally interact with other devices in a different way to the driver.

Bench-type front seats, which typically can accommodate up to three occupants, have now practically disappeared from market; today the front seat has a single structure, and is conceived as a module of components.

Usually the front seat is made by assembling the components listed below (with reference to Fig. 6.144), and made using the technologies indicated in brackets:

- Metallic structure/body (stamped and/or extruded and assembled);
- adjustment mechanisms (stamped and worked with machine tool);
- foams (foaming) and suspensions;
- cover (cut and seam of fabrics);
- trims, plastic covers (injection moulding);
- headrest;
- air-bag for side impact;
- armrest;
- integrated adjustment mechanism.

The assembly, which is usually organized using JIT (Just In Time) procedure for logistic reasons, is called trimming.

Structure

The design definition of the structure represents a fundamental moment of the seat development process, not only with regard to its functions, but also because, being a non visible component of the seat, the tendency is to use the structure or part of it for seats to be installed on different cars, even of different segments.

The structure can be made from different stamped parts, (Fig. 6.145), by beams with different cross-section depending on their function, (Fig. 6.146), or by an assembly of extruded and stamped parts, (Fig. 6.147), joined together by welding or riveting.

Today the laser welding process, thanks to a higher work speed, has replaced the old CO_2 welding systems. In some applications, to assembly components, self-drilling riveting are used, offering an important advantage to join parts made of different materials such as steel and aluminium.

In particular in applications where composite structures are used, for example seats of sports cars, assembly uses adhesive bonding or threaded elements.

For most applications, the principal material used is high strength steel for stamping (yielding limit between 500 and 800 MPa). Both cold rolled and

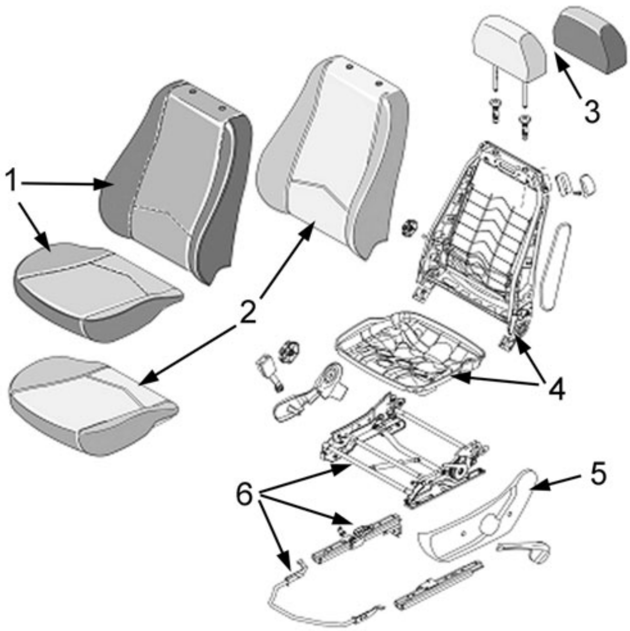


Fig. 6.144. Components which comprise a seat: covers (1), foams (2), headrest (3), structure and suspension (4), plastic trim (5), interface structure between floor and mechanisms, slides, handle, which is the activation control of slides (6).

hot rolled typologies are used; the thickness of the metal sheet is about two millimeters for cold rolled sheets and three millimeters or more for hot rolled sheets.

Low strength stamping steel (with yielding limit around 200 MPa), are used for components with no structural function, such as the supporting brackets of the power assist system.

Nowadays, due to growing request for high impact performance, the seat structure is usually conceived almost completely using high strength steels.

When weight reduction is particularly important, and consequently some additional cost is considered acceptable, different materials and manufacturing technologies, such as magnesium, usually in alloy with aluminium (AM60B), can be adopted for the internal structure. Such alloys are injected into high pressure die casting moulds within a controlled atmosphere.

The design of structures made using this technology, needs particular attention in order to obtain a product with the required mechanical characteristics, meeting the target on terms of lightweight with an acceptable increase in costs (Fig. 6.148).

For extreme applications, such as race car seats, carbon fibre composites are often used, enabling the lowest weight to be attained while ensuring the required

Fig. 6.145. Structure made by joining different stamped parts.

performance, but with high cost and production typically limited to a few pieces per day.

From point of view of safety belt installation, seats can be divided into:

- Traditional seats or LBTS (Low Belt To Seat), i.e. seats where only one or two of three attachment points of belt are located on the seat structure, usually in a low position, over the slides. As has already been illustrated in the section on safety belts, the attachment of the buckle assembly (L2), is nowadays standardized on seats while the opposite attachment (L1) has only recently been applied on seats and typically only on five door cars.
- Seats with on board safety belt or ABTS (All Belt To Seat), also called ISBS (Integrated Seat Belt System), i.e. seats where all three attachment points of the safety belt are mounted on the seat itself. These seat are developed and produced only for applications where there is no central pillar to enable attachment of the belt, such as for some spiders or the central seats of mini-vans, etc. In this case also the retractor and pillar loop are mounted on seat. Moreover this solution also needs a number of specific technical adjustments in order to ensure correct operation of the retractor; in fact different angles are possible due to its installation on the rear part of backrest.

The peak loads applied on the structure in the case of impact (when the seat must resist the inertial load created by the occupant wearing the safety

Fig. 6.146. Structure made with beams of different cross-section.

belt), required an over design of the ABTS type compared to an LBTS seat, and specific design for each component.

The use of ABTS seats, could find wider application also on cars which do not specifically need to adopt this type of seat because they are able to restrain better without further compromising comfort. However this application can be used only when design and manufacturing solutions do not need low weight and costs; see Figs. 6.149 and 6.150.

In general, seats with four attachment points for safety belts, developed for sport car applications, can be provided. Substantially they are seats with two lower attachment points and two way on the backrest for the upper line of safety belts. Usually they are fixed on the roll bar or to other part of vehicle structure.

Adjustment mechanisms

The main mechanisms are:

- Length adjuster;
- backrest recliner;
- height adjustment of seat;
- under knee support;
- easy entry system (only for two/three doors cars);
- power adjustment.

Adjustment mechanisms are the only devices of seat which allow to adapt seats to all possible occupants (population percentiles), optimizing their postural position and thus perceived comfort and safety.

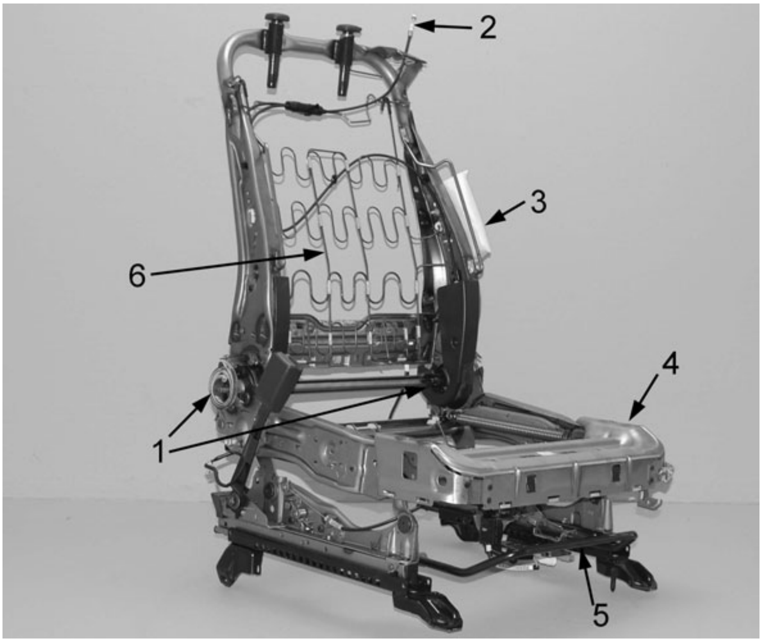


Fig. 6.147. Structure of front seat for three door cars: bilateral continuous backrest recliner adjustment (1); cable to control unhooking of seat (admittance to rear seats) (2); thoracic side-bag (3); cushion structure with suspension system (4); unhooking slides device (5); backrest structure with suspension system (6).

Slides

Slides represent a standard device which enables the adjustment of the longitudinal position of the seat, comprising a part fixed to the floor and a mobile part on the seat structure. The two parts are linked to each other by means of latch, requiring a handle, usually in an arch shape, which is located on the front lower part of the seat. The handle releases the latch, as can be seen in Figs. 6.151 and 6.152.

Slides mounted on the seat must ensure the following functions:

- Structural integrity; in fact they are subject entirely to the loading on the seat and also from the safety belts during impact; release of the slides is absolutely not permitted;
- absence of play and creaking, also after many thousands of fatigue cycles;
- relatively low operative loads.

Traditional design schemes feature rolling ball elements located between the two steel parts of the slides. These rolling elements aim to reduce sliding friction

Fig. 6.148. Structure of a seat made of die-cast magnesium.

and plays. Today all slides are usually made by four ballways or by two ballways coupled with two needle rollerways. The position of the balls and needles inside the profiles, and consequently the graph of reaction loads exchanged between profiles (usually patented), are a peculiarity of products made by different manufacturers in the market and are very important with respect to reaching the target in terms of loads, plays and creaking (Figs. 6.153 and 6.154).

The balls and needle rollers are maintained in position along the length of the slides by means of a stamped cage made with plastic techno–polymers materials in a similar way to conventional linear ball bearings.

The slides are made of high strength steel (exhibiting a yield load of between 500 and 800 MPa), with a thickness that can vary between 1.6 and 2.0 mm. Spacers for fastening the seat to the floor, and support brackets for the operating device, are welded to the slides.

In the case of seats with the safety belt mounted on board, or in particular applications which develop high impact loads, the slides are reinforced.

As for all mechanisms, also the production of slides requires specific know–how, which is absolutely necessary for stamping in order to maintain the required precision in terms of straightness and for assembling slides with balls and needle rollers. In this way the required precision between elements, needed to balance operational loads and play, can be ensured.

Backrest recliner

This mechanism, today installed on all seats, allows the backrest to be tilted and contributes, together with other mechanisms, to define the driver set-up and optimized comfort conditions.

Fig. 6.149. Structure of a seat with on board safety belts (ABTS).

The backrest recliner can be divided in two typologies:

- Continuous;
- discontinuous.

In the first, which are more widely used than the second type (in Europe, USA and Japan), the adjustment is made by means of epicyclic gears operated with a handle the rotation of which enables continuous adjustment which permits the driver to position the backrest at the desired angle.

Instead, in the discontinuous type of recliner, adjustment is made possible using a handle to free the lock of the backrest which is then positioned by pushing to overcome the reaction load of a spring. The manoeuvre is then completed by operating the handle in order to lock the backrest in the new position, i.e. at the closest notch to the desired position.

The handle can be located on either the left or right side of seats, but correct handling has to be ensured.

As for slides, also for the backrest recliner and for all other mechanisms of the seat, the absence of play and creaking, and appropriate operating loads, have to be ensured.

From a the structural point of view, the static and dynamic strength of these components is fundamental to obtain the required safety performance in the event of impact, in particular with respect to side impact and luggage restraint tests. The range of backrest recliners on the market are designed to ensure performance between 1,500 and 3,500 Nm which can reach 4,500÷5,000 Nm for

Fig. 6.150. Seat with safety belts on board.

ABTS seats, as shown in Fig. **??**. Fig. 6.156 shows connecting flanges between the cushion structure and the backrest structure.

The application of the recliner on the seat structure can be unilateral or bilateral, depending whether the adjustment device is on only one side or on both sides.

The seat with unilateral recliner is evidently less expensive, but has lower structural characteristics and the play between the backrest and cushion tends to be higher than the bilateral solution which today is more used.

Height adjustment of seats

For the driver seat, the height adjuster is a standard mechanism in practice, while for the passenger seat it is not present for some low and medium segment cars.

Height adjustment of seat allows the optimization of drive set-up and contributes to comfort and posture.

Essentially it is made of an articulated parallelogram which is located between the cushion structure and slide for longitudinal adjustment. The parallelogram comprises four connecting rods, one (or in some cases two) of which has a set of teeth which provide the interface with the real adjustment mechanism.

The geometry of the parallelogram usually requires rear connecting rods which are shorter than the front ones in order to obtain a forward rotation

Fig. 6.151. Slides with rolling elements (A).

Fig. 6.152. Slide.

movement of the seat. In this way, when the seat is in its highest position, the angle of seat is near to the horizontal, a position which is preferred by the lower percentile, the articulation angle of the knee being more open.

Fig. 6.157 shows the conformation of parallelogram with electric power; Fig. 6.158 shows the operation mechanisms with electric power.

From the point of view of the movement mechanism, two typologies of seat height adjuster exist:

- Continuous adjustment (pawl), this system most widely used today; operation is made using a gearing down mechanism with a clutch which disengages only during operation; when mechanism does not operate, the clutch locks the parallelogram by means of a pinion which engages the set of teeth on one of connecting rods (Fig. 6.159).

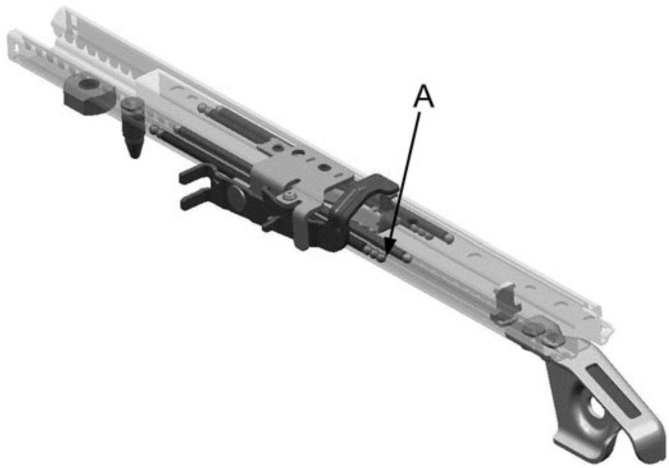


Fig. 6.153. Slides, showing the presence of four ballways

- Discontinuous adjustment; in this case, the mechanism opens and closes the engagement of a shaped cam on the teeth of the connecting rods, in this way, the movement of the parallelogram is enabled or locked.

In both cases, the movement of height adjuster is assisted using a spring system which acts against the weight of the occupant. The load of the spring usually designed to reach equilibrium for a 50%ile person in a half stroke position. The springs used usually are gas springs or a torsion rod which is easier and more economical.

Seats for high segment cars may have also a tilting function for the cushion, usually enabling the front part of cushion to be lifted or lowered independently of other possible movements.

The tilting function is obtained by incorporating an additional mechanism with a couple of additional connecting rods inside the front part of the cushion.

A possible variant to adjusting the seat height is height adjustment of the cushion only, the scope being to reduce costs and facilitate design. This solution has met with limited use in practice since the cost reduction has been less than originally expected and because of the ergonomic criticality which arises due to relative movement, along vertical axes, between the backrest and cushion. This causes a change in the position of the lumbar rest, (located on the backrest) with respect to the position of the occupant.

Under knee support

The under knee support is a further adjustment used primarily on high segment or sport cars. It allows an adjustment of the length of cushion by means of a rotation-translation movement of the front part of the cushion. The advantage

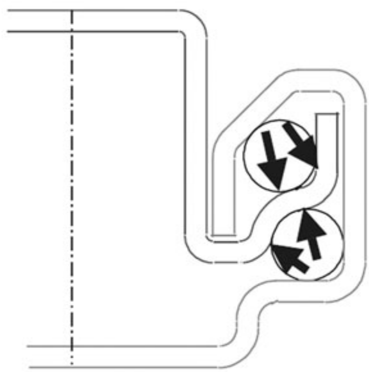


Fig. 6.154. Slides with four ballways.

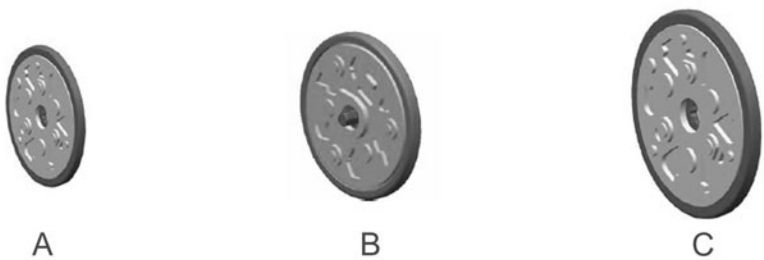


Fig. 6.155. Backrest recliners: (A) for static load on the backrest below 1,900 Nm; (B) for load below 3,500 Nm; (C) for load below 5,500 Nm.SR1

of this system is that it is possible to change the support of the rear part of calf and thigh, reducing tiredness in the leg.

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Easy entry system

This device allows an easier entry to rear seats for vehicle with only two access doors. The more complete and widely used solutions for this device allow the seat to be scrolled forward along the slide by means of handle located on the external upper or lower side of the backrest. This device enables simultaneously forward tilting of the backrest, with a pre-defined angle, while ensuring that the backrest does hit the instrument panel during forward scrolling of the seat.

This device can be applied either on both seats or just one; usually it has a memory mechanical system which enables the seat to move back automatically to its initial position following activation.

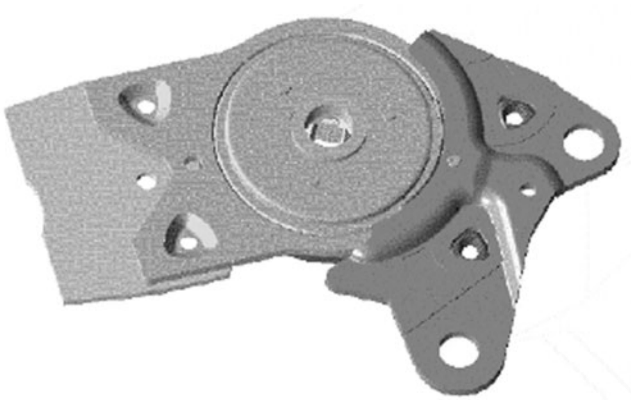

Fig. 6.156. Connecting flanges between cushion structure and backrest.

Power adjustment

For all adjustment and handling mechanisms, in particular for high segment cars, the use of electric power for adjustment has proved to be a commercial success. Often these systems are integrated with electronic memory, usually connected by means of CAN wire connection, and other functions (for example adjustment of mirrors, pedals, and steering column) which allow the preferred set-up of drivers to be memorized.

Slides with electric power differ from those with hand power since the locking system is substituted with a device comprising a worm screw which is operated by electric motor, by means of a flexible metal cable, or by a rack and pinion (with directly mounted motor).

For the adjustment of backrest, electric power can be used only with continuous adjustment. The operation gear motor is mounted on the adjuster through a fluted shaft.

In the same way, also height adjustment and tilting of the seat can be powered electrically, substituting the clutch mechanism with a gear motor with a worm screw system.

Classification of structures according to adjustments

In general, depending on the mechanisms mounted on the structures, systems can be classified as follows:

- Two way; only longitudinal adjustment (forward, back);
- four way; longitudinal adjustment and tilting of backrest (forward, back, higher or lower angle);
- six way; longitudinal adjustment, tilting of backrest and height of seat (in addition to above, height or low);

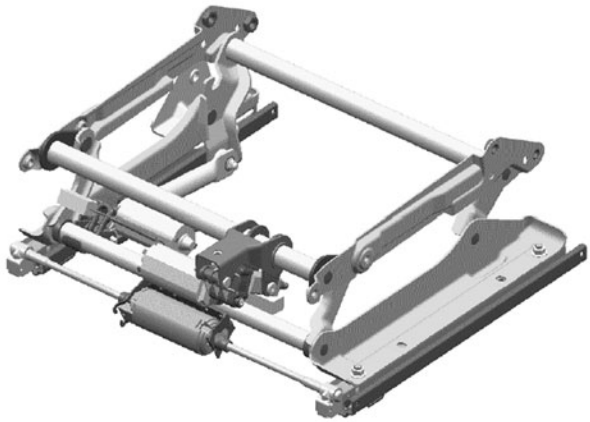

Fig. 6.157. Height adjustment of seat: configuration of parallelogram with electric power.

- eight way; longitudinal adjustment, tilting of backrest, height of seat and tilting;
- ten way; longitudinal adjustment, tilting of backrest, height of seat, tilting and under knee support adjustment.

Foam and suspension

Foams and suspensions aim on one hand to isolate the body of the occupant from vibrations transmitted to the cockpit through the vehicle suspensions and propulsion systems, and on the other to better distribute contact pressures.

Up to the 1950's, helical springs were used for vibration isolation. As is well known, if the mass of occupant is supported by a system comprising only springs with limited damping, the trend is for increasing vibration levels up to and around the mass-spring resonant frequency, before becoming attenuated at higher frequencies. For this reason, a simple mass-spring system represents a poor vibration isolator at lower frequencies, particularly near to the resonance, while it is excellent for higher frequencies.

If damping is introduced in parallel with springs, the amplification around the resonance is reduced but insolation at higher frequencies is also compromised. In general, however, the global behavior is improved for broadband vibration excitation.

Polyurethane foams (belonging to same family as illustrated previously for foamed dashboard), both with open or closed cells, exhibit a complex behavior which is similar to a simultaneously parallel and series system of springs and dampers, with a damping value approximate to 20÷40% of critical, which has been found to be very effective in practice.

Their application to seats can be made in different ways.

Fig. 6.158. Height adjustment of seat: operation mechanisms powered electrically or mechanically.

For the cushion, which has to bear almost the entire weight of the occupant, polyurethanic foam and spring system can be used as follows (Fig. 6.161):

- Foam on a rigid back support (usually made by steel or aluminium stamped sheets, as shown in Fig. 6.161A);
- foam on a support made with different types of (usually patented) springs (an example is shown in Fig. 6.161B);
- foam on a support made with thin steel rods which are shaped and connected themselves in order to exhibit nonlinear deformation under load (e.g. spider's web, as in Fig. 6.161C);
- foam on a support made with rubber and fabric strips (for example Sisiara® as shown in Fig. 6.161D);
- foam on a support made with a wire steel web welded and connected to the seat structure by means of small springs (for example Pullmaflex®, as in Fig. 6.162C).

For the backrest, the foam and suspension system are usually made to be similar to those of the cushion with exception of solutions made with a back support in metal sheet and rubber strips (Fig. 6.162).

Each solution described have advantages and disadvantages, as summarized in Fig. 6.163.

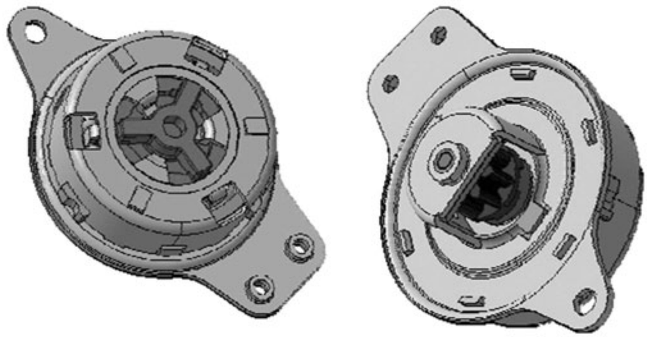

Fig. 6.159. Height adjustment mechanism with continuous adjustment and pawl.

Fig. 6.160. Adjustable under knee support.

Maximum damping is clearly obtained with open cell poliurethanic foam on a stiff base plate; however, in this case, relatively high foam thickness is needed (e.g. more than 80 mm) to obtain an acceptably soft cushion;

This means that the cushion is higher vertically, an aspect which is not compatible with cars that required low H points.

Moreover, the foam suffers a creep effect due to the continuous and repeated compression loads caused by the weight of the occupant. This causes, after a period of use, permanent vertical yielding, and effect which is greater when the thickness of foam is higher. After permanent yielding of foam on cover, an irregular wave is exhibited with a consequent sensation of cushion breakthrough.

Due to this, combined solutions with foam of limited thickness, are preferable. The thickness of foam must be sufficient to distribute pressures with average gradients. Under the foam, a support using one of the different spring systems described above is used, contributing to the static soft effect which is well perceived, particular when a potential customer tests a car statically.

To minimize the loss of damping resulting from reduced foam thickness, more effective spring types have been developed: The spider web steel rods, where steel rods can be shaped in different way to avoid the highly sensitive zones of the human body, such as ischial areas, represent a particularly simple and economic solution. At the same time, a three dimensional shape can be made

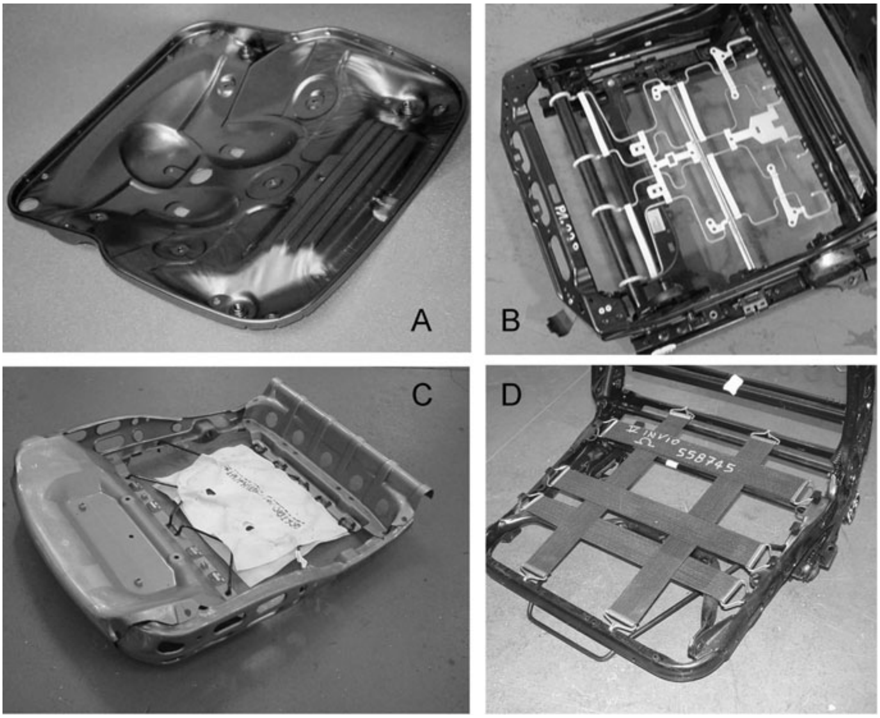

Fig. 6.161. Types of spring and support for cushion foam: A stamped sheet; B Formed wire spring; C spider web made by steel rods; D rubber strips (Sisiara®).

which is suitable for load variations with non linear deformation and friction. In this way, the global damping is only partially penalized.

The impermeability to air of foam used for seats is another drawback. This impermeability arises also with open cell foams because weight of occupants closes possible passage of air within the foam. To solve this problem, some manufacturers put a layer of coconut or other vegetable fibre-based material between the foam and cover. This material enables a good compromise between softness and transpiration to be obtained, (Fig. 6.164).

Fig. 6.165 illustrates foams made completely in polyurethane, completely in fibers covered with rubber and mixed solutions.

Foaming, which is the most widespread manufacturing process used to make foam, is made by introducing a mixture of polyoil and isocyanate at low pressure inside warmed moulds, usually made of aluminium. As with the foamed dashboard seen previously, this mixture expands during polymerization.

To avoid excessive and premature wear of foams, in particular where they are in contact with the metallic structure of the seat, usually on the rear part of

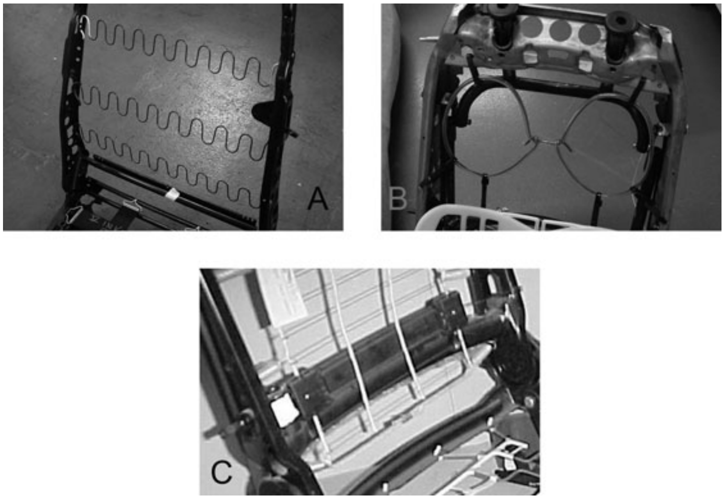

Fig. 6.162. Support and springs system for backrest foam: A Resisto® springs; B spider web made by steel wire; C Pullmaflex® made by steel wire.

foams, pieces of protection cloth are co-moulded by inserting them inside mould before foaming.

In order to optimize comfort and side containment of occupants, in particular with regard to front seats, different types of formulation for foams are used for the central and side parts. In this way lower density foam for central parts and higher density for side parts can be obtained.

Moreover, it is possible to place stiffer foam inserts within the foam in order to create the most critical geometries of trimmed seats, such as those used in sport cars, and improve side containment capacity.

The most important characteristics of a foam are: Lift, which is the reaction due to application of load on a defined area, stiffness and density. These three elements are not directly dependent on each other; for this reason, all are necessary to define the foam characteristics correctly .

Due to its importance, seat comfort is the subject of continuous innovation. In particular climatic comfort can be improved by means of ventilation devices which use cold or warmed air obtained using, for example, Peltier cells, located under the seat cover or using cold air, extracted from the ventilation pipes for cooling rear occupants or, more simple, using fans located directly on the seat.

As concerns well-being, it is now well known that a continuous and irregular movement of foams on the body leaned zone allows better blood circulation in tissue and thus reduced sense of tiredness. For this reason, seats equipped with bags located on foam under the cover have been made. These bags are filled and emptied with compressed air with adjustable and predefined sequences (Fig. 6.166).

Mounting type \ Parameter	Foam thickness	Damping vibrations	Pad sensation	Project adaptivity
Steel spring	+	- -	+ +	-
Steel spider web rods	+	-	+	+
Steel rods web	+	-	+	+
Elastic strips	+ +	+	-	-
Stamped bottom plate	- -	+ +	- -	-

Fig. 6.163. Strengths and weaknesses of different seat foam support types.

Fig. 6.164. On the left polyurethanic foam; on the right coconut fiber covered with rubber.

Covers

Generally covers have different characteristics depending on their use and components. While aesthetics represents a common target for all applications, technical characteristics also influence the selection of covers.

For a vehicle seat, the technical properties of the cover are evidently very important and include:

- Good mechanical properties;
- excellent wear resistance;
- excellent light resistance;
- good workability.

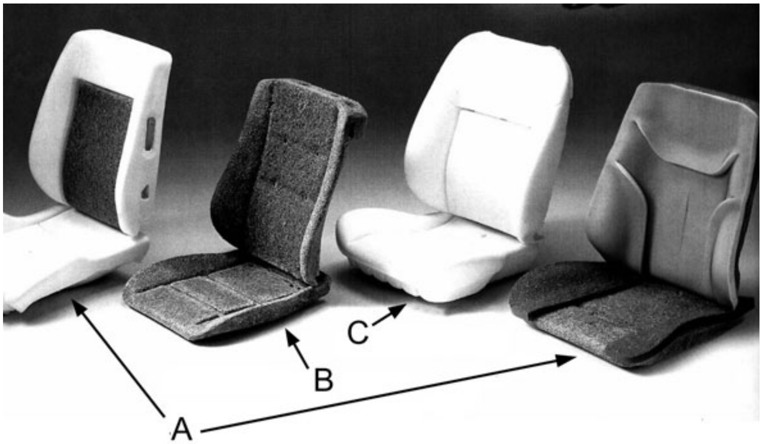

Fig. 6.165. Different types of foam for seats: mixed solutions (A), coconut fiber (B), PU foam (C).

Until the 1970s, imitation leather was widely used, but since many years has been substituted by textile materials.

Today the use of imitation leather is strict limited to the lateral cover and rear backrest, parts that do not make contact with the occupants, or to the most economic versions of low segment car.

Today the covers most widely used are fabrics; these products and technologies would require a specific description beyond the scope of this book. Here it is appropriate to just mention specific aspects of relevance to automotive seats.

Essentially there are two main families of fabric: Circular fabric and woven fabric, (Fig. 6.167); various solutions have been studied to improve tactile aspect during the finishing process.

Due to their increased use in car applications in recent years, velvets are gaining in importance. They are obtained by putting yarns perpendicular to the basic fabric structure which are then cut to the desired length.

The yarns used to make fabrics are obtained from polyester synthetic resin, progressive substituting polyamide fibres, due to better characteristics in terms of wear resistance, self extinguishing properties, and because they are less expensive.

Natural fibres such as wool are also used for particular applications.

The three most important characteristics of fibres are:

- Structure;
- trim strips;
- color.

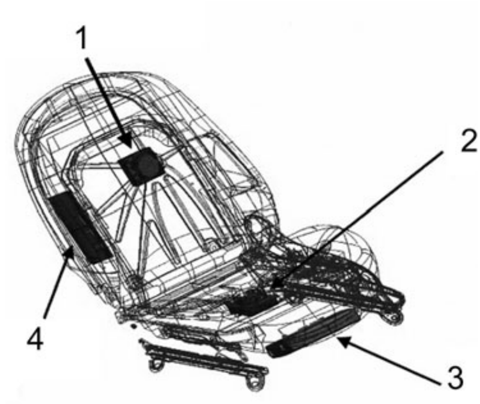

Fig. 6.166. Ventilated seat with massager: backrest fan (80 x 80 mm) (1), cushion fan (80 x 80 mm) (2), electronically controlled massage unit (3), pump (4).

The structure is the characteristic which best defines the type of fabric and its fundamental requirements such as cost and workability; it is also the aesthetic base defined by trim strips. The structure also defines the family of fabric (woven fabric, circular fabric), with their main subdivisions; practically it identifies the frame used to make the fabric.

The workability of fabric is identified above all by its extension which heavy influences the trimming phase. In fact higher extension facilitates this operation and reduces cases of tendinitis often manifest in the workmen assigned to this operation:

- Woven fabrics have a longitudinal and transverse mean percent extension of 3;
- line circular fabric has a longitudinal mean percent extension of 4 and transverse one of 6.5;
- circular fabric has both values equal to 11.5.

The trim strip corresponds to the design of fabric, and as already mentioned, depends on the structure; it is obtained by varying the layout of yarns of different colors, as it is shown in Fig. 6.168.

Velvets with their woven fabric structure facilitate the choice of trim strips if the density of the little bow is low; if density is high, trim strips can be only unit or melange. The Jacquard circular fabric velvets allow freedom of choice for trim strips, and do not depend on the density of little bows.

The color is the last characteristic that can be defined; its choice does not depend on the structure and trim strips. It is important to underline that different behaviors in terms of sun light resistance do depend on the color which can also have a significant influence on the cost.

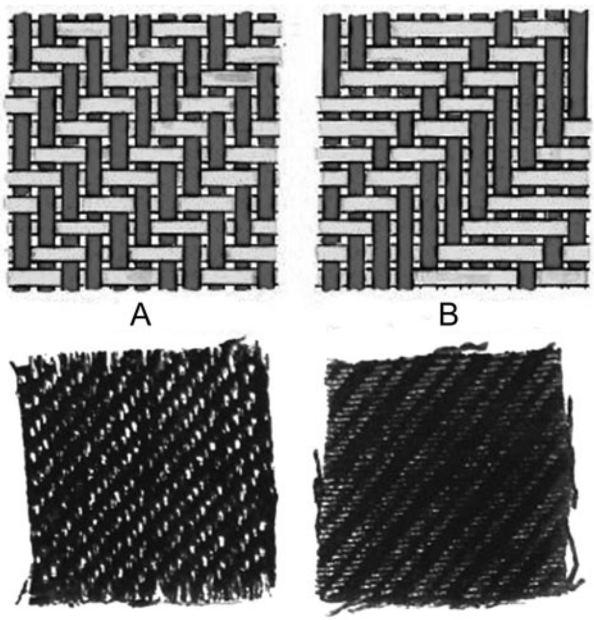

Fig. 6.167. Examples of woven fabric. Case A, diagonal trim strip, SAIA frame number 4, case B, diagonal strips, SAIA frame number 8.

Besides fabrics also used for seats are bovine leather, with particular treatment to prevent ageing, and ultra thin synthetic polyester-based fibres worked with a patented process in order to obtain materials like fustian, also called Alcantara®.

Seat covers are made by working the materials with a tailor process: Cut and sew, (Fig. 6.169).

The cut enable various sizes of seat cover material to be defined that, when joined together, create the cover or dress of the seat. The geometric definition of sizes depends on the seat style model and on the subsequent optimization to improve use of the cover material, performed by appropriately positioning the different templates on the cover material, in order to reduce to a minimum the scraps.

Sewing is performed using a machine similar to those used by tailors to join the different parts of cover material.

Trimming is the dressing operation of seat. The cushion and backrest covers are coupled with respective foams, which are located on the seat structure. The covers are then fixed to the foam using plastic or metallic rods located appropriately.

Around the perimeter, the covers are fixed directly on the seat structure.

Since it is evident that sewing and trimming are both manual operations, alternative process have been developed on the years, in particular:

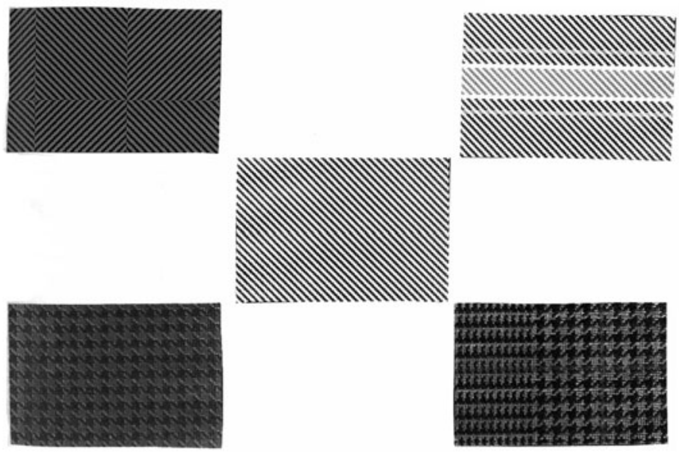

Fig. 6.168. Different typologies of trim strips.

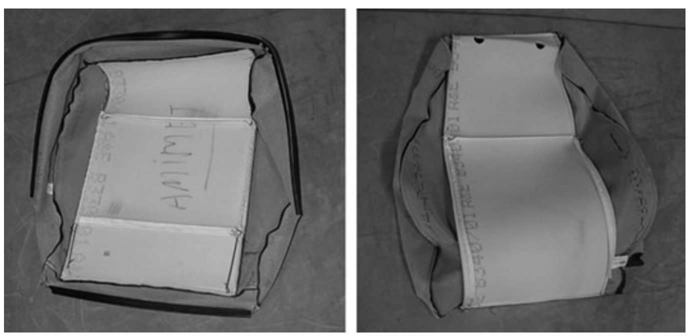

Fig. 6.169. Examples of covers: on the left cushion cover, on the right backrest cover.

- In-situ foaming;
- adhesive bonding.

With in-situ foaming the cover is placed directly inside the foaming mould for the cushion and backrest, as has already been discussed with respect to the door panel and in particular with regard to the covered three dimensional solution and injection reaction technology. The foam thus obtained is already covered, as shown in Fig. 6.170, which then only has to be fixed onto the structure.

This technology, which had seen important applications on low segment cars, has not proved a success and nowadays is used only for particular and limited applications, or for specific seat components, as will be seen subsequently. The diffusion of this technique has been limited for the following main reasons:

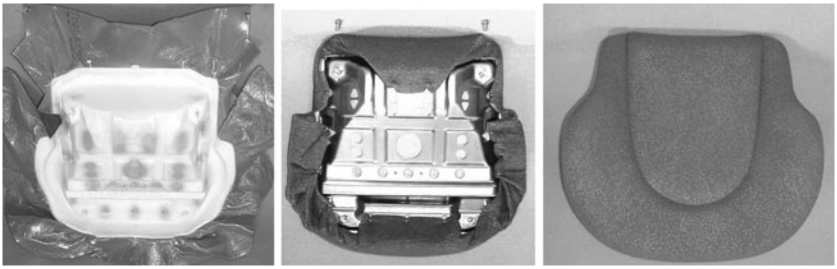

Fig. 6.170. In-situ foaming.

- The important limitation of foam shapes due to the need for the cover to be placed inside mould and positioned by means of suction;
- reduced possibility to select fabric with suitable properties (elasticity) to be put inside foaming mould;
- the relative cost of scraps, since it is not possible to divide the foam from the cover;
- the non transpiration of foams, because, inside the cover, a waterproof barrier has to be put to avoid infiltration of the liquid foam during the manufacturing process.

A possible variation of in-situ foaming is adhesive bonding. In this way, part of traditional trimming is substituted by gluing the cover on the foam. Also this solution has not found widespread application due to the low design freedom due to process restrictions. Moreover the layer of adhesive between the foam and the cover, which has to be treated, reduces the transpiration.

Trims

Usually the trims are plastic elements made by injection moulding, used to cover mechanisms, as shown in Fig. 6.171.

Polypropylene based materials are often used which are grained and mass colored. Particular types of charge are not required because these components do not face specific requirements in terms of impact resistance and high temperature; instead parts located under the windscreen have such needs. For the same reason, for trims also ABS is used, a material with a higher dimensional stability.

Headrest

This component has long been classified as an integral component of the seat; today it is a integral part of the front seat.

The headrest has a double function: To provide a comfortable (soft) load-bearing surface for the head during running of vehicle (in practice only for the

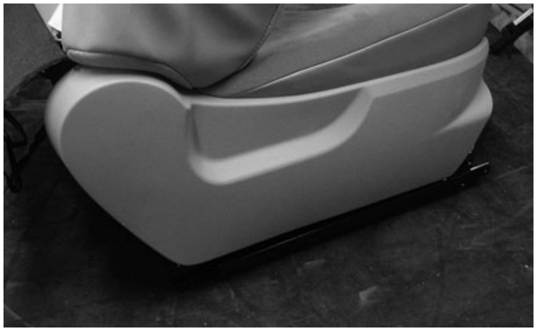

Fig. 6.171. Cover element for seat mechanisms.

front passenger because the driver should normally keep the head away from headrest for better side and front visibility), and while supporting the skull particular in the event of impact. In this way the loads on the rachis are minimized, in particular when, due to rear collision, the inertia force tends to push the head rearwards, while the thorax tends to move forward, or during rebound caused by front impact (see Volume II for further information).

These two functions have two different contrasting needs: For comfort, the headrest requires a certain thickness of foam, while for safety in the event of a collision, a stiff reaction is needed to limit the displacement of the neck. One solution to this problem is as follows:

- Relatively stiff headrest structure, with a thickness of foam of about three centimeters;
- specific design and shape of the headrest structure and foam, in order to accommodate the shape of the skull base and cervical spine in the event of rear collision;
- headrest sufficiently near to the head in order to intervene rapidly, (Fig. 6.172).

Many devices, termed anti whiplash, have been developed and patented to reduce neck injuries, usually using inertial mechanisms. One of these, for example, uses a two degree of freedom connection (horizontal movement and rotation) between the backrest and cushion. In the case of impact, the system pulls back and simultaneously rotates the backrest; in this way, the seat follows the back and head movement, as shown in Fig. 6.173.

Another system uses an equalizer which, when pushed by the back of the occupant, positions the headrest near to the skull of the occupant, as shown in Fig. 6.174.

The wide use of height adjustable headrests is highly important, particular in terms of ensuring the correct position as a function of occupant height, even more important if the headrest has a ergonomic shape.

Fig. 6.172. Ideal configuration to contain head during rear impact, (a: head acceleration).

From the safety point of view, the headrest is classified by means of:

- A static protocol (RCAR), which essentially measures the horizontal distance between the head and the headrest, and the vertical distance between the top of the occupant's head and the top of the headrest; based on these measurements a score is defined, which increases if the headrest is higher and nearer to the head;
- different dynamic protocols (Euro NCAP, insurance ratings, etc.), which measure the occupant neck injuries due to rear collision at a defined speed (16 and 24 km/h).

The headrest comprises the same components and is made with the same manufacturing technologies as the seat: The connection structure with the top part of the backrest, polyurethane foam, height and in some cases angular adjustment mechanisms, and cover, are shown in Fig. 6.175.

In contrast to seats, for the headrest the in-situ foaming technology is relatively widespread since the simple geometry of this component enables the problems already seen for seats to be avoided (Fig. 6.175).

In general, for the most economic headrests which usually do not have adjustments, the foam can be made using integral/microcellular polyurethane foam, the main advantages being that it can be mass colored; an aesthetic skin (like a non trimmed steering wheel) can be created as usual. In this way, the cover material and consequent operations (cut, sewing and trimming) are not necessary (Fig. 6.176).

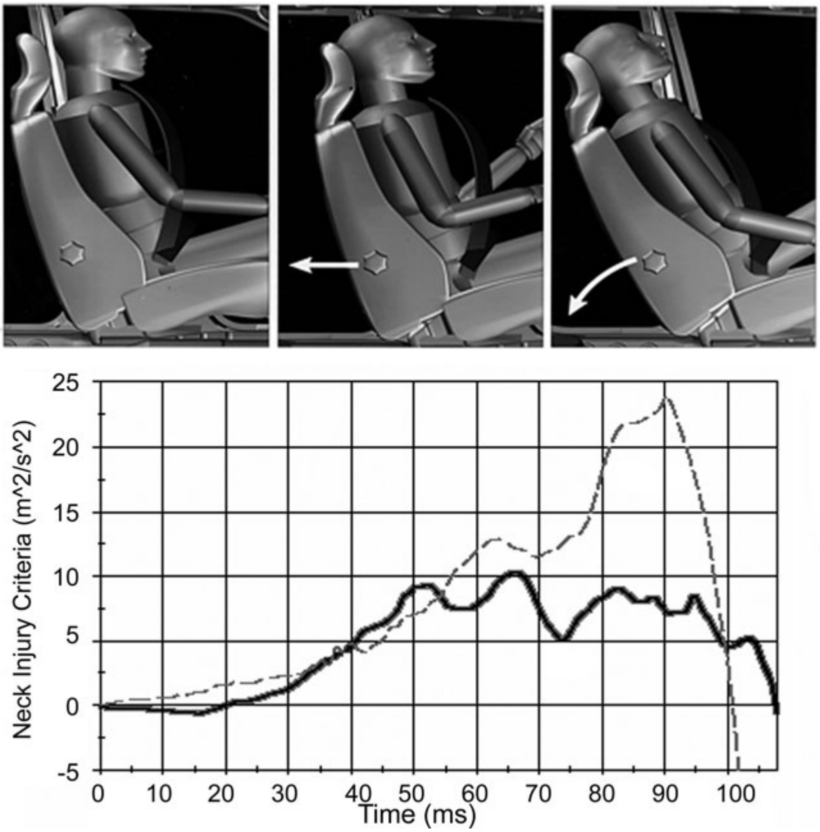

Fig. 6.173. Top: seat with anti whiplash device; bottom: comparison of NIC index between a common seat (dotted line) and seat with anti whiplash system (continuous line).

Side-bag

Today this component is largely used on front seats. It is located on external pillar of backrest located in a cavity in the foam.

The pillar of the seat structure has to have specific design to bear the reaction force from the side-bag during filling and deployment phases.

The deployment of the side-bag can require the opening of an aesthetic door (cover), which is mounted on the housing of the bag module (Fig. 6.177) or tearing a specific seam on the backrest cover. The first case corresponds to side-bag with non integrated cover, the second case to side-bag with integrated cover (Fig. 6.178). This second solution does not change the aesthetics of the seat but in this way the cover of the backrest becomes also the cover of the side-bag and thus becomes part of the safety system. Therefore during its definition and design, it is necessary to adopt safety criteria and ensure traceability.

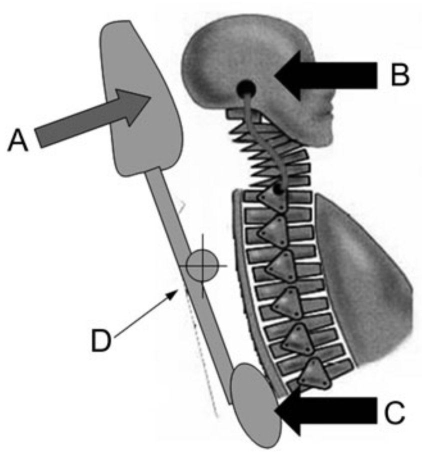

Fig. 6.174. Anti whiplash device activated by occupant movement on backrest: induced movement of headrest (A), movement of head during rear collision (B), movement of backrest during rear impact (C), centre of rotation (D).

As in other cases, the presence of a non visible cover has to be put in evidence by means of the air-bag inscription which is required on the same cover.

Armrest

This component is practically standard on high segment cars and an optional for other segments. It can be located on the console or on the seat.

The solution mounted on the seat is generally more ergonomic because the position of the armrest does not change with respect to the H point: In fact, the armrest moves with the seat. With this solution the internal side pillar of the backrest has to be designed to bear the required static load. The armrest must not hinder the buckling operation of the safety belt; for this reason occasionally the armrest has to be rotated upwards, an operation which has to be ensured (Fig. 6.179).

In some cases, a space which can contain small objects is obtained on the armrest.

As concerns its components and manufacturing technologies, the same considerations as for the headrest apply.

Integrative adjustment

Some seats offer the following integrative adjustments:

- Lumbar adjustment to modify the convexity of the backrest in comparison with the nominal position, and changing the position and thus the backrest foam support in the lumbar region. Fig. 6.180 shows a type of adjustment known as butterfly.

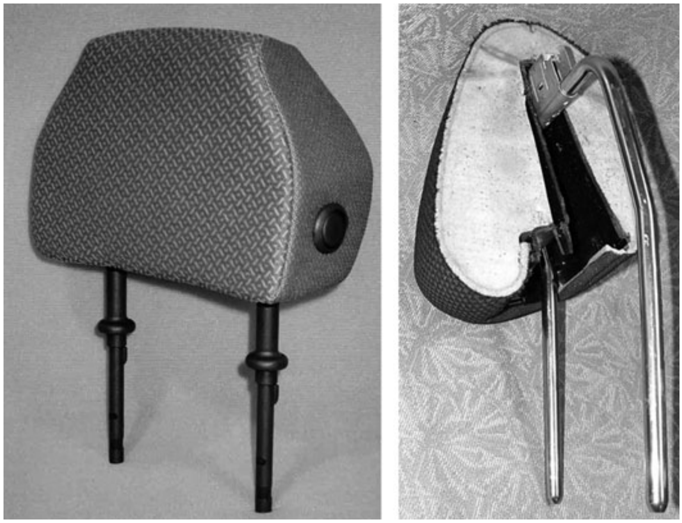

Fig. 6.175. Example of a conventional headrest on the left; headrest made with in-situ foaming on the right.

- Adjustment of small side elements of the cushion and backrest to enable adjustment of side containment. These devices, usually adopted on sports cars, can have an instantaneous and continuous adjustment of small side elements using accelerometers appropriately located on vehicle. From the design point of view, these devices can be attached to a small metal frame hinged onto the seat structure, or by pneumatic bag which are operated by a small compressor and electro-valves.

In general the need for flexibility, in particular for larger cars, has led to mechanisms being developed which allow the backrest to be folded on the cushion in order to obtain a little table (Fig. 6.181). The mechanism has a secondary hinge on the backrest.

Fig. 6.176. Example of a low cost headrest, made without cover material.

Fig. 6.177. Front seat with side-bag.

Design criteria

Front seats must undergo test approval both as concerns the single components and the seat module. These tests can be made on the bench or on the vehicle.

The tests for seats regard ergonomic and postural comfort (static and dynamic), structural durability and reliability, in particular as concerns the mechanisms, those relative to front, rear, and side impact and acoustic performance.

Homologation of seats is essential. Firstly the position of point H is verified, measured using a SAE dummy which is located on the seat in its rearmost position. The position of H point has to remain within a 50 mm wide square centred on R point (the reference point indicated in Fig. 6.182).

Other homologation tests include the attachment points of safety belts and of the seat to the floor and semi static tests to ensure adequate protection for front impact. Moreover the backrest has to resist static loading equivalent to a longitudinal inertial load of 20 g.

After frontal and side impact tests on the complete vehicle, which are required by European (and non-European) rules, specific measures on seats are not required; nevertheless possible fractures of seats lead to serious consequences which can be measured by the dummies located inside cockpit.

For example, possible vertical fracture of the front seat structure can promote the submarining phenomenon, when the occupant slips forward and under the lap part of the safety belt. Consequently the biomechanics parameter relative to legs, thorax and in some cases, also head is affected. To avoid submarining, all seats have front part of cushion appropriately designed with reinforcements and cross members.

Fig. 6.178. Side-bag with integrated cover.

On front impact tests, simulated using a sled, the inertial effects on seats are also verified. In particular, the effect of two free mass which normally weigh 18 kg and have a predefined distance from the front seats backrests. The obtained effects have to ensure absence of mass intrusion with respect to the occupants.

Moreover the seat structures must not emit noise and vibrations, or amplify vibrations coming from floor. Vibration comfort tests are made on the vehicle and on simulator platforms (i.e. vibration tables or shakers), which are able to recreate the acceleration levels measured on the car floor on the road.

The use of these dynamic simulators represents the artificial reproduction of a sensation which can be felt on the car and used to compare behavior and perception after hours of operation, simulated under strictly repeatable conditions as regards temperature, humidity, vibration, noise, etc. as may be required. Indeed, the fatigue of the vehicle occupants is manifest in a measurable way, and thus numerical comparable, and depends on the length of exposure to vibrations and/or other discomfort factors; in generally this should exceed two hours.

Another use of the vibration table is to enable immediate and rapid comparison of seats mounted on the same table one after the other.

As usual, bench tests enable typical problems of road tests to be overcome, such as non repeatability, contingencies of any kind caused by traffic, attention required during test drives and the high cost of realizing complete prototypes (more details are provided in Volume II).

6.5.2 Rear Seats

For many years, the rear seat essentially had function of providing a comfortable sofa, usually fixed, where, especially on the first vehicles, the owner was seated.

Fig. 6.179. Front seat with armrest.

With the advent of the car with rear tailgate, and thus the need to manage the volume of luggage area and number of transportable passengers depending on requirements, the rear seat has seen a radical transformation over recent years, in some cases becoming comparable to the evolution of the front seat.

Generally the rear seat is obtained by assembling the same types of component as used for front seats, but with different geometry or design concepts.

Structure/adjustment and movement mechanism

These are the most different components with respect to the front seat considering their design concept; these can be divided into two categories:

- Three volume cars;
- two volume cars and station wagons (with rear tailgate).

Three volume cars. In this type of vehicle, the luggage and passenger transport functions are completely separate; thus the rear seat has remained, almost in all cases, a comfortable fixed sofa without adjustment mechanisms.

The structure of seat is made by a simple frame or metal, (Fig. 6.183) which is fixed to the body floor by means of brackets, bolts and nuts.

Solutions exist comprising the backrest fixed with a hinge, which can be folded on the cushion to allow to transport bulky but light loads.

Fig. 6.180. Examples of butterfly lumbar support (A), made in plastic.

For two volume transformed to three volume cars for a specific market, the original seat solution described below is often maintained.

Two volume cars. In these vehicles it is possible to increase the volume of the luggage area by completely or partly folding the rear seat; the folding can be obtained with an entire seat or a divided seat, which is usually divided in non equal parts (usually 40% and 60% of width, as shown in Fig. 6.184).

In this way it is possible to manage the luggage volume and the number of passengers in a modular way.

The subdivision in two equal halves is used only on cars which are homologated to transport two passengers on the rear seat.

Seats can have different folding configurations as follows:

- Fix and fold: The cushion is fixed and the backrest, which is hinged, can fold onto the cushion to create a new luggage volume, which can be varied if the seat is sub-divided.
- Flip and fold: The cushion, which is front hinged to the floor, flips against the backrest of the front seat and then the backrest, which is always hinged to floor, folds to the floor. In this and previous cases the backrest of the rear seat must have a stiff rear wall in order to bear the weight of the load which may be placed on it. To best use the load surface, the floor of vehicle must have a specific design, as shown in Fig. 6.185.
- Fold and tumble: The backrest folds onto the cushion where it is hinged, then both tumble against the backrest of the front seat. Also in this case,

Fig. 6.181. Mechanism which allows folding of the backrest on cushion in order to obtain a small table.

as can be seen in Fig. 6.186, the floor of car must have a specific design; if, as in Fig. 6.185 the floor is to be used, an additional step to level the floor is necessary. The characteristic of this solution, which was developed for mono-volume cars, is that it is easy to remove seats from the compartment if necessary. Usually the seats have a geometry very similar to that of front seats.

- Fold and dive: The backrest folds onto the cushion thus creating a unique body that is dived under the floor; in this way, the volume of charge is increased without removing the seats. Clearly the floor requires to be design specifically to facilitate the handling of the seats, which are usually very similar to front seats. This solution is normally adopted on SUV or minivans.

To increase slightly the luggage volume without folding the seats, if necessary, it is possible to til the backrest from the 23° optimum comfort value, to 19°. This tilting is possible using two different fastenings where the backrest is fixed.

Another system used to ensure the maximum exploitation of the luggage volume without folding seats, usually used when there are no rear seat occupants, is to adopt a longitudinal slide with angular adjustment using a non continuous device, positioning the seat in the most forward position with backrest at the minimum tilt angle (Fig. 6.187).

The folding seats which have been just described, must be reinforced to resist the inertial loads in the event of impact. These loads are due both to the presence of the occupants on the seats and to the luggage.

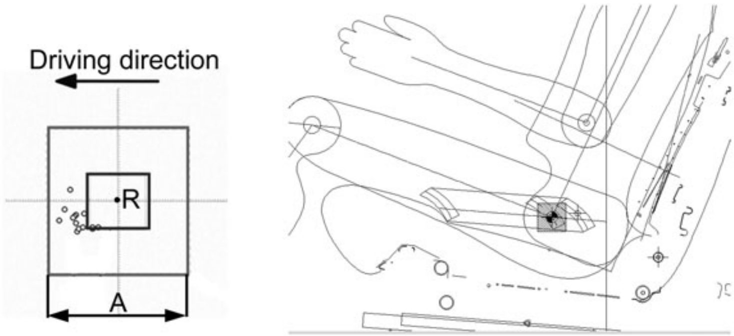

Fig. 6.182. Verification of H point position in comparison with R point during homologation. On the left limits of H point and values obtained from production are put in evidence. The side of square A is 50 mm.

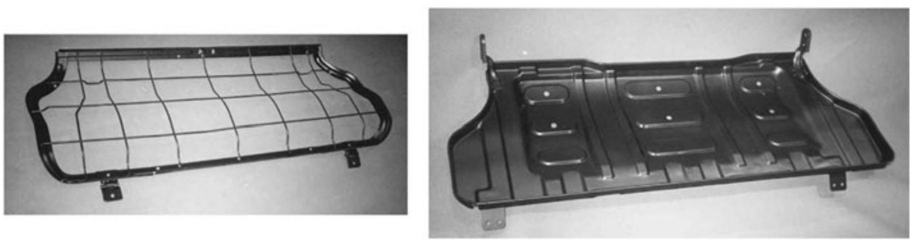

Fig. 6.183. Rear seat structure, wireframe on the left, stamped steel sheet on the right.

In Fig. 6.188, a typical structure of a divided rear seat is shown.

Because the loads are highly asymmetric in the case of impact, seats are subject to flexing and torsional deformations which can lead to deformation against the back of passengers. To limit the effect of this load, the structures are usually made of high strength steel with peripheral crown, sometimes reinforced with diagonal beams or with metal sheets welded around the perimeter. The hinges are designed to absorb part of the impact energy, transformed into deformation of the connection brackets and, if necessary, also of the floor.

In the flip and fold solution, the backrest of the seat is connected to the floor by the hinge, and also to the body side with lower attachments which allow the transversal play to be eliminated (Fig. 6.189); the upper fastening is made with a lock, very similar to those used for side doors, applied to the top of the backrest and completed with a striker fixed to the body side (Fig. 6.190).

In general, the almost standard adoption of the third fastening point for the safety belt of central passenger, as can be seen in Fig. 6.188, leads to positioning the retractor on the backrest, causing additional loads in the event of impact as a consequence.

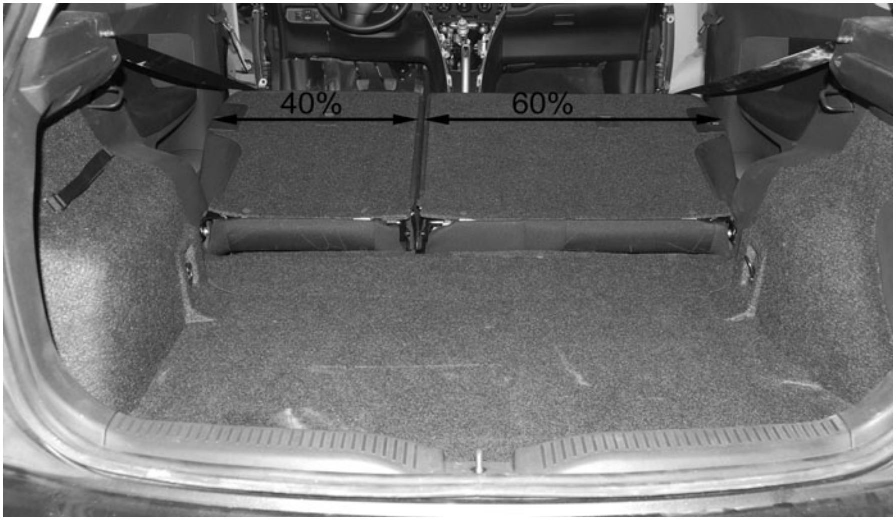

Fig. 6.184. Divided rear seat.

To conclude the analysis of rear seat structures, it is important to consider the strength tests due to luggage impact, which are covered by different regulations in force, as summarized in the table shown in Fig. 6.191 and 6.192.

Today, numerical simulation codes are available which enable the results of experimental tests to be predicted with high levels of confidence (Fig. 6.193).

As concerns the other components, such as the covers and the trimming, the same considerations apply as for the front seats. However, as regards springs and foam, the situation is usually more simple because both the backrest and the cushion are made using polyurethanic foam on the structure. Moreover, the

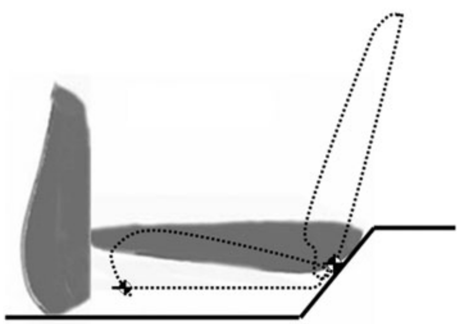

Fig. 6.185. Flip and fold rear seat type.

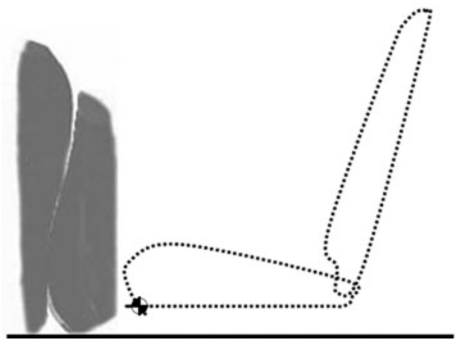

Fig. 6.186. Fold and tumble rear seat type.

headrests of rear seats are essentially integrated with the backrest; however they can restrict rear visibility for the driver (Fig. 6.194).

6.5.3 Child Seats

R 44 regulation specifies five classes of the children transportation devices on car, defined according to the child's weight:

- 0 class, child weight must be less than 10 kg, baby seat (cradle);
- 0+ class, child weight must be less than 13 kg, baby seat (cradle);
- 1 class, child weight in the range 9 to 18 kg, baby seat or adapter;
- 2 class, child weight in the range 15 to 25 kg, baby seat or adaptor;
- 3 class, child weight in the range 25 to 36 kg, adaptor.

The term baby seat refers to a seat or housing which can contain the child's body, equipped with an integrated safety belt system with three or five fastening points.

The adaptor is a spacer located on seat, enabling the correct use of the vehicle safety belts by positioning the child appropriately.

The devices can cover more than one class of those defined in the R 44 regulations, for example classes 0, 0+ and 1.

The child seat is certified by the supplier using a homologation plate, while the car maker is responsible for the system to fasten the child seat to the vehicle seat. On the plate, the reference class must be indicated.

Usually it is possible to find on the market seats which can be used for children from 0 to 3 years, and seats for children from 3 to 12 years (however with a height lower than 1.5 m).

Above these ages or heights, children can use the vehicle seats and safety belts directly.

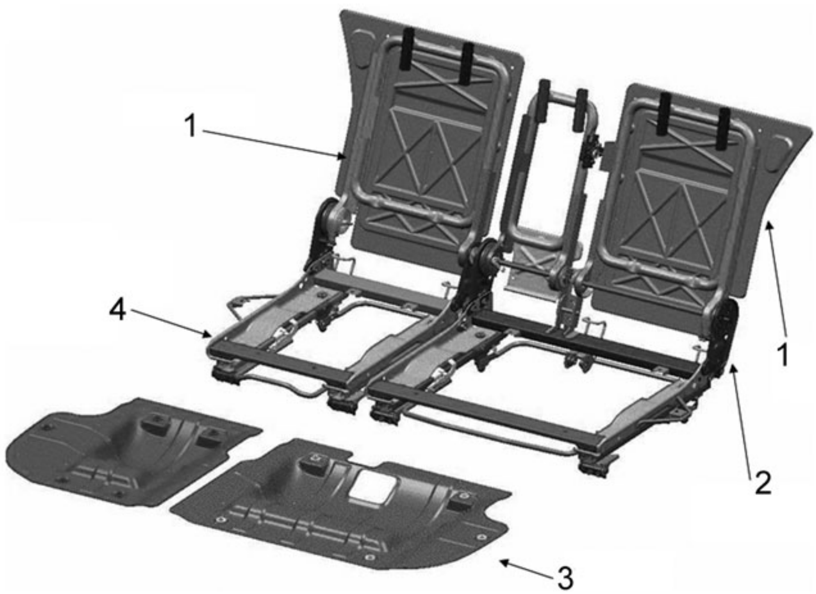

Fig. 6.187. Structure of the rear seat with longitudinal slide and tilting adjustment of backrest. Components: backrest bottom (1), backrest adjustment articulation (2), cushion bottom (3), floor interface between structure and mechanisms, slides, handle (4).

Usually child seats are restrained by the safety belt of vehicle, with grooves for the vehicle safety belts, or a hooking mechanism which are welded or bolted to the seat structure. Such fastening devices are called Isofix® (Figs. 6.195 and 6.196).

In the past only two Isofix® attachments per seat were available; however if the seat on which the baby seat is located is not stiff enough, a pitching rotation cannot be avoided during impact: This can be dangerous for the motion of the child's head. Today solutions use three Isofix® attachments, one of these being located over the backrest of the child seat, on the rear part of the seat, to avoid rotation (Fig. 6.197).

Some car manufacturers do not arrange the seat with Isofix® attachments, but supply as an option a rear seats with an integrated folded child seat, equipped with safety belts with five attachment points.

The design, construction and verification of child seats use methods and criteria which derive from those of adult seats, although specific developments concerning the cover fabrics and shapes has been introduced.

It is important to consider the problems associated with child seats also when front and rear seats are designed.

Fig. 6.188. Typical structure of a divided rear seat.

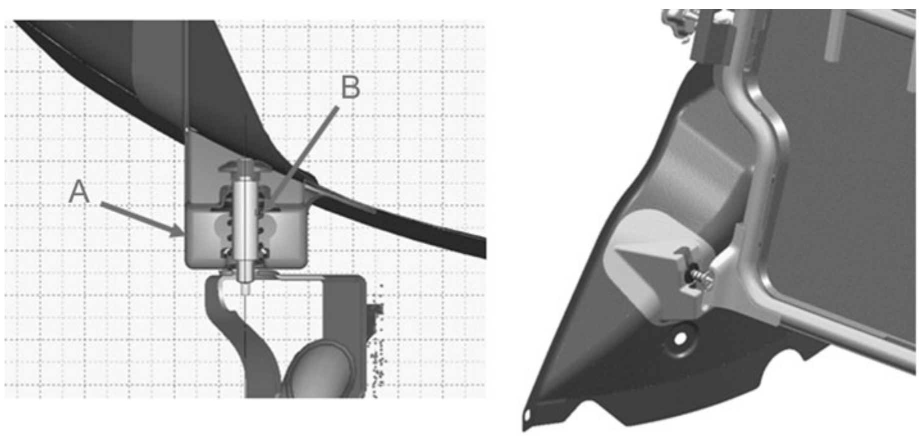

Fig. 6.189. Lower connection between the body side and seat structure with a device to eliminate play. Shown are the bracket welded to wheelhouse (A), and the hinge with spring to allow elimination of play in the Y direction (B).

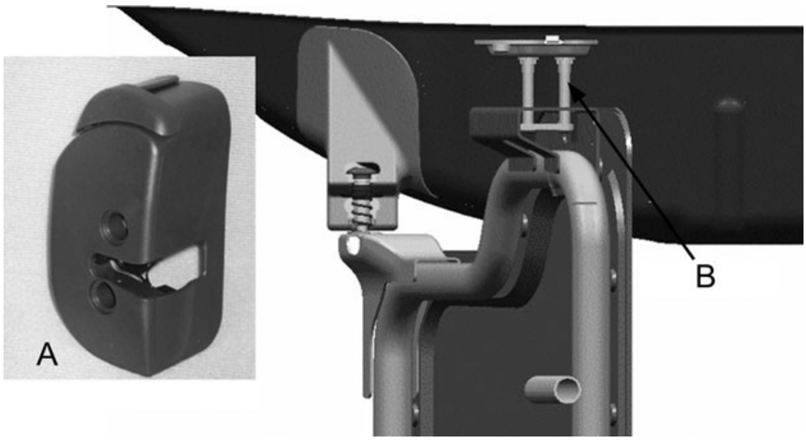

Fig. 6.190. Upper fastening between the body side and seat structure made by lock (A) and striker (B).

STANDARD OR RULES	M (kg)	D (mm)	PULSE	DELIVERABLE CRITERIA
DIN 75410-2	2x18 +10	200 0	20 g min	Load containement without ruptures
ECE 17/07 (OM.)	2x18	200	ECE 44	Max instrusion 100/150 mm, without rupture
IOCU	2x35/55/80 dependig load volume	0	ECE 44	Load containement without ruptures

Fig. 6.191. Test standards for rear seats.

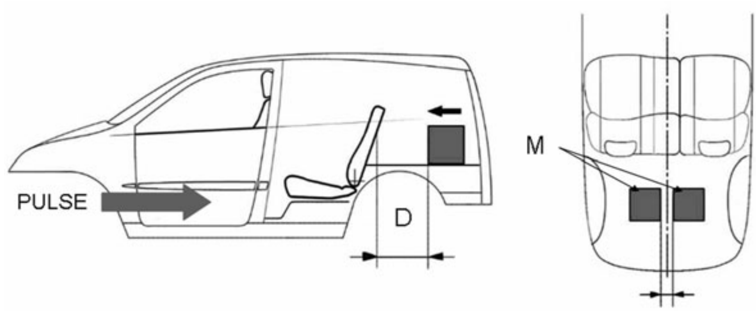

Fig. 6.192. Dynamic strength tests for rear seats due to transported loads.

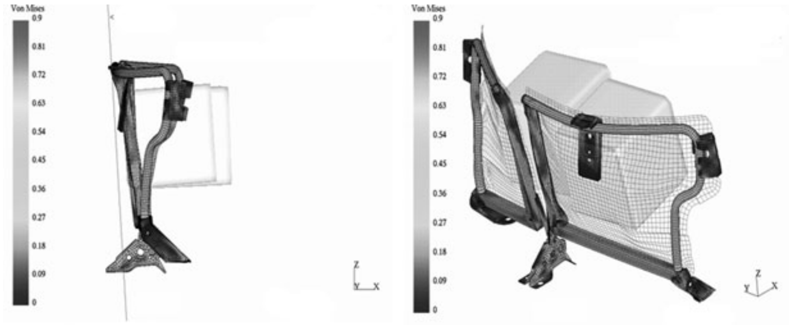

Fig. 6.193. Simulation of luggage impact against the rear seat.

Fig. 6.194. Headrest for rear seats, functional positioning on the left, positioning without passenger on the right.

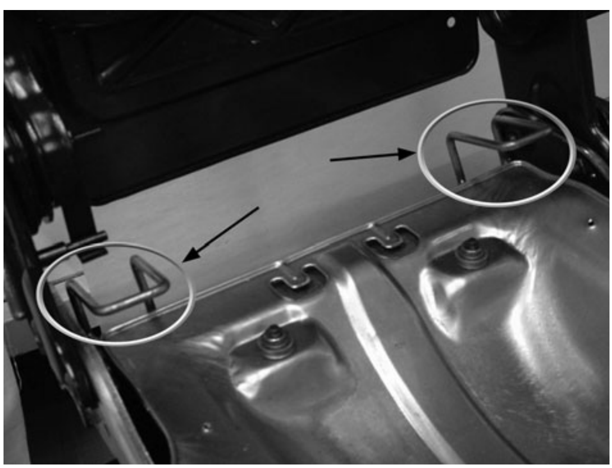

Fig. 6.195. Isofix® attachments on the cushion structure.

To reduce risk of injury in front impact, the child seats must be located on the rear seats, except for those cases, clearly, where rear seats are not present (for examples spiders).

If located on the front seat, child seats must be mounted in the direction defined, and if passenger air-bags are present, these must be switched-off to avoid potential injuries during the deployment of the bag.

To conclude it is also necessary that the safety belts for the seats where child seats can be located must be long enough to wrap around and restrain the baby seat. To verify this, an archetype of children seat identified in the regulations (called Gabarit) is used, as shown in Fig. 6.198.

6.6 Air Conditioning System

Of the many issues which the first car designers faced, the air-conditioning system, or simply heating the vehicle, was not a primary concern. Indeed the passengers faced the elements in the same way as when riding on a carriage, typically using blankets in the winter.

One of the first heating systems used on vehicles used the heat from the combustion engine, by channeling into the passenger compartment the air from the engine compartment used to cool the engine, resulting in an unpleasant odor. Nevertheless this system was optimized progressively and for several decades continued to be used on cars with air-cooled engines.

Other types of systems attempted to use the heat of the exhaust gases. However the decisive turning point corresponded to the introduction of a heater.

6.6.1 Heater

The heating system for a car, which uses the heat of the engine cooling liquid to warm the cockpit, was introduced for the first time on mass production vehicles during 1940s and early 1950s. The system comprises a heat exchanger (radiating mass) located inside the cockpit. Inside this radiating mass, the hot liquid from engine cooling system flows. If part of the air passes through the radiating mass, this air is warmed and can be used to heat the cockpit; this is the principle of the heater.

The heating group or heater, shown in Fig. 6.199, is usually located between the firewall and the instrument panel, and comprises:

- Radiating mass;
- fan for air distribution;
- housing and air distributor;
- control group.

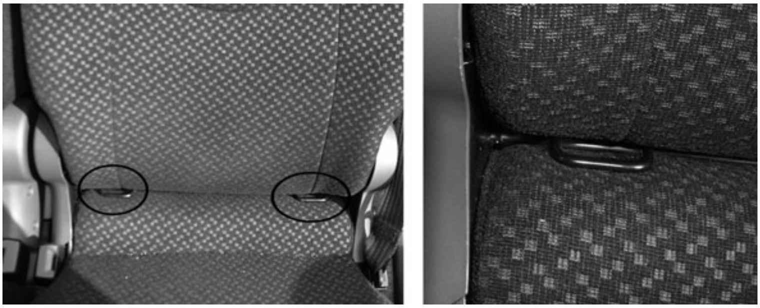

Fig. 6.196. Isofix® attachments for the child seat.

Fig. 6.197. Positioning of the third attachment points.

Fig. 6.198. Children seat archetype, called Gabarit.

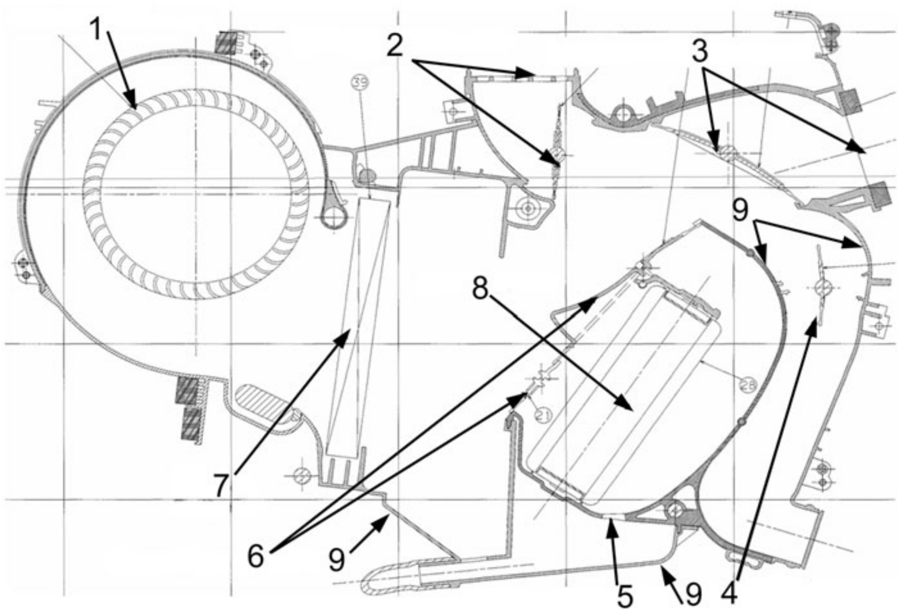

Fig. 6.199. Heating group. Components: air induction fan (1), flap door and defrost exit (2), cover and ventilation vent exit (3), cover and air ventilation exit for feet-level (4), drain condensing hole (5), air mixing plates (6), particle filter (7), radiating mass (8), housings (9).

Radiating mass

This heat exchanger is the heart of the heater, since the heat is extracted from the radiating mass and introduced into the cockpit.

The radiating mass incorporates:

- Round tubes and flat fins;
- parallel flows.

The solution with round tubes and flat fins corresponds to the basic solution used for all heat exchangers of the air-conditioning (Figs. 6.200 and 6.201). Tubes and fins are made of copper or aluminium. The hot liquid from the cooling system enters via connection (1) and, after flowing through the pipes (5), exits from connection (2). The air to be warmed (6) is conveyed perpendicularly to the radiating mass and is warmed via the fins (3) and pipes (5).

The solution with parallel flow, which is an evolution of the previous one, applies very flat aluminium pipes which enable reduced frontal surface compared with the exchange surface. Between these pipes, a series of aluminium fins are located which have a particular shape so as to increase the thermal exchange with air. The pipes are assembled on an aluminium collector and small tank. In the

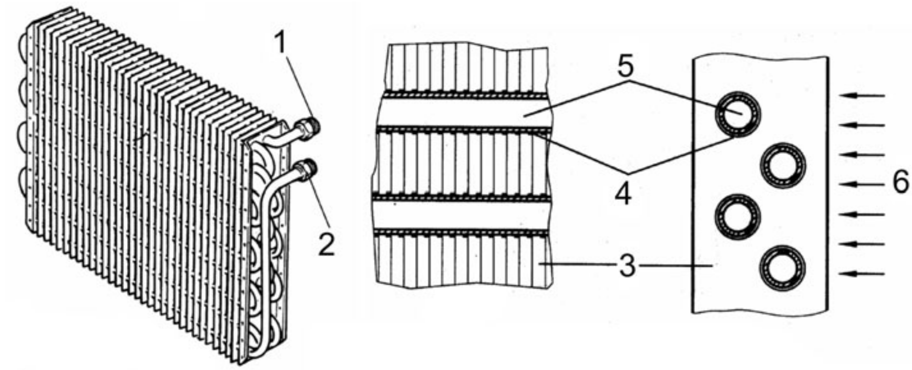

Fig. 6.200. Condenser with pipes and fins. Components: entry connection (1), exit connection (2), fins (3 and 4), pipes(5), air flow (6).

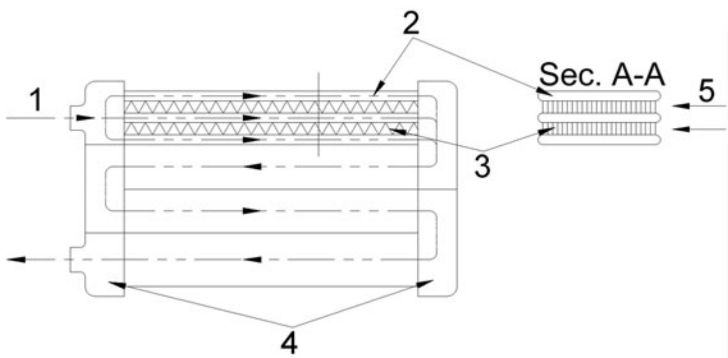

Fig. 6.201. Scheme of parallel flow radiating mass: warmed fluid (1), pipes (2), fins with flap (3), manifolds (4), air to be warmed (5).

past, they were made using injection moulding in polyamide glass reinforced, whereas today they are made in aluminium. To increase the efficiency of this exchanger, the warming fluid flows along the pipes many times, using a separator on the collector; from here also the term parallel flows derives (for more detail, see Figs. 6.201 and 6.202).

This configuration enables exchangers with high performance and with the same overall dimensions to be obtained; the exchange efficiencies are 40-45% higher than those obtained with the round pipes and flat fins solutions, although costs are higher. While providing the same performance, with the parallel flow solution it is possible to reduce overall dimensions and weight.

To assemble the parts of the radiating mass, the most common technologies are:

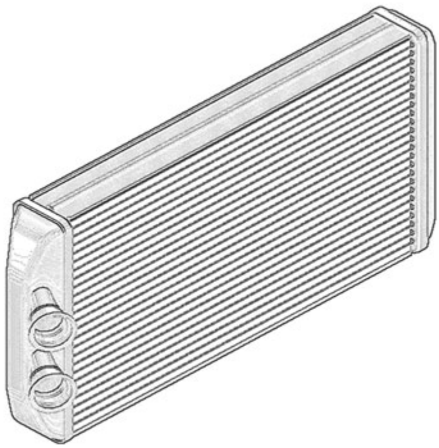

Fig. 6.202. Parallel flow heater.

- Expanding, for masses with round pipe and flat fins;
- braze welding, for masses with flat pipes and fins with deflectors.

Expanding is a mechanical process, creating the mechanical continuity between pipes and fins by expanding the pipes inside the hole made on the fins. Interference is reached by means of plastic deformation. This assembly process was widely used in the past to make many different types of exchangers with pipes and fins.

Vacuum braze welding can be performed also in a controlled atmosphere, allowing a good mechanical assembly and excellent fitting between trays, collectors and pipes to be achieved. For this process, the trays have to be made in aluminium. The vacuum braze welding was conceived earlier, but brazing in a controlled atmosphere offers an important advantage, being a continuous process, particularly well suited to high production volumes.

To adjust the temperature of the air exiting the radiating mass, and thus also the temperature of the cockpit, the radiating mass may have a valve varying the flow of hot fluid coming from engine cooling system. Today this solution is not very frequently used to control the temperature. Nowadays, radiating masses without valve are used predominantly, the hot liquid coming from cooling system always passing through the mass: Temperature adjustment is made via an air mixing process.

Fan airflow

The task of the electric fan is to extract the air from outside and bring it towards the radiating mass through a cochlea where the fan is contained.

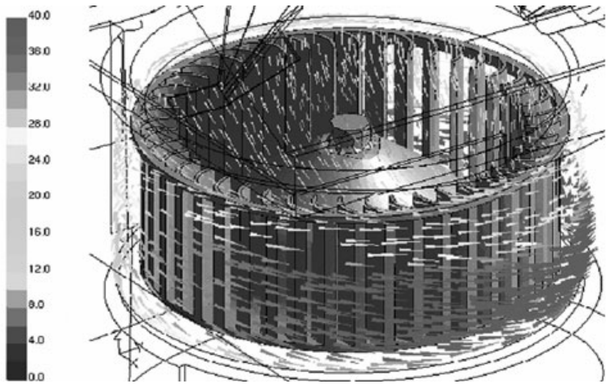

Fig. 6.203. Example of fluid dynamic simulations used during the design of an electric fan.

In the past the electric fan was axial whereas today it is centrifugal, the design of which needing careful definition in order to limit emitted noise, particularly since it is located inside the cockpit. Another very important aspect is its absorption of electricity; in fact the fan is an important item in terms of the electric balance and overall energy efficiency of a car. This is particular important in very hot or cold climates, where the use of the fan is more intensive.

For this reason the design of the impeller fin shape and its housing requires high precision in order to obtain the lowest energy loss in the incoming air-flow and silent operation.

Fig. 6.203 shows results of a calculation of flow around the fins, from which it is possible to observe the distribution of velocity along the fan axis. The non uniformity is due to the convexity of central part, where usually the electric motor is located. To cool this motor, flow spillage is taken from the lower part of the cochlea.

Also relatively critical is the design of the air-flow section between the fins; here it is important to avoid vortices which can create noise during normal operation.

Also the housing for the centrifugal electric fan, called also cochlea, contributes to determine the overall performance of the system. The most critical aspect of cochlea is the nose, i.e. where separation occurs between the flow exiting the fan and the flow exiting the cochlea. In particular, its fillet radius requires particular attention because here a vortex can be generated (see Fig. 6.204).

Housing and distributor

The housing (Fig. 6.199) comprises several different parts due to assembly reasons; it is injection mould using a polypropylene material with a mineral charge (talcum). This choice of material is due to its low cost, and because the part does not have aesthetic function or particular resilience requirements.

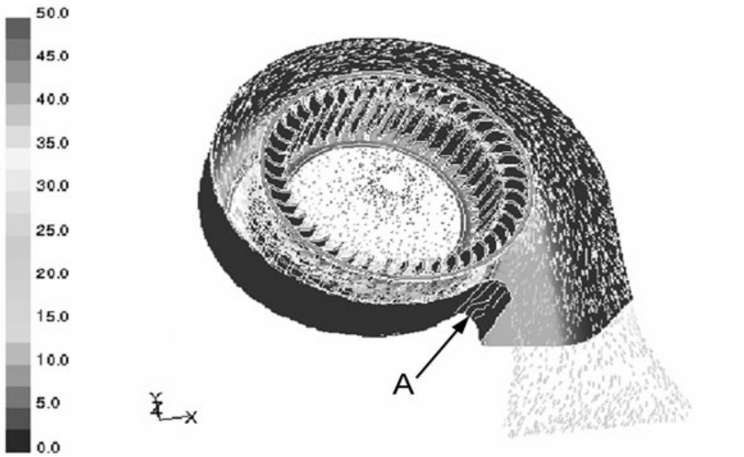

Fig. 6.204. Example of fluid dynamic calculations, used during the cochlea design, in particular the nose (A).

Nevertheless good dimension stability is necessary to ensure correct matching between different parts without any air leakage.

To improve dimensional stability and thus the air tightness, a special formulation with high crystalline polypropylene is used for more complex housings. This material also enables weight reduction because it is possible to reduce the wall thickness due to its better mechanical properties.

Connected or integrated with the housing is the air distribution subsystem, an assembly of small doors to manage the air-flow through the cockpit, (Fig.6.199), as described subsequently.

6.6.2 Control Groups

By means of the control groups, shown in Fig. 6.205, the vehicle occupants can manage the following functions:

- Air temperature adjustment;
- air distribution;
- entry of exterior air or recirculation;
- air-flow.

For the heater, in particular, since it is mainly managed by a mechanical drive, the control groups are provided with the heater group. The connection between the controls and the groups is made via flexible metallic cable.

Fig. 6.205. Heater or air conditioning manual control group (the switch on/off control for the air conditioning is indicated).

Usually the temperature is controlled mechanically; its action inside the heating group can alter depending on whether there the valve for the radiating mass is present. If present, the control acts on valve opening and closing. When the valve is not present, the warming fluid always passes through the radiating mass (see Fig. 6.199). Before the heat exchanger, one or more small doors are located which allow either all the air-flow to be conveyed onto the radiating mass, (maximum warming case) or to completely avoid flow onto the mass, (absence of warming).

Instead, in the intermediate positions, the air passes both through the radiating mass and via an alternative route avoiding the mass; the two air-flows join together again beyond the mass. In this way, an intermediate degree of air warming is obtained, which depends on the mixing of the two flows defined by the position of the mixing door.

Correspondingly, the temperature control acts on the mixing door. Since the cold and hot air-flows are mixed below the radiating mass, the temperature adjustment is defined by means of air mixing.

The air distribution control is always a mechanical device; with this mechanism the occupant can choose the desired air distribution from the different possibilities.

The air intake control allows the opening and closing of the door with the exterior. In a tunnel, for example, it enables pollutant air to be avoided from entering into the cockpit.

Today this possibility has been substituted by the air-blow by function. This function enables the outside air intake to be closed and, at the same time, it opens an air intake inside the cockpit, so that the fan can suck the air from the cockpit rather than from the exterior.

The flow control, being electrical, is the only non mechanical control, activating the suck fan and managing the velocity. This usually is non continuous with four speeds, enabling the maximum air-flow to be reached independently of vehicle speed.

The possibility of managing the air-flow is not only useful to reduce the warming time of the cockpit (warm-up), but is indispensable to reduce the defrosting time of the windscreen and side glass. These aspects are defined with homologative rules.

Moreover, the electric fan can work with higher velocity when the valve is closed and there is no mixing of air-flows. In this way it can act to cool the cockpit.

6.6.3 Air Conditioning

The history of air conditioning in the automotive field started in 1954 when the first summer cooling system, combined with a cockpit warming system, appeared on a mass production car in the United States.

From that moment, the installation rate of air conditioning system immediately saw rapid evolution, becoming an essential feature for most vehicles sold. However, it is necessary to consider that before the 1990s, only air cooling, as opposed to fully air conditioning, was used for automotive applications; these systems were designed to produce only cold air for the cockpit during the hot times of the year. They did not allow air temperature control but only enabled the variation of air-flow admitted to the cockpit.

Subsequently true success and market penetration of air conditioning in vehicles has been possible with the development of a system capable of managing and controlling the climate inside the cockpit. In fact, with today's systems, it is possible to adjust the temperature and the degree of moisture inside vehicle whatever the external weather conditions.

As shown in the histogram of Fig. 6.206, in 1965, only few vehicles were equipped with air conditioning in Europe. At the start of the 1980s the percentage of air conditioning vehicles on vehicles sold in the USA and Japan was more than 80%, while in Europe it was lower than 20%; since then market penetration has grown constantly and rapidly to reach 60% by the year 2000. This increment has concentrated on middle segment models; in fact at the beginning of the 1990s, air conditioning on the higher segments in Europe had already reached almost 100%.

Starting from the beginning of the 1990s, the filtration of entering air into the cockpit and automatic climate control were further introduced. These two optionals have migrated from application to the high to the low segments, and have become fundamental elements of air conditioning systems. By 2005 the proportion of air conditioned vehicles installing an air filter already approached 100%.

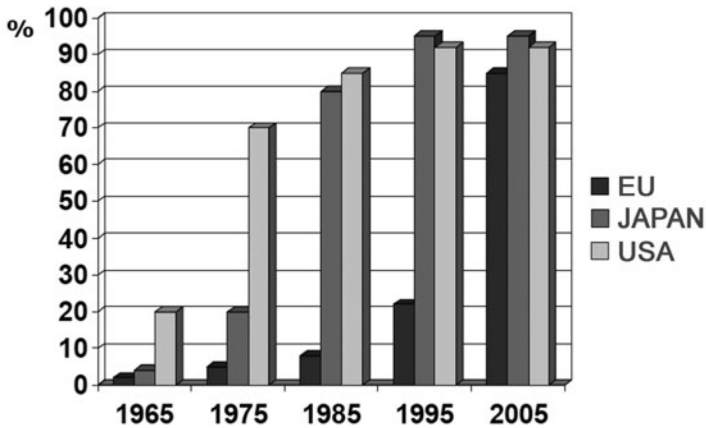

Fig. 6.206. Percentage diffusion of air conditioning system in the different markets.

At the end of the 1990s automatic air conditioning was installed also on the lower segments; today for the B segment the proportion is approx. 60%, for the C segment about 80% and for D segment it exceeds 90%; for higher segments, 100% has already been reached.

Whereas the heater already gave a significant contribution to cockpit climatic comfort, clearly most appreciated for situations in which the exterior temperature is low, the air conditioning system has enabled excellent climatic comfort conditions to be reached, controlling the climate within the so-called comfort zone (see Volume II). In fact this system allows the temperature and the moisture inside the cockpit to be adjusted and controlled whatever the external weather conditions.

Driving in optimum comfort conditions reduces tiredness and thus improves safety in terms of the attentiveness of the driver; moreover, the introduction of air with a controlled temperature and low moisture content enables rapid demisting of the glasses, improving the visibility conditions during driving, also increasing the active safety of the vehicle in this way.

To pass from the warming group to the air conditioning system, it is necessary to install on the vehicle a refrigeration system to extract the moisture by dehydrating and cooling the treated air.

Refrigeration system

The main components of a refrigeration system, taking part in the thermodynamic cycle of the cooling fluid, are (see Fig. 6.207):

- The evaporator (1);
- the compressor (2);

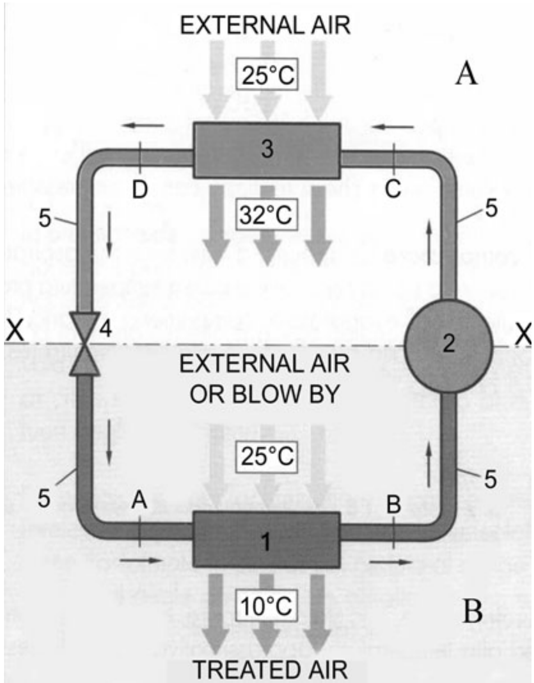

Fig. 6.207. Scheme of the refrigeration cycle indicating the main components. A zone of refrigeration cycle: high pressure, high temperature; zone B of refrigeration cycle: low pressure, low temperature. Reference values: Section A: $p = 2.5$ bar, $t = -4.6°$C; Section B: $p = 2.5$ bar, $t = -4.6°$C; Section C: $p = 20$ bar, $t = 105°$C; Section D: $p = 20$ bar, $t = 52°$C.

- the condenser (3);
- the expansion valve (4);

these components are connected to each other by means of pipes (5).

Refrigeration work cycle

Nowadays the most commonly used refrigeration fluid in the air conditioning systems for vehicles is known as R134a. Until a few years ago a product known as R12, with different names depending on the supplier, which has the chemical formulation CCl_2F_2 (di-chlorine-di fluorine-methane) was usually used. Since this product contains Chlorine (Cl_2) in its molecule, it belongs to a groups of products, the so-called carbide fluorine chlorines (CFC), to which responsibility for the depletion of the Ozone stratosphere layer (O_3), with consequent damage to the ecology of our planet, has been substantially attributed.

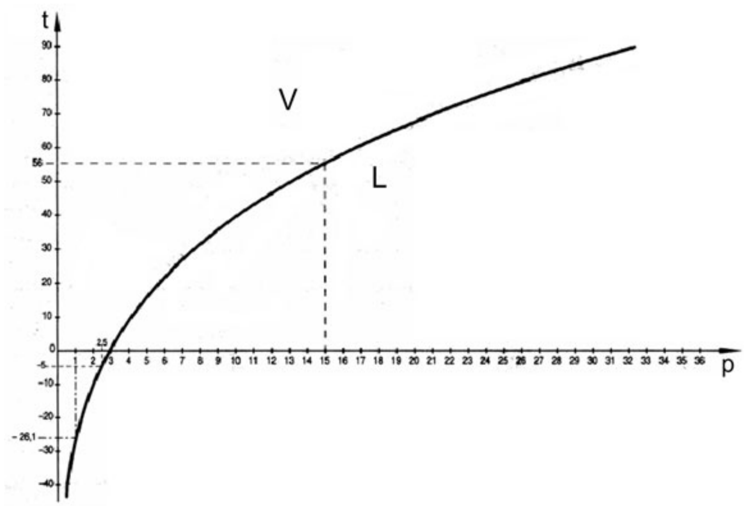

Fig. 6.208. Pressure-temperature chart for R134a cooling fluid. The curve divides the vapor from the liquid zone.

Since today CFCs cannot be used, a number of alternative compounds have been identified which offer similar technical properties but without chlorine content, thus being less dangerous in terms of ozone layer depletion. In particular, to substitute the R12, a substance coded R134a, with chemical formulation is CH_2FCF_3 (1,1,2-tetra ethane fluorine, HFC) has been widely adopted.

However, from 2011, also this refrigeration fluid must be substituted due to its contribution to the greenhouse effect, as discussed subsequently.

Focusing on R134a, it is possible to understand why the properties of this fluid are particularly well suited for refrigeration by examining its key characteristics which include (see Fig. 6.208):

- Low boiling temperature at sea level (1 bar) $-26.1°C$ (for the R12 is $-29.8°C$), facilitating the refrigeration of the hotter air which flows along it;
- high condensation temperature, with pressure around 15 bar, facilitating widespread diffusion of the heat accumulated on the fluid to the outside of the condenser;
- high values of vaporization and condensation latent heat, at different temperatures and pressures, allowing high heat exchange. (The latent heat is the heat which has to be supplied to or extracted from a unit mass of substance to obtain a change of state.)

The relatively low pressure used in the refrigerating cycle enables heat exchangers (condenser and evaporator) with reduced overall mass; the high value of latent heat allows high heat exchange levels per unit mass, this limiting the total mass of the fluid in the circuit with a consequent saving of system cost.

At this point it is appropriate to examine the conditions of the cooling fluid inside the refrigeration cycle with reference to Fig. 6.207, starting from section A.

The first component met by the cooling fluid is the evaporator, which is usually located inside the cockpit. When it is integrated with the heating group, together they become the air conditioning group; in the following, the acronym HVAC (Heating Ventilation Air Conditioning) is used.

Since the evaporator aims to extract the heat from the cockpit, the average temperature of its walls has to be lower than that of the air to be cooled.

To cool the cockpit, it is necessary to work in one of the following two different ways:

- Wash it with fresh air which is forced into the cockpit from the outside through the evaporator; in this way, the hot interior air is pushed out through a dedicated passage;
- suck the interior air, cool it and then return it to the cockpit via the evaporator.

The second way is generally better when the exterior temperature is high because, by recycling the interior air volume, a more rapid decrease of interior air temperature can be obtained.

For this reason, when in such climatic conditions, automatic air conditioning systems start by using recirculated air, whilst in the normal conditions exterior air is used.

The refrigeration fluid receives the heat extracted from the cockpit air through the evaporator, passing from the liquid phase to vapor with the same temperature and pressure. The heat necessary for this change of state, with constant temperature and pressure, is the latent heat.

In section B, at the evaporator exit, the fluid has about the same initial temperature and pressure but has absorbed the heat coming from interior cockpit air or exterior air which will be introduced into the cockpit.

Since the refrigeration cycle is a closed cycle, the refrigeration fluid must have the same characteristics as initially at section A. To do this, it must release heat to the exterior; however the external air has a higher temperature than that of the refrigeration fluid. So, to enable spontaneous heat transfer, the temperature of the fluid has to be increased to become higher than the exterior temperature. This is performed by the compressor which sucks the vapor at the exit pressure from the evaporator, compressing the fluid and discharging it at higher pressure and temperature at section C. The compressor also circulates the fluid around the circuit.

In this condition, the refrigeration fluid can enter in the second heat exchanger of the system: The condenser enables the transfer of both the heat accumulated in the fluid on the evaporator, and the transformation heat of the compressor. In this phase, the pressure of the fluid will be constant while the temperature will be constant only during condensation phase. In fact, usually the fluid entering the condenser is overheated, while at the exit it can be only cooled. Condensation pressure and temperature will be maintained between appropriate values to enable the transformation from vapor to liquid. This transformation is made by transferring the condensation latent heat to the condenser cooling air. The specific aspects of this thermodynamic cycle will be treated again in Volume II.

To return the refrigeration fluid to the conditions of section A, it is necessary to pass it through an expansion device comprising a narrowing channel and a variable or fixed section in order to drastically reduce the pressure and thus the temperature. The result is a bi-phase liquid and vapor mixture with higher proportion of liquid.

In addition to the refrigeration components already illustrated, a dehydrating filter is used. Usually it is located between the condenser and the expansion valve in order to extract any external moisture from the circuit. The presence of liquid (water) inside the compressor, which is not compressible, would cause breakage. The wire filter keeps the work remainder and the external body which can be present inside the system. The filter casing behaves also as an accumulator; this function is necessary to offset the flow variation of refrigeration fluid which takes place in the thermodynamic fluid.

Main components in the refrigeration system

After examining the refrigerating cycle and the system which makes it possible, considering also the refrigeration fluid, it is appropriate to analyze the main components of the refrigeration system which are:

- Evaporator;
- compressor;
- condenser;
- filter;
- expansion valve;
- pipes and connectors.

Evaporator

As already mentioned, the main function of the evaporator is to extract heat from the air pushed into or contained in the cockpit. However, the evaporator has also another very important function which is the dehydration of the air.

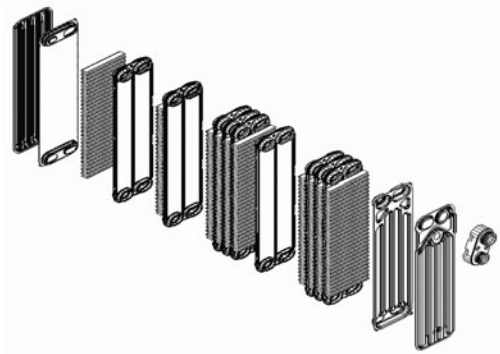

Fig. 6.209. Plates evaporator and fins with deflectors.

In fact when the air goes into contact with the external cold surfaces of the evaporator, it reaches its dew point and release moisture as condensation. The condensed water is gathered in a specific tank and then it is evacuated by purpose made channels.

The heat exchanger performing the evaporator function can comprise:

- Round pipes and flat fins;
- parallel flows;
- plates and fins with deflectors.

The solution with round pipes and fins, as already seen with respect to the radiating mass, was used in the past whereas today has been substituted by plates solution with deflectors.

The plates evaporator is made with an assembly of hollow plates (see Fig. 6.209), made of aluminium, with a U shaped cavity. Inside this cavity the refrigeration fluid flows. This flow is disturbed by a series of interposed obstacles, aimed at improving the thermal exchange.

The fins with deflectors are located between the adjacent plates. They are made by a series of small metal sheets, the shape of which is defined to create a turbulent air-flow. Fig. 6.210 shows an evaporator in this condition enabling low weight and reduced overall dimensions.

Usually the components of the evaporator are assembled in an automatic process and brazed together using vacuum brazing or in a controlled atmosphere.

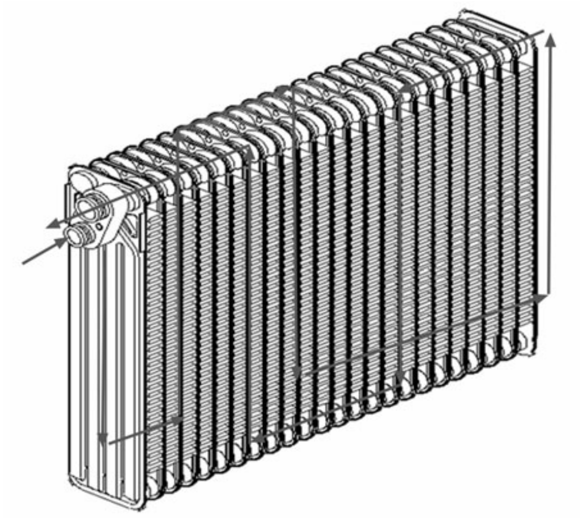

Fig. 6.210. Evaporator with plates and fin, joined by vacuum brazing.

Compressor

The compressor is one of the most important components of the refrigeration cycle, in terms of the performance and reliability of the system and from a cost perspective.

The function of compressor, as has already been mentioned, is:

- To enable the circulation inside the circuit;
- to increase the pressure and thus the temperature of the refrigeration gas leaving the evaporator at low temperature and low pressure.

The main components of the compressor are:

- Housing, integrating a number of components and suitable brackets for installation on the engine;
- internal mechanism to enable fluid compression;
- unidirectional valve system, to enable suction and delivery of the fluid;
- connectors, for the circuit pipes (usually part of the housing);
- pulley and clutch group, to drag the internal mechanism;
- lubricant oil.

The compressor can be classified based on the constructive solution and function principles adopted:

- Power energy types: Dragging with belt transmission from thermal or electric engine;
- internal kinematic mechanism for the compression of the fluid: with axial pistons, rotating blades or spiral blade;
- possibility of displacement adjustment: Fixed displacement, variable displacement with internal or external control.

For the first applications, fixed displacement compressor was applied. Starting from the 1980s, the first compressors with variable displacement appeared on the market.

The primary scope of the variable displacement compressor was to improve the driveability of vehicles, in particular when the air conditioning system is engaged, and during the acceleration.

The fixed displacement compressor can be activated only with a discontinuity (for example with an electromagnetic clutch). For this reason, during engagement, there is a sharp absorption of torque with a consequent influence on the acceleration of the vehicle.

The market growth for the variable displacement compressor has been constant and gradual over time. However penetration has been slowed down by its higher cost, due to the higher number of components required and its greater complexity. This has also involved a low affordability for the first solutions on the market. Nowadays the market presence of variable displacement compressor is about 90%.

Fixed displacement compressors in Europe are present in the lower segment, mainly due to its lower cost, while in emerging countries they are still the most widely used compressor.

In the following only the most widely used compressors for the automotive market will be considered.

Axial reciprocating compressor with fixed displacement

These are compressors with multiple pistons, usually five, seven or ten. The number of pistons is chosen so as to reduce the torque fluctuation due to pressure pulse and inertial force of crank mechanism.

Fig. 6.211 shows a section on the shaft of a typical axial reciprocating compressor with fixed displacement, with single acting pistons is shown.

The reciprocating motion of pistons (4), is driven by a cam made by a plate inclined with respect to the rotation axis. This plate is connected to the drive shaft (1); the plate has a flange with the spherical joint for rods. This flange can rotate respect to the plate and it can change its slope. The slope and thus also the stroke of the piston are defined by the cam. The rotation is avoided by means of fixed tapered gear (5). To allow the relative rotation between cam (2) and flange (3), an axial needle roller bearing is interposed.

On the basic axial reciprocating compressor with fixed displacement but with double acting pistons, important construction variation exist with respect

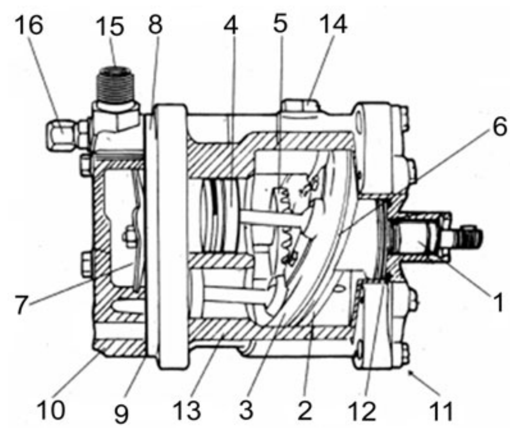

Fig. 6.211. Axial rotating compressor with fixed displacement (wobble type). Components: 1 shaft, 2 cam rotor, 3 rods control flange, 4 piston, 5 drive gear, 6 needle roller bearing, 7 combined suction/exhaust valve, 8 valves plate, 9 head cylinders seal, 10 head cylinders, 11 front cover with drive hub, 12 O-Ring seal gasket with square section for the tight between cover and body, 13 compressor body, 14 oil intake/exhaust cap, 15 nipples, 16 service valve.

to pistons operation. In Fig. 6.212, it is possible to observe that there are no rods used to constrain the pistons. The inclined plate (3) drives the reciprocating motion of pistons (1), only interposing a special slide (2) joined to the pistons with a spherical head. This solution allows consistent increase of maximum flow to be obtained, considering the same overall dimensions for simple effect compressor.

In both typologies of this type of compressor, a series of reed valves are arranged on the head of cylinders group to allow the refrigerant suction and exhaust phase.

Lubrication is made by splashing oil, generated by the rotating bodies. The sealing is made by means of tightness between the bodies inside the compressor. However it is not possible to ensure a complete absence of oil in the refrigerating fluid. Because the presence of oil is not appropriate, it is necessary ensure that the level of oil in the refrigerating fluid remains lower than a predefined value in order to avoid its accumulation in the heat exchangers which reduces their efficiency.

Rotating compressor with blades

The operating scheme of this compressor is shown in Fig. 6.213, also with fixed displacement. Inside the compressor body (1), which has the stator function, a cylindrical chamber is contained. In this chamber the rotor (2) is located. The rotor is a cylinder with a lower diameter than that of interior stator

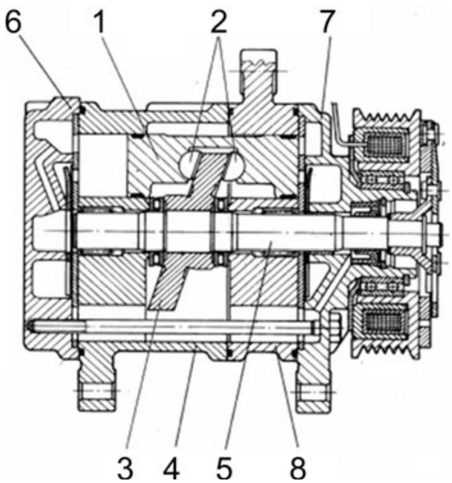

Fig. 6.212. Reciprocating axial compressor with fixed displacement (swash plate), double effect pistons. Components: 1 double acting pistons, 2 slide, 3 inclined plate, 4 rear body cylinders, 5 shaft, 6 rear cap, 7 front cap, 8 front body cylinders.

chamber to be located inside. The rotor and the stator are not coaxial, but the distance between the two axis is equal to the difference between the internal cylinder radius of stator and rotor. A series of grooves to house the blades are obtained in the rotor (3).

During the rotor rotation, the blades move outwards due to centrifugal force, creating a contact strip with the stator cylinder. In this way a series of chambers are created with a cyclical increase and decrease of volume. The increase of volume causes suction of the fluid through specific opening (9), due to the rotation of rotor the sucked fluid is compressed and then expelled through the exhaust opening (5).

Being a possible evolution of the conceptual scheme just described, Fig. 6.214 shows a solution made by a stator with an internal elliptical section and a cylindrical rotor. The diameter of the rotor is equal to the lower ellipse axis, but with a coaxial rotation axis. With this solution, considering the same rotation speed, the pumping frequency is doubled thus providing a further advantage in terms of vibration reduction because the resultant pressure distribution of the rotor is balanced.

The lubricant system of rotating blades compressor (Fig. 6.215), is based on the difference between the intake and exhaust pressure. This pressure difference favours the oil distribution wherever it is required through canalizations which start from oil collection chamber (a) where the pressure is equal to the exhaust one.

The oil is then conveyed to intake and is again sent with the high pressure refrigerant to collection chamber after separating it from refrigerant by means

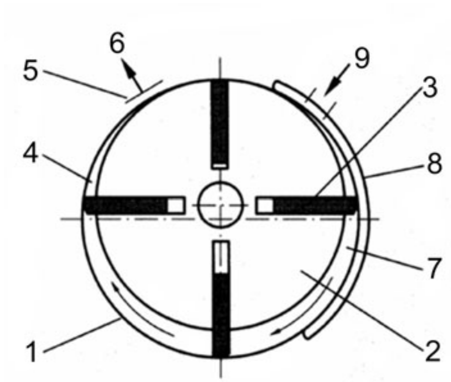

Fig. 6.213. Rotating compressor with blades. Components: 1 body compressor, 2 rotor, 3 blades, 4 high pressure side, 5 exhaust valve, 6 pipe connection, 7 low pressure side, 8 intake valve, 9 pipe connection.

of separator (7). The rotor in the circuit improves also the sealing between the rotor and the heads (d), and between the blades and the stator cylinder (f), with positive effect on the volumetric efficiency.

The oil separator is made using a cyclone, (Fig. 6.216), the oil entering inside it through a tangential canal (c). The oil separator activates an organized vortex. Since the drops of oil have a higher specific weight than the refrigerant fluid when in the gas phase, they are pushed against the exhaust duct due to the centrifugal force. Here, due to gravity, they go down onto the oil interception wire, and then into the lower collection chamber.

This fluid/air separation system was initially adopted only on rotating compressor, but nowadays it has extended also to the variable displacement axial compressor, ensuring a more effective results even though their integration into this type of machine is more complex.

Spiral blade compressor (scroll)

The pumping element of this type of compressor is a rotor and a stator with the same shape both made of a single frontal blade with spiral shape; the blades are in contact along different generating lines. The rotation of one spiral respect to the other one, creates decreasing volumes towards the rotor centre; in Fig. 6.217 it is possible to see the different operation phases.

The advantage of scroll compressor is made by an operation with reduced vibration and by an high volumetric efficiency. On the other hand, the construction of fixed and mobile spiral blades needs special equipment and a very sophisticated system of assembly due to strict dimensional tolerances.

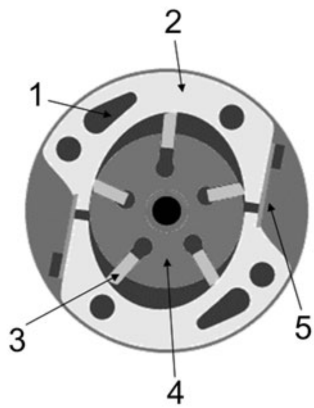

Fig. 6.214. Blades compressor with elliptical internal chamber. Components: 1 manifold, 2 stator, 3 blade, 4 rotor, 5 exhaust valve.

Axial compressor with variable displacement

Although it is possible to make different solutions, nowadays this type of compressor with variable displacement is the only one on the market in the automotive sector.

The fundamental difference of this type of compressor compared to those with fixed displacement, is that the cam has a continuous variable tilt, between a defined angle range. In this way it is possible to change the stroke of pistons and thus the displacement, from a minimum value, which can be also void, (cam or rotating plate tilt angle equal to zero respect to vertical), to a maximum value.

The adjustment of displacement is made using a valve located at the rear head of the compressor and driven by intake pressure (see Fig. 6.218).

The characteristics of this compressor are represented on chart in Fig. 6.219, the curves representing the maximum displacement value; it is possible to note that, as with any volumetric machine, the torque varies only slightly with angular speed, while the power increases significantly.

The reduction of displacement due to a reduction of thermal load on the system determines the displacement reduction, and the initial conditions are again established.

With the table in Fig. 6.220 it is possible to notice that a compressor with variable displacement is very compact with low and overall dimensions weight, even though its construction is complex.

The displacement adjustment valve, shown in Fig. 6.221, is made with a body (1), inside which the sensing and adjustment devices are located. In particular there is an elastic capsule which is sealed and in depression (2) located in a chamber in connection with the compressor intake manifold (D). The construction of the capsule enables the length of this capsule to be varied depending on the exterior pressure variation. There is also a stalk (3) to enable the capsule

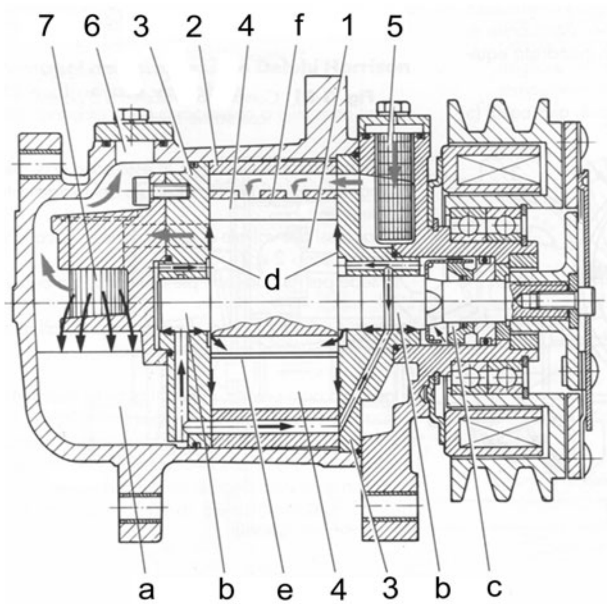

Fig. 6.215. Lubricant system for rotating compressor with blades. Components and parts: (a) oil collection chamber, (b) rotor bearing pins, (c) oil seal, (d) head rotor bearings, (e) blade bases, (f) blades cylinder contact, 1 rotor, 2 stator, 3 heads, 4 blades, 5 refrigerant input connection, 6 refrigerant exit connection, 7 oil separator.

to adjusts the narrowing (X), through the mushroom located on the low part of stalk, and the narrowing (Y), by means of sphere (4), which is opposed by the spring (5).

The calibration of the valve is determined as a function of the average low pressure value which enables the efficiency of the system to be optimized. For most systems, the average reference value for the low pressure chosen for the valve calibration is 1.5÷2 bar (150÷200 kPa) of relative pressure.

The compressor displacement, as has already been seen, is determined by the stroke of pistons; this stroke is constrained by the cam tilt of the inclined plate. It depends on the result from the sending pressure effect on head pistons, and by the opposite effect made by the compressor carter pressure on the bottom of pistons (see Fig. 6.221). The pressure inside the carter is adjusted by adjusting valve as a function of suction pressure.

Referring to Fig. 6.222, if the exit pressure of the evaporator and consequently the suction pressure of the compressor increases above the calibration point of the valve, the capsule (2) becomes shorter, the stalk (3) goes down, the narrowing (Y) closes and the narrowing (X) becomes larger; in this condition, the compressor displacement is not sufficient. As a consequence of this

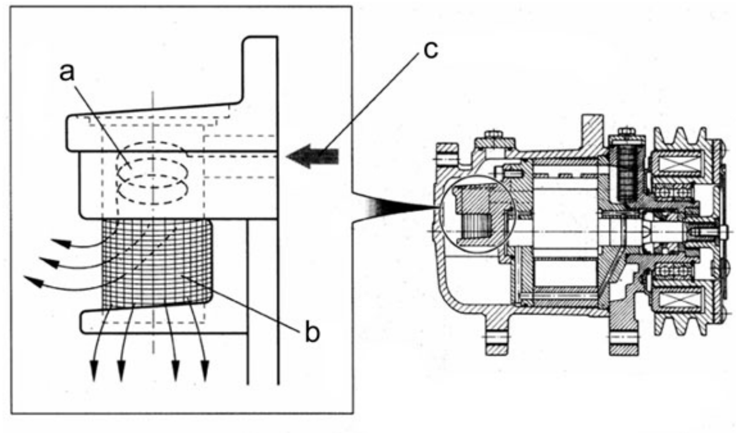

Fig. 6.216. Oil separator, indicating: (a) oil and refrigerant exhaust duct, (b) oil interception wire, (c) refrigerant exhaust.

adjustment, the pressure in the carter becomes equal to the suction pressure; in this condition, the difference between the sending pressure and that in carter reaches its peak, consequently the tilt of cam increases and thus also the displacement and the yield of system.

If the pressure at the exit of evaporator, and thus at suction of the compressor, decreases (excessive compressor displacement), the length of the capsule increases, the stalk is pushed up, the narrowing (X) decreases until closing, the narrowing (Y) opens, the carter pressure increases, the angle of inclined plate decreases and thus also the compressor displacement decreases, as shown in Fig. 6.223.

The main advantage due to continuous and adjusted operation is: Elimination of rough variations of resistance torque.

In addition, improved performance of the system can be obtained as a consequence of the elimination of oscillations of the treated air (e.g. temperature).

Variable displacement compressor with external control

The compressor just described can be defined a variable displacement compressor with internal control because the displacement variation is managed by the refrigerant fluid pressure inside the refrigerating circuit.

In other variable displacement compressors, the adjustment is made using an electro-valve, which is managed by an electronic control unit outside the compressor. The advantages of this control relate to the possibility to operate on the displacement adjustment, with an higher number of vehicle system parameters and thus not being tied to the circuit pressure.

An obvious result is the possibility to set to zero the displacement when the accelerator is pushed to the bottom enabling a reduction in the performance of

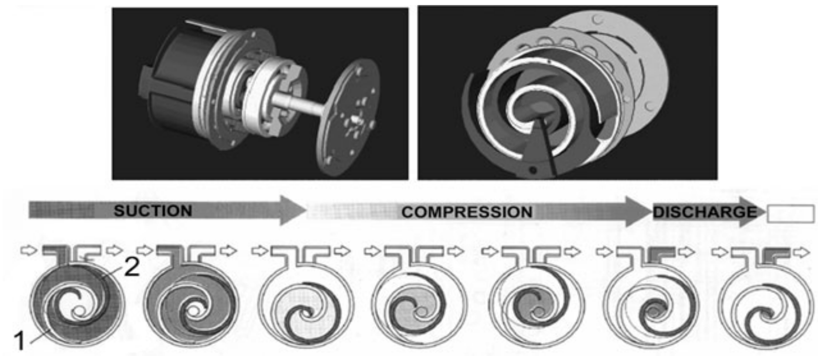

Fig. 6.217. Spiral blade compressor (scroll). Fixed spiral 1, orbiting spiral 2.

a vehicle during overtaking to be avoided. Many other possible applications also exist.

The extension of integrated electronic systems, also considering the advantages mentioned before, is leading to increasing growth in the use of this type of compressors. Nowadays in Europe the 50% of variable displacement compressors have external control.

Electric compressor

A recent tendency concerning automotive compressors is electric operation.

This solution allows to separate the compressor velocity from that of the thermal engine; in fact they are not always compatible with each other (for example when a very hot car is in slow traffic with the engine close to idle). Moreover the compressor can work always in the best conditions and activate the air conditioning system both when the thermal engine is switch-off, although not for an excessive long time. It is also possible to use a timer with a remote control.

One current limit to the extension of this system is the supply voltage that is between 120 and 400 V, not simply available today on cars with thermal engine.

Compressor clutch

This component is treated separately from the compressor although now can be considered to be integrated with it.

The transmission of motion, from thermal engine to the compressor, is made via a belt and pulley system (multiple V type). The driving pulley transmits the motion to the compressor by means of a friction clutch with an electromagnetic actuator (see Fig. 6.224).

When the spool (3) is not excited, there is no contact between the drag group (1), which is fixed to compressor shaft (8), and the pulley (2) which is

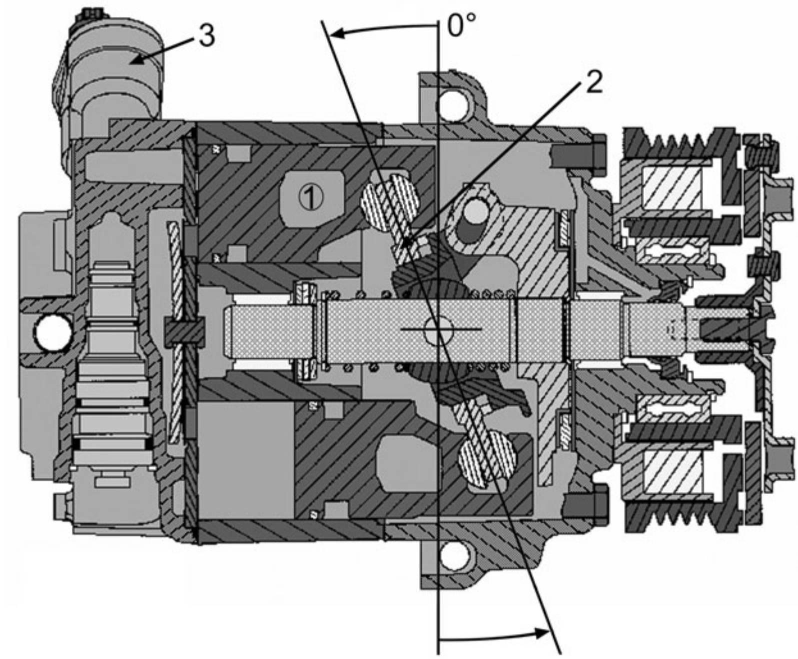

Fig. 6.218. Axial rotating compressor with variable displacement. Parts: piston 1, cam 2, valve 3.

always dragged by the thermal engine; it turns neutral on bearing (4) and thus the compressor does not work.

When the spool is excited, an electromagnetic field is created, creating an attraction force on the drag plate, (a) in Fig. 6.225: The drag leafs (b) are bent and the plate goes in contact with the pulley, thus creating a unique body.

The plate dragged in rotation by the pulley, by means of spring (b), transmits the motion to hub (c). It is mounted on the compressor shaft so it causes the compressor to operate.

When the system is activated, the clutch engagement and disengagement are determined by control and adjustment devices of the refrigeration circuit, such as the anti ice thermostat on the evaporator or pressure switches.

For systems that use a variable displacement compressor, usually the anti ice sensor is not mounted, because the adjustment is managed by the valve of the compressor displacement.

It this way the electric clutch is usually engaged only when the system is activated and otherwise is disengaged. Maximum and minimum protections can also operate on this function.

The growth in the use of the variable displacement compressor has led to the reduction in the use of the electromagnetic clutch. Today the pulley is always

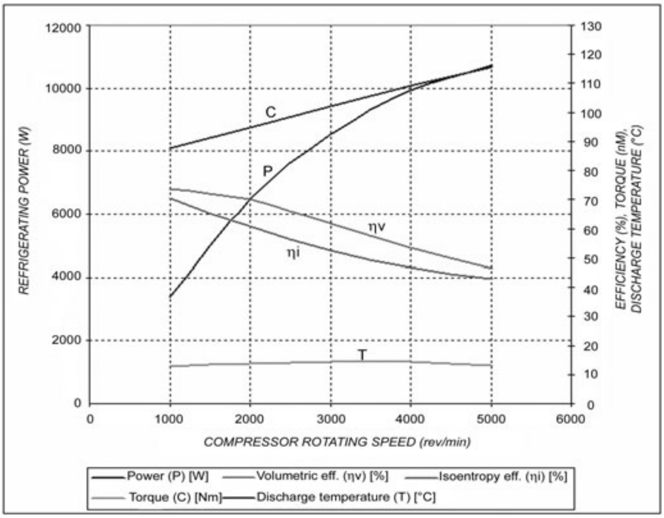

Fig. 6.219. Characteristic curves for the axial compressor with variable displacement.

engaged. In this way it is possible to reduce the torque impulse due to the compressor, and the weight is reduced of about 20%.

Nowadays, the need to reduced CO_2 emissions has led some manufacturers to consider again the use of the electromagnetic clutch, because the continuous rotation of compressor, also when idling, results in additional fuel consumption.

Condenser

The condenser, as already mentioned, is an exchanger used to extract from the evaporator the heat absorbed in the compression phase by the refrigerant fluid, where warmed gases are created.

The types of condenser usually used are:

- Round pipes and flat fins;
- parallel flow.

The solution made by pipes and fins, used in the past, as has already been seen for the other two heat exchangers, has been substituted by the parallel flow solution, for the reasons already illustrated. The most widely used assembly technology is brazing in controlled environment.

An important evolution of the condenser was made at the end of the last century, with the integration of the accumulator and filter. Consequently the layout of refrigerant plate was simplified, costs were reduced, and system efficiency increased thanks to higher under cooling that can be obtained with this solution.

Parameters				
TYPE:	6 pistons, plate mechanism, continuos variation of displacement	6 pistons, plate mechanism, continuos variation of displacement	7 pistons, plate mechanism, continuos variation of displacement	7 pistons, plate mechanism, continuos variation of displacement
LENGTH:	195 mm	195 mm	206 mm	206 mm
DIAMETER:	114 mm	114 mm	124 mm	129 mm
DISPLACEMENT (CC):	7 - 125	7 - 135	6 - 165	7 - 185
DRY WEIGHT:	5,2 kg	5,2 kg	6 kg	6,3 kg
POWER (2000 rev/min):	6.040 W	6.520 W	8.200 W	9.300 W
WORK SPEED				
CONTINUOS MAXIMUM:	8.000 rev/min	8.000 rev/min	8.000 rev/min	8.000 rev/min
TRANSITIONING:	9.200 rev/min	9.200 rev/min	9.200 rev/min	9.200 rev/min

Fig. 6.220. Typical parameters for some axial compressor with variable displacement. The power shown in the table is the refrigerating power and not the absorbed mechanical power.

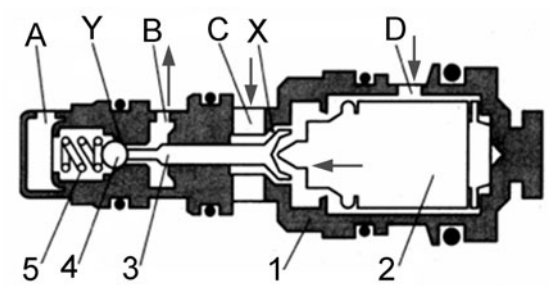

Fig. 6.221. Displacement adjusting valve for axial compressor. Components: 1 body valve, 2 elastic capsule (with bellows), 3 stalk, 4 sphere, 5 spring. A connection with sending manifold (HP), B exit to interior carter, C return to carter, D connection with intake manifold (LP), X narrowing carter/low pressure, Y narrowing carter/high pressure.

In most installations, the condenser is located in the front part of vehicle, immediately before the radiator for engine refrigerating fluid. This solution allows the condenser to exploit the maximum external air-flow, which is created when the vehicle moves, in particular at high speed. When the speed of vehicle is low (under 30 km/h), the dynamic air-flow is also limited. In this case the passage of air through condenser is ensured by an electric fan.

The position of condenser, compared to radiator, causes a reduction of radiator efficiency, because the input air of radiator, after crossing the condenser, has a temperature higher of about 5÷10°C than ambient.

Expansion valve

The functions of expansion and adjustment valve are:

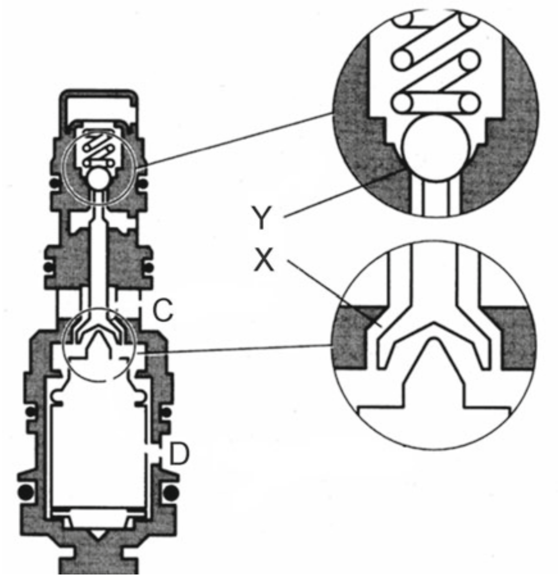

Fig. 6.222. Details of displacement adjustment valve. In evidence the flow A from carter, the flow B to suck (L.P.) and the details of X carter/low pressure narrowing and Y carter high/pressure narrowing.

- Drastic reduction of pressure and, consequently, of liquid refrigerant temperature coming from condenser;
- generation of a bi-phase mixture at the evaporator entrance with low temperature and pressure;
- continuous adjustment of refrigerant flow at the evaporator; in this way, at the different load thermal condition, it may completely evaporate reaching a sufficient degree of overheating, to ensure only refrigerant at gaseous state at the entry to the compressor.

The expansion valve typologies are:

- L valve
- block or H valve;
- orifice tube.

L expansion valve

This valve is shown in Fig. 6.226 comprising a body (1), with the entry (2) and exit (3) connection for refrigerant; the narrowing is made with a hole (4), after which there is expansion and atomizing of the liquid refrigerant. In the

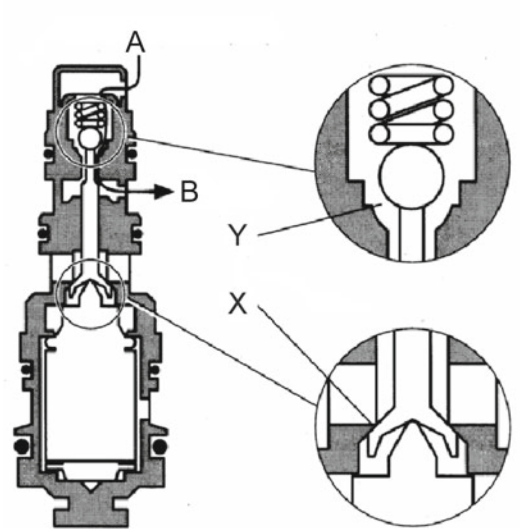

Fig. 6.223. Detail of the displacement adjustment valve: A: outlet to the compressor (H.P.); B: outlet to the carter; X: high pressure narrowing; Y: low pressure narrowing.

body there is also the adjustment valve for refrigerating fluid, it is made by a diaphragm (7) located in a capsule (6), joined to thermometric sensor. This last one is made by a copper capillary (8), at the end there is a spiral (9a) or a case (9b); this part should be placed where it is possible to measure the temperature.

Inside the capsule, the capillary and the thermostatic sensor there is a fluid with the same characteristic of the refrigerant used in the system. The adjustment of refrigerant fluid, through the valve, is made thank to the mixer (5). A spring and the connection pins act on this part (11); in fact the pressure variation measured by diaphragm operates on these parts.

This valve is inserted in the system as shown in the scheme of Fig. 6.227 and is termed expansion valve with internal equalization.

The valve shown in Fig. 6.228, differs from the previous one in that it has a capillary tube (a) with a connection which allows to transfer at the basis of the diaphragm the pressure at the entry of the evaporator. It takes the name of expansion valve with external equalization; the position of valve inside the system in Fig. 6.229 is shown.

Regardless of the valve typologies, the operation is as follows: The valve tends to close the passage in the calibrated hole, when the fluid degree of overheating is less than a predefined value.

When the degree of overheating exceeds this value, the thermostatic sensor, located at the exit of evaporator, sees the higher temperature. The pressure

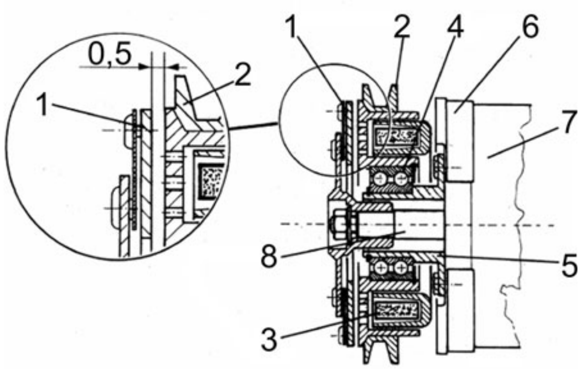

Fig. 6.224. Friction clutch with electromagnetic actuator. Components: 1 drag plate group, 2 pulley, 3 spool, 4 bearing, 5 pulley rest hub, 6 compressor head, 7 compressor body, 8 compressor shaft.

inside the sensor-capillary-capsule system increases, acting with a force F_{ps} on the diaphragm that deforms itself inward the expansion valve. Through the connection pins it opens the adjustment valve, which is contrasted by the F_m force, acted by the spring and by the F_{pr} force, determined by the refrigerant pressure downstream the narrowing (and thus at the entry of evaporator), and transmitted at the basis of diaphragm through internal equalization canal (10) in Fig. 6.226.

The force equilibrium is shown in Fig. 6.230.

Starting from the different equilibrium conditions between F_{ps} and (F_m+F_{pr}) forces, it is possible to determine the opening of the adjusting valve and thus the optimum entity of fluid flow through the evaporator.

In other words, the valve adjusts the flow as a function of the overheating degree of vapor at the exit of evaporator. If the overheating is higher than a reference value, it is necessary to increase the refrigerating flow, thus the valve opens itself. In this condition, in fact, the F_{ps} terms is predominant on terms sum $(F_m + F_{pr})$.

Block expansion valve

This valve is shown in Fig. 6.231, and is made by a body with parallelogram shape. In this part connections link the orifice for atomization and expansion of refrigerant, the pipes for the flow of refrigerating fluid, and the housing for the adjustment valve and thermostatic sensor.

The design of the valve allows two crossings for the refrigerant, the first made by the refrigerant coming from condenser to evaporator, after crossing the narrowing (9) and the flow adjustment valve (10).

The second crossing is made by the refrigerant coming from the evaporator towards the compressor passing the thermostatic sensor (8) on its route. Then it acts on the basis of diaphragm, like the previous valve with external

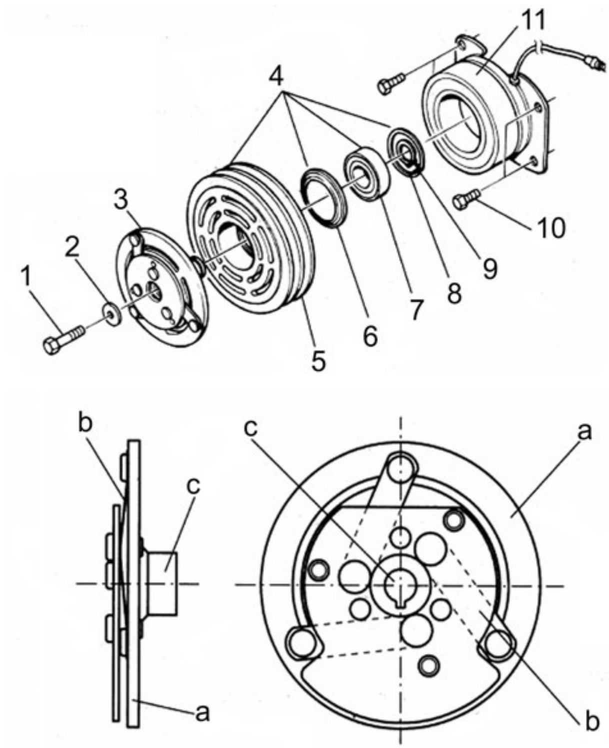

Fig. 6.225. Detail of spool – pulley group: 1 fastening bolt for frontal plate, 2 plate washer, 3 drag group, 4 complete pulley, 5 pulley, 6 dust wall, 7 bearing, 8,9 stop rings, 10 fastening screw for magnetic spool, 11 magnetic spool, a plate, b spring, c hub.

equalization. The second passage has the further connection function in order to obtain external equalization of the L valve, in Fig. 6.229.

The use of this expansion valve type, in order to optimize the system layout, needs an evaporator with the two entry and exiting connections put side by side as shown in Fig. 6.232.

From this description it is evident that a block expansion valve enables the same performance of a L valve to be obtained with external equalization but with a simpler and cheaper layout (having one less tube).

To obtain correct operation and thus excellent system efficiency, using the two valves just explained, the exact positioning of the thermostatic sensor is very important, which has to be nearest the exiting connection from the heat exchanger with evaporator function.

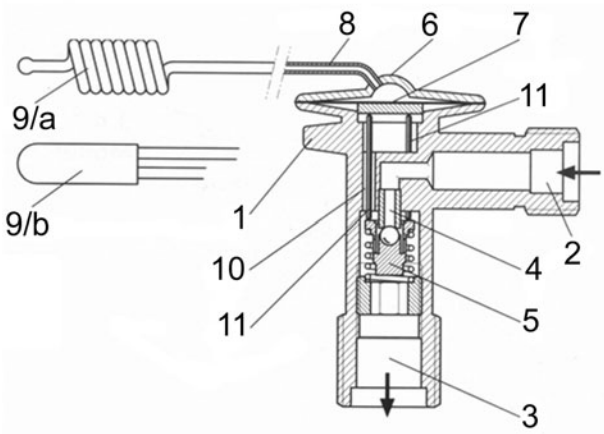

Fig. 6.226. L expansion valve, components: 1 valve body, 2 entry refrigerant connection, 3 exit refrigerant connection, 4 calibrated hole, 5 adjustment valve group, 6 capsule, 7 diaphragm, 8 capillary, 9/a spiral thermostatic sensor, 9/b case thermostatic sensor, 10 internal equalization canal, 11 connection pins between diaphragm and valve.

Evidently, the contact zones between sensor and tube need to be perfectly clear, and have to be ensured by a mutual locking system. They have to be also thermally isolated in order to limit the influence of temperature of the surrounding environment.

The expansion valve has to be located nearest the evaporator to avoid useless cooling, with a consequently reduction of system efficiency and possible creation of condensation.

Orifice tube

With this device the refrigerant fluid expansion is obtained by means of a narrowing made of a small pipe with calibrated diameter (orifice tube), while in the solution examined up to now the narrowing is a part of an automatic adjustment valve. This orifice tube is located in the high pressure pipes sector near the exit of the refrigerant from the condenser.

This type of system has a peculiarity: In fact the filter is not located downstream of the condenser but instead in the low pressure part of circuit, between the evaporator and the compressor, as shown in Fig. 6.233.

This is because the orifice tube cannot ensure that at the exit of the evaporator there is no fluid in the liquid state. For this reason, it is necessary to place the dehydrating filter after the evaporator and before the compressor.

The expansion pipe group appears as a cylinder case (Fig. 6.234), usually in plastic. Inside this case is located the orifice tube (1); this calibrated tube is protected upstream and downstream by wire filters (2 and 3) in order to intercept solid particles that can be dragged by the refrigerant since the diameter of orifice tube is smaller than that of adjustment valve.

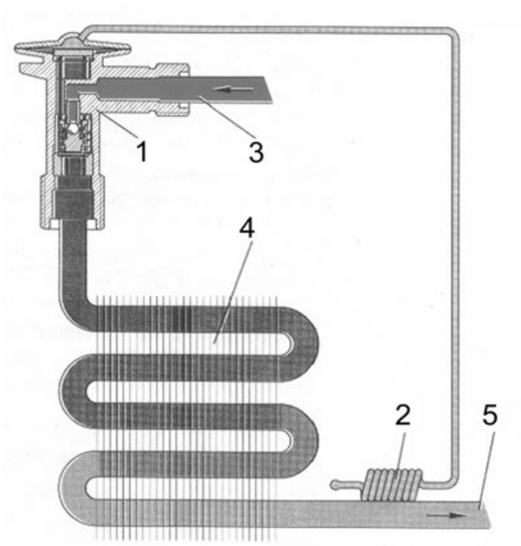

Fig. 6.227. L valve inside the system.

The calibrated tube is the narrowing which determines the drop in pressure and thus the refrigerant temperature at the entry of the evaporator. The work scheme of orifice tube, which works as a flow adjustment, is shown in Figs 6.235 and 6.236 .

Crossing the calibrated tube, the refrigerant undergoes a progressive pressure reduction. When the pressure decreases under the saturation value, part of refrigerant evaporates and a series of bubbles are generated (boiling point). Downstream of the boiling point, the mixture of liquid and vapor determines a flow resistance. This increases with the length of tube which has to be passed by the mixture.

As a consequence, also the refrigerating flow is reduced until an equilibrium condition is reached.

The resistance of the calibrated pipe changes, as has already been seen, as a function of the boiling point. Also this depends on the under cooling degree of the entry refrigerant:

- Low under cooling (exceeding refrigerant fluid flow; point 3'); the position of the boiling point is near to the entry of thee tube; high flow resistance; refrigerant flow reduced;
- high under cooling (insufficient refrigerant fluid flow; point 3"); the position of the boiling point is near the exit of the tube; low flow resistance; increasing of refrigerant flow.

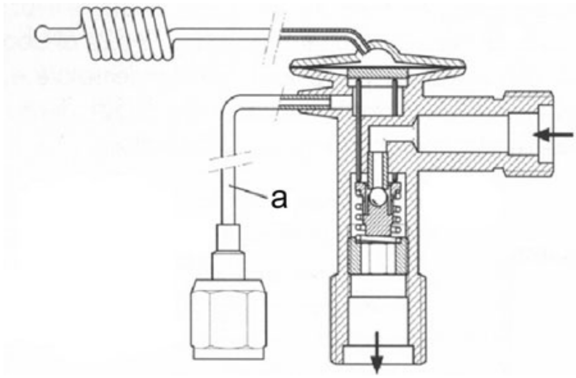

Fig. 6.228. L valve with the tube directly connected with internal pressure of the circuit, in evidence the external equalization tube (a).

The refrigerant exits from expansion tube as a mixture of liquid and vapor, at low pressure and low temperature, and in these conditions it enters the evaporator, (Fig. 6.236).

The ratio between liquid and vapor is approximately:

- Liquid; 70% in weight, 4% in volume;
- vapor, 30% in weight, 96% in volume.

The orifice tube devices appeared at the end of the 1980s. The main reason for their use is the cost, which is about ten times lower than expansion devices with adjustment valves.

Contrasting this cost advantage, the limited diffusion of air conditioning systems with orifice tube is due to:

- High number of cycle (switch-on/switch-off) for fixed displacement compressor (even three times more than a valve system);
- good adjustment of the system at high temperatures and bad adjustment at low temperatures;
- noise;
- more complex lay-out due to the dimensions of the filter, which is necessary for the operation of the system;
- it is not possible to integrate the components with each other, causing an increase of costs of other parts.

For these reasons, less than 20% of systems use the orifice tube; instead the block expansion valve is the most widely used because, as already seen in the installation scheme, it offers the simplest layout and better performance.

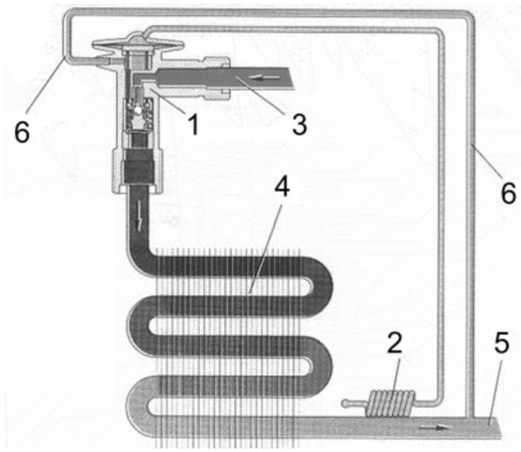

Fig. 6.229. Work scheme for the expansion valve with external equalization. Parts in evidence: 1 expansion valve, 2 thermostatic sensor, 3 pipes from condenser, 4 evaporator, 5 pipe to compressor, 6 external equalization.

Filter

The state transformation of refrigerant and the heat exchange are not influenced by this component.

Its functions are:

- Solid particles interception dragged by the refrigerant fluid and by the compressor oil; this function is aimed at protecting the compressor and avoiding blockage of the expansion valve;
- moisture absorption that can be contained in the refrigerating fluid, in the oil, or at the entry of the circuit in order to avoid the possible creation of corrosive acids or ice;
- accumulation or transfer of the refrigeration fluid, depending on the needs of the system.

The filter is located between the condenser and the expansion valve and can be a single component or integrated with the condenser, except if the expansion valve is an orifice tube.

This component, shown in Fig. 6.237, is made of a metallic body cylinder. On the body there are two entry and exit connections for the refrigerant, and the attachment for the service valve. Inside the housing, there is a dehydrating filter package made of a thick of hygroscopic material, put between two layers of filter material (usually glass fibre), contained between two holed plates.

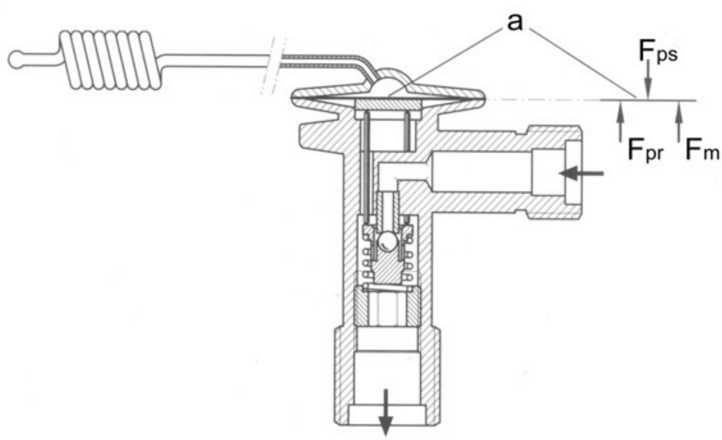

Fig. 6.230. a: diaphgram, F_{ps} pressure force of thermostatic sensor, F_m spring force, F_{pr} refrigerant pressure force, from internal equalization.

The hygroscopic material typically used in this type of application is synthetic zeolite because it has good chemical compatibility with the refrigerant and the compressor oil.

The accumulation function is needed when the compressor intake is higher than the exhaust allowed by the expansion valve. The accumulation is allowed by the free volume in the upper part of tank. If the expansion valve flow is higher than that supplied by the compressor, the exceeded volume in the filter, with respect to the calibration conditions, enables continuous feeding to the valve. In this way it contributes to dampen the pressure impulse made by the pump action of the compressor.

Pipes and connections

The connections between the different components of the system are made using pipes. They are always made by both stiff and flexible parts, necessary to avoid the transmission of vibration coming from engine and to limit the refrigeration fluid noise towards the cockpit.

The most used materials for stiff pipes are Fe360 and 3003 and 3013 aluminium alloys (alloys made by Al, Mn, and Cu).

The flexible pipes are made usually with synthetic rubber, reinforced with textile fabric layers having a defined pattern. The fundamental problem of flexible pipes is the porosity of elastomers. This porosity is one cause of the possible moisture penetration to the tube.

Due to the porosity of non-metallic pipes and connections, emissions from the air conditioning system to the external environment are possible. In the past, the main problem here was to restore the optimum circuit charge. Today an additional problem will be regulation which in the near future will stipulate

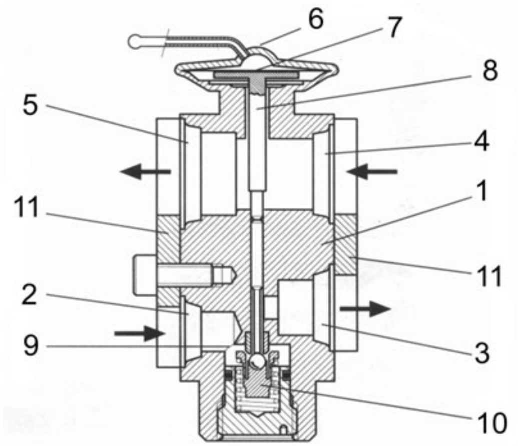

Fig. 6.231. Block expansion valve, components: 1 expansion valve body, 2 refrigerating entry connection (from filter), 3 refrigerant exit connection (to evaporator entry), 4 entry connection (from the evaporator exit), 5 exit connection (to compressor), 6 diaphragm capsule, 7 diaphragm, 8 thermostatic sensor, 9 narrowing, 10 adjustment valve group, 11 fastening flanges for pipes.

emission limits for refrigerant gases from the air conditioning system. Respecting these limits (40÷60 g/years for systems with single or double evaporator) is an homologative constrain for new models starting 2009. Moreover the new rules prescribe also the elimination of R134a, which will be substituted by low greenhouse effect refrigerants starting from 2011.

For these reasons solutions with additional barriers (multi layer) are preferred, and include:

- Veneer type; inside the pipe there is an additional polyamide layer (nylon) that, due to its high density, works as a barrier for possible blow by of refrigerant fluid; due to their stiffness, these pipes cannot have a very small fillet radius without pre shaping;
- barrier type, with two rubber layers and an intermediate polyamide layer, (Fig. 6.238).

These solutions are clearly more expensive but enable an improvement in terms of emissions and offer higher abrasion resistance.

The external diameter of stiff pipes can change from 8 to 15 mm with thicknesses in the range of 1 millimeters for both Fe360 and aluminium alloys. For flexible pipes the internal diameter is the same as the stiff ones, for the external diameters they can be slightly higher.

On the external part of flexible pipe, often there is a sheath for thermal protection, to avoid damages to the lower layers due to the proximity to high

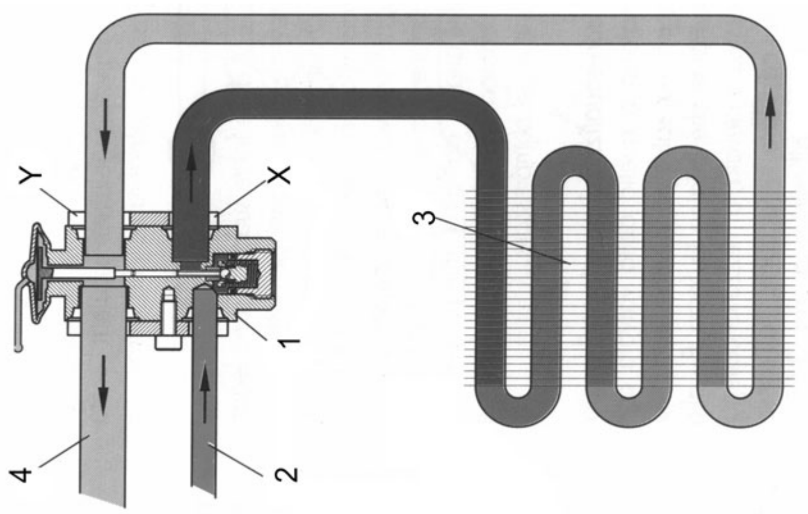

Fig. 6.232. Work scheme for the block expansion valve; in particular: 1 expansion valve, 2 pipes from condenser, 3 evaporator, 4 pipes from compressor, X evaporator entry connection, Y evaporator exit connection.

temperature components in the engine compartment. The flexible tubes, used on circuits where the R134a is used as refrigerant, have to work in a temperature range of between 120°C and −40°C.

The pipes used to connect the components subject to vibrations, such as the compressor, have to be made with flexible tubes. The length of the tubes necessary to avoid the vibration transmission is about 300 mm.

Two different types of connection for pipes are used: The first is quick clutch; the second one is made by rolls flanges connected by nuts. The attachments for stiff pipes are made by flanges brazed at the end of the pipes. The tightness is ensured by a interposed O-ring; the Fig. 6.239 shows an example of connection used to join a flexible pipes with a stiff ones.

Service valve and various devices

The service valves are automatic valves used to upload or download the circuit and to control pressure with special diagnostic equipment. These are pin valves, conceptually similar to valve used to inflate tires, as shown in Fig. 6.240.

The main control and adjusting devices, necessary to manage the work and the safety of the system are:

- Switch;
- anti frost thermostat.

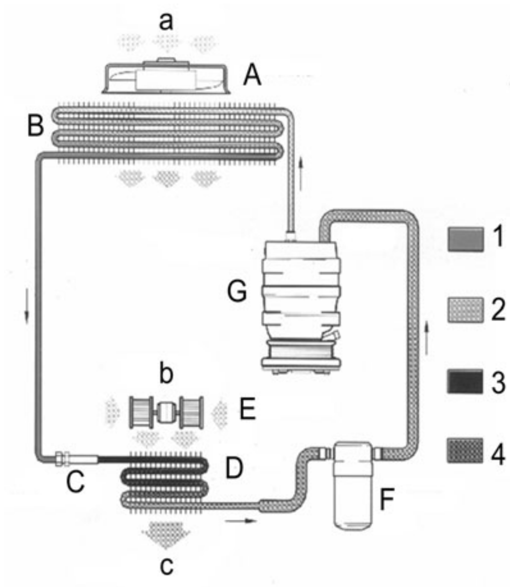

Fig. 6.233. Air conditioning system scheme using orifice tube expansion valve. 1 high pressure – liquid, 2 high pressure – vapour, 3 low pressure – liquid, 4 low pressure – vapour, a external air, b external air and/or blow by, c treated air (to cockpit). A electro fan, B condenser, C expansion tube (OT), D evaporator, E electro fan, F filter, G compressor.

The switch is an electric device to manage the anomalous operations of refrigeration.

Today the thermostat is an electronic device working on the electromagnetic clutch connecting or disconnecting the fixed displacement compressor, according of the temperature of the evaporator or of the air at the exit of the evaporator comparing this value to the calibration one.

From heating to air conditioning

After examining the refrigeration system and its components, now the integration of the heating system with the refrigeration can be examined.

Beforehand, however, it is necessary to consider the air conditioning system for vehicles.

An example of one of the first air conditioning is shown in Fig. 6.241 made integrating an evaporator (1), and electric fan (2). Both these parts are placed in a housing (3). The air is sucked through the ducts, cooled and dehydrated by the evaporator, and then sent to the air ducts (5).

Everything is managed by controls (4) which allow to plug or unplug the compressor and control the electric fan speed.

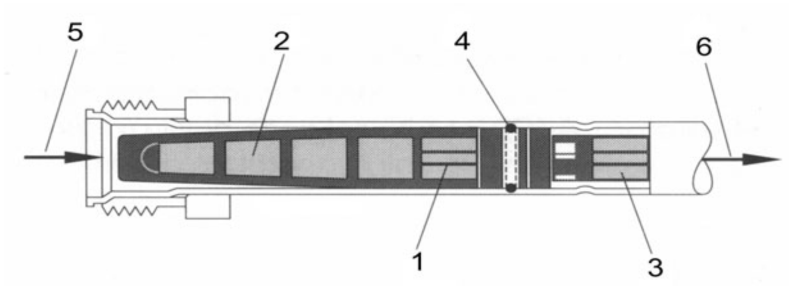

Fig. 6.234. Expansion tube group: 1 expansion tube, 2 entry filter, 3 exit filter, 4 o-ring, 5 entry (from condenser), 6 exit (to evaporator).

Another example is that shown in Fig. 6.242. The semi integrated group is located between the instrument panel and the firewall near a modified heater. In this example, however, an independent and additional electric fan is used in addition to that of heating system.

Now, if the evaporator is placed in the air circuit, upstream of the heater, as in Fig. 6.243, obtained is what is now defined as air conditioning system, i.e. an apparatus where a cooling and a dehydrating elements are placed in series in the air circuit.

These two functions can be activated simultaneously or separately. In this way they allow to obtain the desired climatic conditions inside the cockpit regardless of the external conditions.

Fig. 6.244 shows the section of a conditioning group, in which the heat exchangers for both air cooling and heating are highlighted. The casing includes also a drain for condensation water that is created on the outside walls of the evaporator. The particle filter, which will be illustrated subsequently, needs replacement periodically. For this reason, an easily accessible location must be identified during design.

Sometimes, a PTC (Positive Temperature Coefficient) element is placed in series with the evaporator and the radiating mass. It is an electrical warming element, made essentially with ceramic material which warms up until reaching a defined temperature, and shuts down automatically when the radiating mass reaches the expected temperature.

Indeed, when the temperature of air which flows through the ceramic element increases, the electric resistance of the ceramic increases, and thus the current passage decreases to zero when the specified temperature is reached. The maximum operating conditions are reached when the radiating mass is cold, providing heat that otherwise cannot be supplied by the heater.

One advantage of this device is a reduction of the warm up time for the cockpit, a condition which is greatly appreciated in particular when the

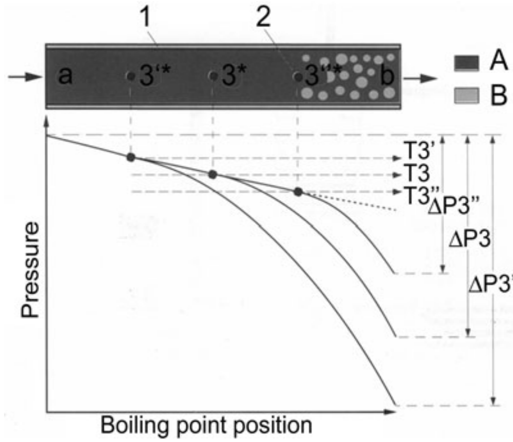

Fig. 6.235. Work scheme of an orifice tube: a refrigerating liquid, b refrigerating liquid + vapor, 1 expansion tube, 2 boil point, 3*,3'*,3"* boil point with different under cooling DP3, DP3',DP3", pressure drops of liquid in the expansion tube with different under cooling, A liquid, B vapor.

external whether conditions are very cold. Is also facilitates rapid defrosting of the windscreen and side front glasses (Figs. 6.245 and 6.246).

The evolution of the air conditioning system has lead to the introduction of automatic air conditioning systems classified as follows:

- The semi automatic system, where the temperature and the air speed are controlled;
- the fully automatic system, where not only the temperature and the air-flow but also the air distribution and, in some cases, the recirculation are controlled.

All vents displacements are generated by electric actuators receiving input from the electronic control unit that processes the signals coming from sensors appropriately located in the car, including:

- Sensor to detect the solar radiation; there may be several units when, for example, there is bi-zone air conditioning;
- external temperature sensor;
- internal temperature sensor, also in this case there may be more units;
- temperature sensor for the air at the exit of HVAC group;
- air quality sensor; to insert the blow by.

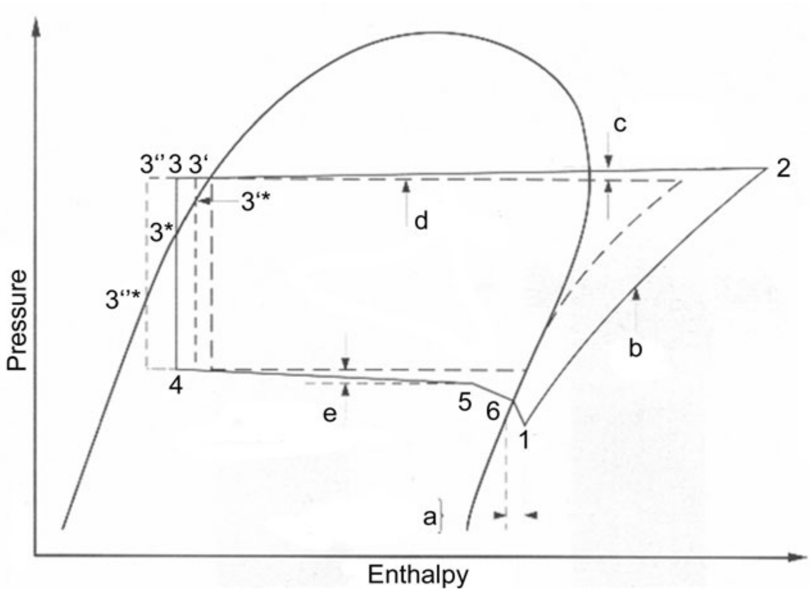

Fig. 6.236. 3,3',3" start of expansion with different under cooling, 3*,3'*,3"*, boil point with different under cooling, 1-2 compressor, 2-3 condenser, 3-4 expansion calibrate tube (OT), 4-5 evaporator, 5-6 accumulator/dehydrating, 6-1 suck tube (from A/D and compressor).

Today, the mechanical controls, usually applied to the heater, have practically disappeared, having been substituted with electrical controls.

6.6.4 Air Distribution in the Cockpit

Having examined the way in which the air is taken from the exterior and how it is treated, it is now appropriate to consider how this air is introduced inside the cockpit by means of ducts and vents.

Beforehand, however, it is necessary to address briefly an issue of great importance for the vehicle occupants: The quality of the air introduced into the cockpit.

Air quality

Today it is possible to use filtration systems that can decrease the gaseous (smells) and solid pollutant. The use of anti smell filters is conditioned by their efficiency and relatively short life.

Some examples of filters with active carbons are available, but they have quite large dimensions and are used only for particular applications.

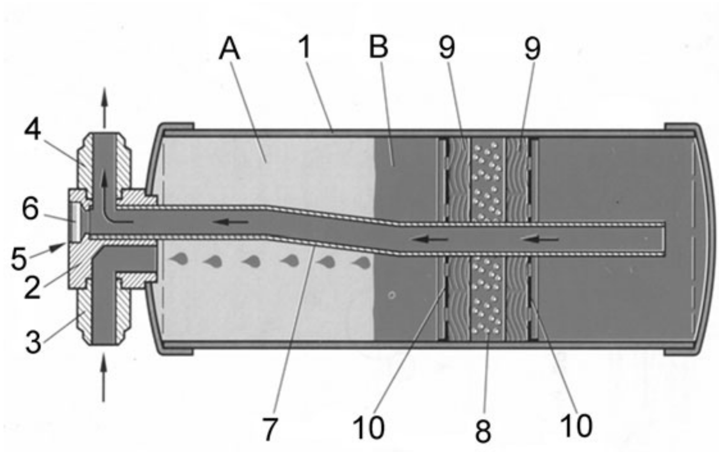

Fig. 6.237. Accumulator, dehydrating filter: 1 housing, 2 connection block, 3 entry connection, 4 exit connection, 5 service valve (it is not visible), 6 warning light glass, 7 draw pipes, 8 hygroscopic material, 9 micro filter, 10 hole plate, A vapor, B liquid.

In different applications other than automobiles, new technologies, such as ionization, electrostatic cleaning and modular filtration, have been developed: These technologies may also find application in the automotive sector in the future.

The filtration of solid particles is made by means of filters made by non-woven fabric or by particular types of paper; these filters have a panel shape, where the filtrating surface is crimped to increase its dimension.

These panels allow a good air depuration over an acceptable lifetime (more than 15,000 km).

The position of vents and intake ducts, taking air from the air conditioning system, largely determines the correct air distribution inside the cockpit.

Due to the small space between the instrument panel and the firewall, the intake ducts, air vents and the other numerous connections to the cockpit (Fig. 6.247) often have a highly twisted shape. For this reason the air-flow tends to accelerate and decelerate.

It is therefore necessary to pay considerable attention to limit speed gradient, usually near sudden variations in the section, which can cause vortices that determine anomalous pressure loss and thus flow rate reductions. From this perspective, not to be neglected is the noise associated with turbulent motion inside ducts.

The main issues of the design requirements in this field are: The definition of the air-flow that the ducts have to ensure; regular flows distribution at the different exits, for example between the left and right side air vents, and, last but not least, the absence of noise.

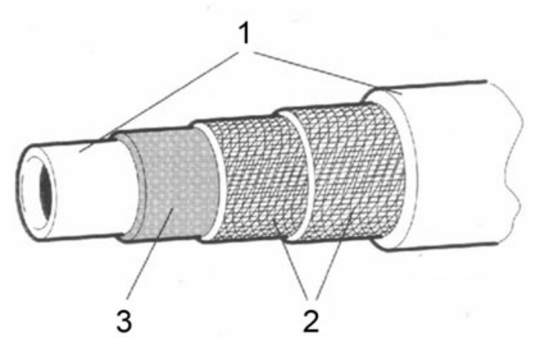

Fig. 6.238. Barrier type pipes: 1 elastomer, 2 double reinforcement with fabric, 3 nylon barrier.

Simulation codes are available that can provide reliable indications to help evaluate the behavior of the fluid inside the ducts, providing hints to optimize duct design.

Depending on the specific air distribution function inside the cockpit, ducts can be classified as follows (Figs. 6.248 and 6.249):

- Defroster and demister ducts (DEF/DEM);
- ventilation ducts (VENT);
- feet-level air ducts (FLOOR).

Defroster/demister ducts

As already mentioned in the section on instrument panels, these ducts have to convey the air to the windscreen and to the front door glasses, according to defined speeds and directions, in order to ensure defrosting and demisting.

These operations are made via holes provided on instrument panel or on specific parts located above, under the windscreen or through defined covers integrated on ventilation side vents. The positions are chosen to direct the airflow towards the side front glasses.

The methods for defrosting and demisting will be examined subsequently.

From the design point of view, the defroster and demister vents may have different configurations:

- Series, when there is a single feeding duct to the defroster and demister exits; this solution does not allow correct distribution between the exits and involves higher noise due to fluid motion inside duct; on the other hand, this solution is more economic because it has only one duct.

- Parallel, when there are two separated ducts, even if they have a single air enter from the HVAC group. In this case the disadvantages of series

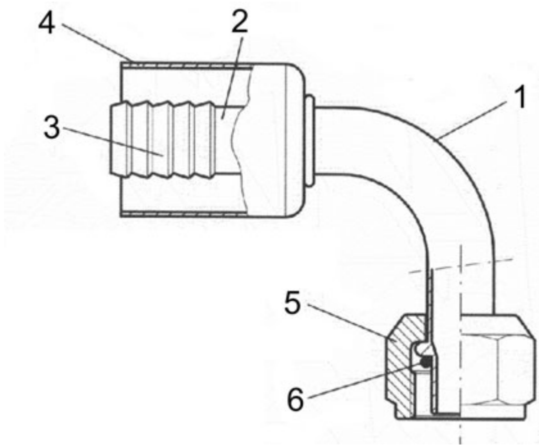

Fig. 6.239. Connection used to join flexible pipes with stiff component: 1 connection pipes, 2 pilot, 3 groove skid, 4 bell, 5 walker female, 6 O-ring seal ring.

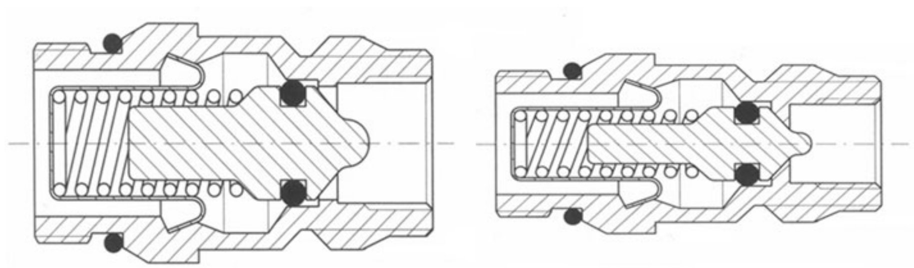

Fig. 6.240. Service valve examples: on the left service valve for high pressure side, on the right service valve for low pressure side.

solution are avoided, and it is possible to have two separated ducts in a single part, as has already been seen in the instrument panel section (Figs. 6.58 and 6.63); the increase of costs is limited to the higher quantity of plastic material.

Ventilation ducts

The VENT ducts convey air, usually cold, from the HVAC to the ventilation vents and thus directly to the cockpit. While in the past the vents were located only on the instrument panel, nowadays, to improve the thermal comfort of rear passengers, one or more vents are located on the rear part of the console.

In this case, there is a specific duct which, starting from air conditioning group, arrives at the rear vents passing through the console on the floor.

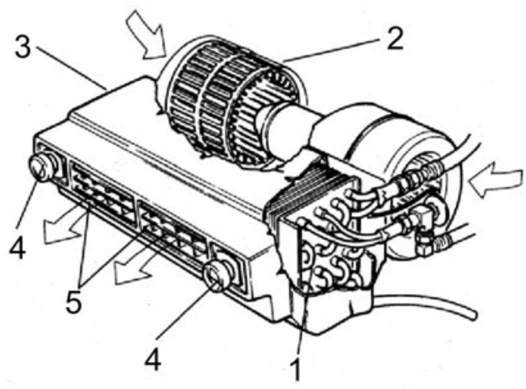

Fig. 6.241. Example of an old air conditioning system.

Feet-level air duct

FLOOR vents for the front passengers are directly made on the lower part of the housing of the air conditioning group.

For the occupants of the rear seats, the air arrives through appropriate ducts passing beside the floor tunnel. They have a relatively flat shape, being placed under the carpet, and end under the front seats. Fig. 6.250, shows one of these ducts made by blowing; its inside flow is verified by means of numerical analysis

Air vents

Air vents usually have relatively small dimensions, both for style reasons and for to the limited space available on the instrument panel. For this reason, the air-flow at the exit may be compared to a jet, i.e. a concentrated flow with high speed, creating a non perfect air diffusion inside cockpit in addition to an annoying noise.

In some cases, for example, when the electrical fan is at the maximum speed (producing a flow rate of about 450 m^3/h), the air vents create a mean output speed of about 7 m/s; assuming that the flow is oriented toward the driver's head, the speed reduces to about $0.5 \div 0.9$ m/s on the face.

The air exit speed from DEF/DEM and FLOOR ducts usually does not produce a feeling of particular discomfort, except if the exits have been designed incorrectly: If, for example, the defroster exits do not orientate the flow tangentially with respect to the windscreen, or the incidence angle is greater than 10°, detachment can occur in advance of the flow vein from windscreen, blowing in the face of the front occupants.

During transition times, when the occupants are in thermal discomfort conditions, jet ventilation is perceived positively; however, as time progresses, it can become highly unpleasant.

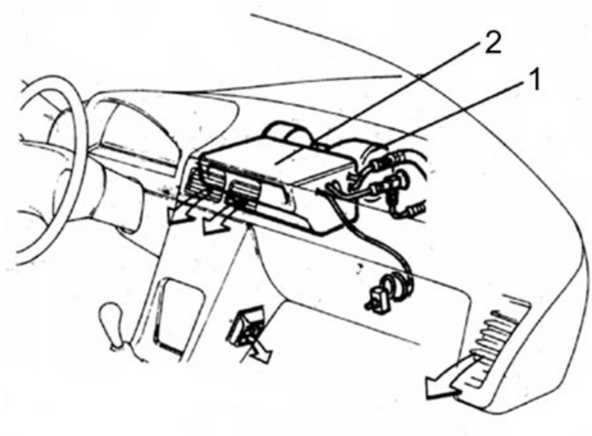

Fig. 6.242. Semi integrated heating group: 1 electro fan, 2 evaporator.

For example, after entering a car parked under summer sun for many hours, a highly unpleasant discomfort is perceived. This feeling quickly decreases thanks to air conditioning with cold air jets at high speed.

Continuing with this situation, however, the attained level of comfort tends to deteriorate, remedy being to direct the flow away from the body or from highly sensitive zones. However the flow should be maintained at a sufficient speed to continue to cool the environment.

In order to not create unpleasant conditions, the air speed has to be maintained in the range $0.2 \div 0.3$ m/s; this velocity can be reached only by using air diffusion surfaces, which enable the same flow to be introduced into the cockpit and thus the same thermal power generated at significantly lower velocity (transpiring instrument panel).

To optimize the air-flow inside the cockpit, apart from the air speed, it is also necessary that air vents are located and designed in an appropriate way.

Fig. 6.247, shows that, nowadays, a conventional sedan has five air vents, with only one for the rear seats occupants; minivans have additional air vents also for third seat line passengers.

During the planning phase, the air vents have to be located at a particular height range with respect to the R point. A typical example is made by central vents: Its position cannot generate an air-flow that directly aims towards the hand of driver when holding the steering wheel.

Moreover the air vents must have an orientation possibility both in the horizontal and vertical directions. In this way an air cone at maximum flow can be directed at the occupants. Usually the maximum tilting angle is in the range 30° to 40°.

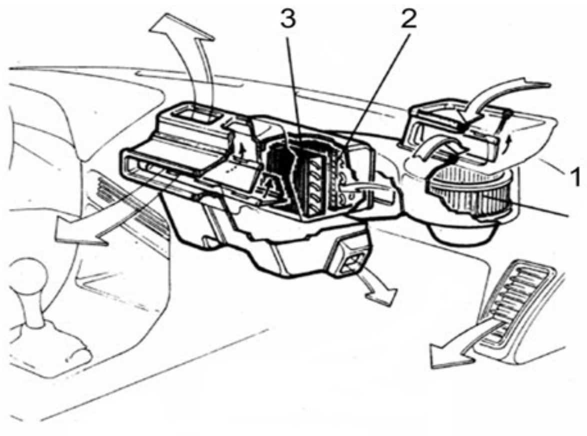

Fig. 6.243. First example of air conditioning group: 1 electro fan, 2 evaporator, 3 heater.

Distribution of air inside the cockpit.

For heating, the basic distribution of the air is FLOOR type, the aim being to send hot air to the lower part of cockpit. This air tends to rise with natural convection. When the temperature is very low, and if there is an automatic air conditioning system, during the vehicle starting, air distribution is put in DEF/DEM to reduce the possibility of glass misting .

For cooling, or during transition cool-down time, the distribution is VENT; so, as opposed to the previous case, the cold air goes towards the upper zone of the cockpit, then sinks down.

For demister and defrosting actions on glass surfaces, the basic distribution is DEF/DEM so the air, in particular if it is hot, clears the windscreen and side front glasses more rapidly.

Also bi-level distributions exist which are a combination of the two previous conditions:

- FLOOR/DEF when, for high moisture and low external temperature conditions, glasses surface need to be cleared, simultaneously sending hot air towards the occupants' feet and the glasses surfaces;
- FLOOR/VENT when, also for cooling, a stratification is required to warm the lower zone of the cockpit.

In the case of automatic air conditioning system, there are also three level distribution examples.

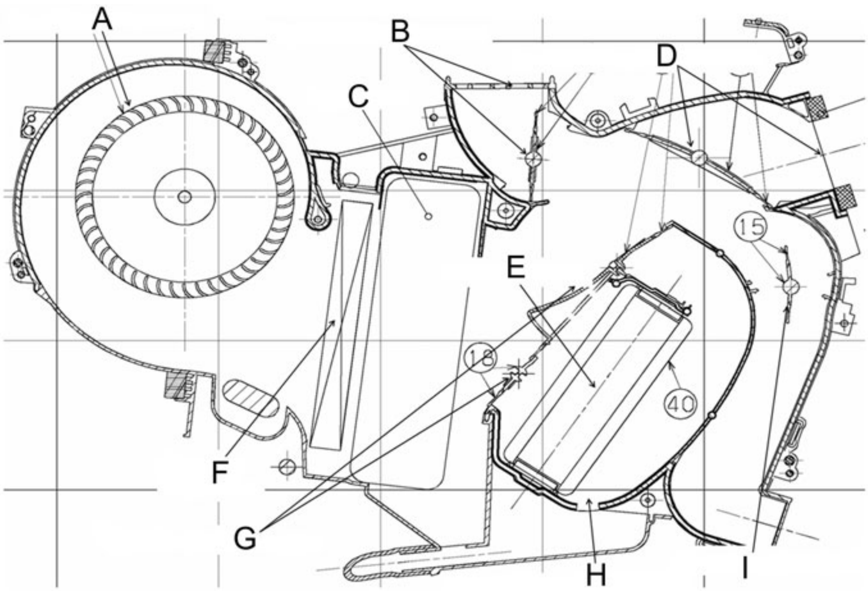

Fig. 6.244. Section of an air conditioning group: A intake air impeller, B defrost door and exit, C evaporator, D ventilation door and exit, E radiating mass, F air filter, G air mixture doors, H drain for condensation water, I foot door and exit.

To complete this discussion, it is necessary to pause still on two configuration of air conditioning: The multi zone and the transpiring surface (transpiring instrument panel). The first one is now widespread, the second one is not completely applied, being limited to luxury cars.

Multi zone

Multi zone systems represent the possibility to adjust the climate inside the cockpit in an independent way, within certain limits, from one zone to another.

A bi-zone air conditioning, that allows the driver and front passenger to select different desired climatic comfort conditions, operates on the mixture of hot and cold air, or on mixture and distribution.

The first of these, which to date it has been applied also on B segment car, is generally the more widespread, used to obtain bi-zone air conditioning. The air-flow towards the evaporator and radiating mass is divided by means of a longitudinal septum. In this way each portion of the heat exchanger corresponds to one occupant. Dividing also the air door in two parts, the driver and passenger can each adjust, within limits, their target temperature in an autonomous way.

The second approach, used on high range cars, is accomplished in almost the same way, dividing in two parts also the different air distribution doors. In this way each user can decide autonomously to adjust the direction and air-flow

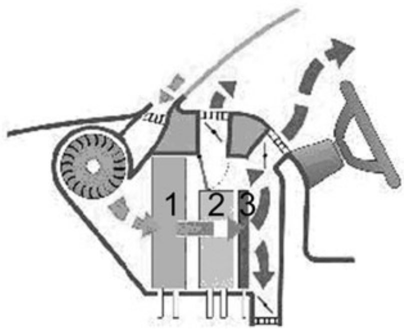

Fig. 6.245. Scheme of a PTC electric heater installation: 1 evaporator, 2 heater, 3 electric heater.

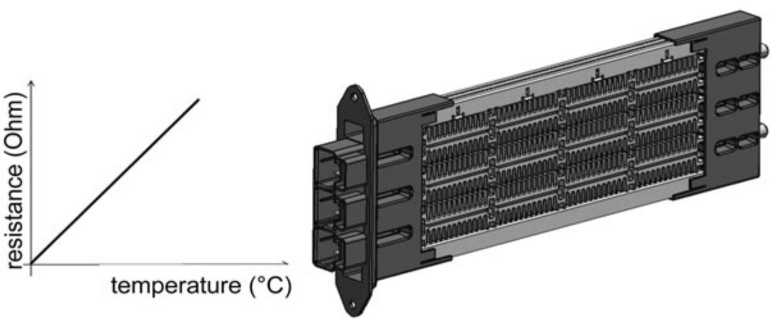

Fig. 6.246. Additional electric PTC heater and its electric characteristic.

within his zone of the cockpit (for example floor and floor/vent). In this case the mechanisms of the air distribution doors have to be independent for the two users.

Recently, also three zone air conditioners have become available. With these devices also the passengers seated on the rear seats have the possibility to control their climate conditions independently with respect to the front seat occupants.

Three zone air conditioners are used on high range vehicles and on some minivans where also the passengers of the third line of seats can adjust their temperature.

Because the cockpit is made of a finite volume (on average between three and five cubic meters), the temperature differences between one zone and another cannot exceed 3 degrees, whilst the distribution can be modified in a subjective way.

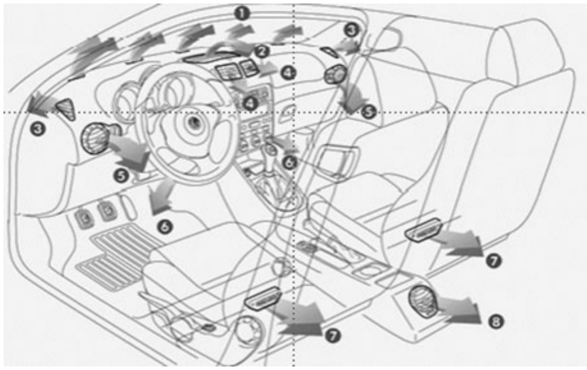

Fig. 6.247. Air diffusion inside the cockpit.

Transpiring surface

Previously discussed was how it is necessary to have lower air speed than that allowed by the air vents, at the end of transition time.

To reduce the speed with the same flow, it is necessary to increase the diffusion area. Considering the desired speeds, this increase of area is possible only using the transpiring instrument panel.

In fact, considering a maximum flow of 450 m^3/h, in order to obtain a diffusion speed of 0.2÷0.3 m/s, an area of about one square meter should be required, i.e. the total surface area of the instrument panel on average.

Without entering into details, it is clear that the design of the instrument panel should be changed completely. For example a transpiring surface could be made of fabric over a porous structure under which a plenum is located. The air to be distributed arrives in this plenum from the air conditioning group.

Moreover it is important to remember that it is not possible to eliminate the four air vents; they must be maintained to avoid unacceptable cool-down time.

Intermediate solutions between today air vents and the transpiring instrument panel are implemented in some high level cars, adopting air diffusers with perforated covers of large dimensions used to distribute air inside the cockpit, as can be seen in Fig. 6.251.

Controls group

In contrast to the warming group, the air conditioning group, due to its different typologies, has a range of controls including:

- Manual adjustment controls;
- semi-automatic adjustment controls;
- automatic adjustment controls;
- bi-zone automatic adjustment control.

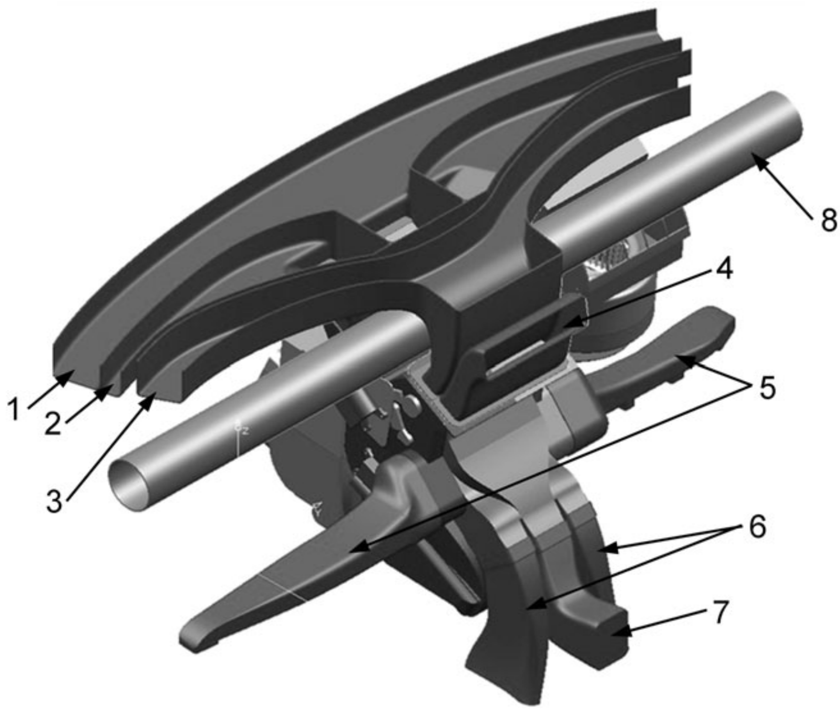

Fig. 6.248. Ducts system under instrument panel for air distribution: defroster duct (1); demister duct (2); duct for side air vents(3); central air vents (4); front seat feet-level air duct (5); rear seat feet-level air duct (6); console vent duct (7); structural cross beam for instrument panel module (8).

Manual control groups

This type of controls, in practice is now used only for air conditioning groups. It is very similar to that of the heating group controls with mechanical actuation. An exception is the electric fan with an on/off control being added to activate the compressor (Fig. 6.205).

Semi-automatic control groups

The use of this type of control is set to decrease in future It enables the automatic management of the temperature and flow (adjusting the speed of the electric fan), but not the air distribution which is managed manually (Fig. 6.252).

As for all automatic systems, it is possible to switch-off both the automatic control and the refrigeration cycle. Blow management is made by means of a control key.

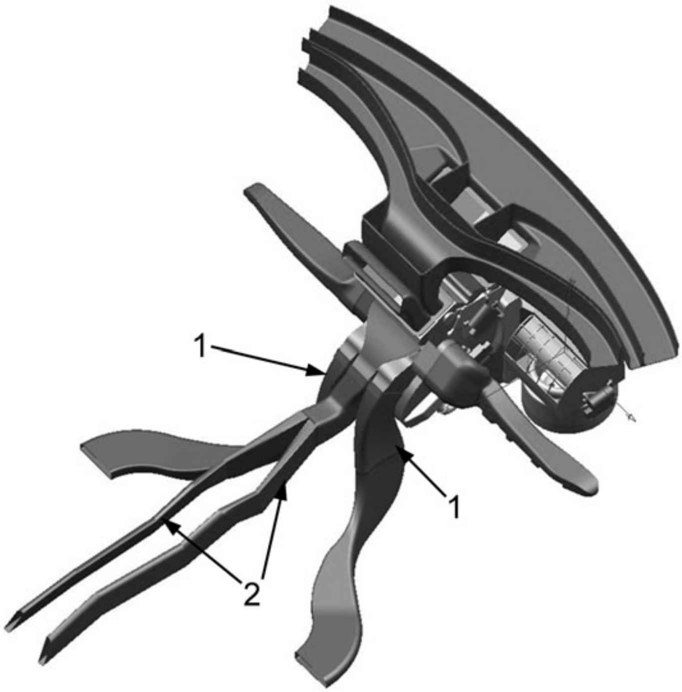

Fig. 6.249. Air ducts for rear passengers feet (1) and for vents on console (2).

Automatic control groups

In this case, all functions are managed automatically. Several types of automatic controls exist as a consequence of the different climatic configurations which have to be managed. Apart from the basic mono zone configuration (Fig. 6.253), a bi-zone system relative only to the temperature requires two temperature controls. Instead if there is a bi-zone relative also to the distribution, also two controls for distribution are required (Fig, 6.254). Finally, for the three zone system, only one additional control located on the rear zone of cockpit is usually required.

For the automatic air conditioning group, the control groups are usually supplied disconnected since they are usually electric controls without mechanical constraints (e.g. flexible cables). They can be connected during the assembly phase of instrument panel modules for example.

6.6.5 Design Criteria

In contrast to previous years, all components of the air conditioning system are now made by external suppliers instead of the car manufacturer. Often the suppliers are different for the different parts.

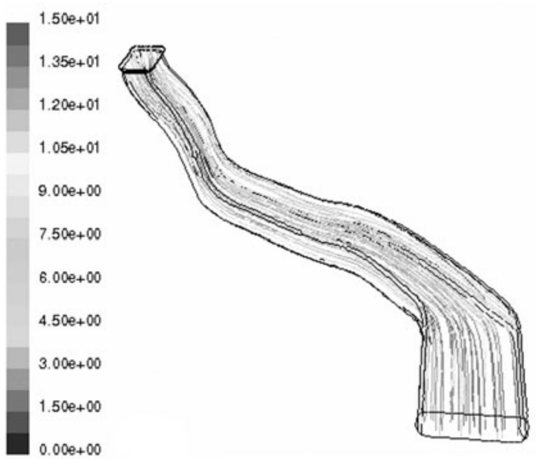

Fig. 6.250. Examples of flow calculation inside a duct for the feet-level air distribution.

Two sets of drawings describe the function and the design of the components: Those developed by the car manufacturer and those by the suppliers. The first ones are usually represented by an outline drawing indicating the dimensions that are critical for the manufacturer and the overall tolerances that must be respected for correct installation of the components on the vehicle. Moreover these drawings have a set of technical statements, as attached documents, oriented to describe the required functions of the system on the car.

These technical statements form part of the supply agreement between the supplier and manufacturer.

Characteristics and specifications

These include all specifications that the components have to satisfy and the constraints that the manufacturer want to impose on the freedom of the design ideas of the supplier.

The first category includes the legal requirements depending on where the vehicle will be sold and refer essentially to external visibility (see Volume II).

The second category includes specifications deriving from the manufacturer experience, also relating to results obtained during testing, from other suppliers or via benchmarking of competitors.

Other specifications regard the types of components to be used, including electric connectors and pipes connections, the coloring/trims of visible parts and type of external fastening.

As concerns the external fastening, it is important to remember that they must ensure resistance during mounting, easy accessibility for normal maintenance and sufficient stiffness, in particular with respect to the components (such as the compressor) mounted on the engine.

Fig. 6.251. Example of instrument panel showing the perforated surface for the air diffusion (A).

Fig. 6.252. Semi automatic control unit for air conditioning control.

In fact, due to the engine excitations which cover across a wide range of frequencies, a resonance lower than 400÷500 Hz can result in high noise and vibration at certain engine speeds.

A specific issue regarding these specifications regards water infiltration inside the cockpit which can be caused or by rain or condensation water due to humid air in contact with the evaporator or pipes at low temperature.

The external air intake is by definition an entry canal for external water but, since it cannot be avoided, the evaporator and radiating mass housing have to be designed so that:

- The discharge of water to external is facilitated by appropriate drain pipes;

- the housing has to be protected by a grid of appropriate material in order to avoid the entry of leaves and other objects which can block the drain;

Fig. 6.253. Example of automatic control group.

- in the connecting joints between housing and distribution pipes, the rivet holes (if any) have not to be below the expected level of the stagnating water.

The stagnation of water has to be avoided as much as possible, also because it can enable putrefaction processes for organic substances or mould growth which create undesirable smells inside cockpit. To avoid this:

- The geometry of lower parts of housing has to avoid stagnation zones;
- the evaporator has to be inclined so that the drainage of condensation is facilitated;
- the external surface of the evaporator on the air side has to be treated with water repellent; These considerations do not apply to the radiating mass since it is always crossed by hot air.

Particular attention is required for the hot water pipes which must be located to facilitate the discharge of trapped air or vapor. Each part of the system should be located under the expansion de-aeration tank for the engine cooling system.

6.6.6 Innovative Trends

In the recent years the architecture and the characteristics of the individual components of automotive air cooling systems have improved significantly as concerns weight reduction, overall dimensions, performance and functions. In the coming years, it is possible forecast further evolutions aimed at respecting

Fig. 6.254. Example of bi-zone automatic control group.

not only the new and more complex regulations of car manufacturers, but also future legislation.

At the moment the main innovation activities being undertaken by car manufacturers and suppliers of air conditioning systems include:

- Increasing the efficiency of air conditioning systems, to reduce fuel consumption;
- substituting the refrigeration fluid (R134a) currently being used with new ones exhibiting lower greenhouse effects.

Efficiency increase of air conditioning system

This activity was initiated as a result of the new EU directives for the homologation of new vehicles with air conditioning system. Involved is the design, manufacturing and integration on the vehicle, of air conditioning system with nominally the same performance as the systems used today, but consuming less energy for its operation (electrical and mechanical energy generated by fuel combustion).

The technical solutions identified, can be summarized as follows:

- For all vehicle market segments, application of variable displacement compressors with external control, and air conditioning control in the cockpit, integrated with the engine control system, in order to minimize the power absorbed by the compressor, as a function of engine speed and the air conditioning performance demand by the occupants.
- Introduction of additional components into the air conditioning system in order to increase the efficiency. An example is the insertion of an intermediate thermal exchange on the high and low pressure refrigeration pipes in

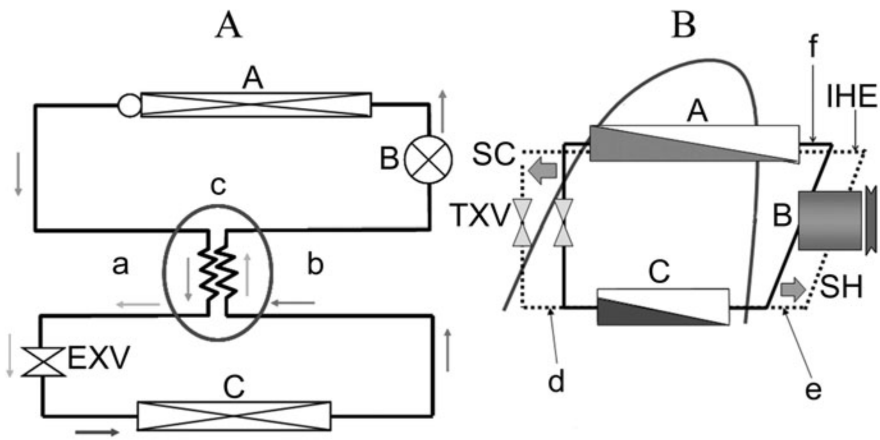

Fig. 6.255. Scheme of air conditioning system with intermediate exchanger (IHE). System scheme (A); P-h diagram (B). Details in the picture: condenser A, compressor B, evaporator C; high pressure zone a, low pressure zone b, internal thermal exchanger c, increase of enthalpy step on the evaporator d (higher refrigerating power), increase of overheating at the entry of compressor e (to be reduced at minimum), conventional cycle f.

order to increase the refrigeration system performance by about 5%, and reduce fuel consumption due to the air conditioning system by 15-20% (depending on the thermal load of the air conditioning system) as shown in Fig. 6.255: The aim is to limit the absorbed power with the same compressor performance, since lower condenser operating pressure means reduced work of compressor with lower displacement.

- Use of sensors and control strategies which are more sophisticated than those currently in use, in order to minimize the energy consumption of the system. A first example of innovative sensors is the recent introduction of cockpit temperature sensors based on a mapping of the thermal radiation (infrared), emitted by occupants and by internal surface of vehicle. A second example is the use of temperature and relative moisture sensors of the air inside the cockpit, by which it is possible to minimize the absorption of compressor power.

Reaching the correct comfort level for occupants depends also on relative moisture level in the surrounding environment and not expend energy to reach too dry interior air conditions. In fact it is well known that, beyond a certain point, very dry air can cause breathing problems as the mucous membrane is affected.

The use of such sensors will also require an updating of the algorithms and strategies for the cockpit control system.

Substitution of actual refrigerating fluid

Recently an EU directive has been approved to prohibit, starting from 2011, the homologation of new vehicles that use a refrigerant with GHP (Greenhouse Heating Potential) higher than 150 (see Volume II), (the refrigerant today in use has a GHP equal to about 1.400). This fact has resulted in a rapid rise in research related to new refrigerants compatible with the new regulations.

The most significant research and development is focusing on the following fluids:

- R152a, with a GHP index equal to 120, already known and used in other fields (therefore available at an industrial level), but characterized by its high flammability;
- new fluids with a GHP equal to about 5, still under development and therefore not yet qualified in terms of human toxicity and flammability with respect to automotive applications.
- CO_2, with a GHP index equal to 1;

In particular the use of CO_2, which is already in an advanced state of validation both in the laboratory and on prototype vehicles, will require the substitution of current components with completely different solutions due to the high pressure and operational temperature (e.g. 130 bar at 150°C).

The use of flammable refrigerant fluids, even if compatible with some of the current components of air conditioning systems, cause higher system complexity due to the need to introduce (for safety reasons in case of accident or fluid escape) an additional circuit for the circulation inside cockpit of a non flammable fluid. Usually applied is a mixture of water and glycol similar to that used for engine cooling. This additional circuit requires installation in the engine compartment of an intermediate exchanger to enable heat exchange between the glycol and water mixture and the refrigeration fluid. Its circulation is relegated inside engine compartment. It is also necessary to add an electric pump to enable the circulation of fluid in the additional circuit.

No clear direction has emerged yet regarding the new refrigeration fluid to be used in future; nevertheless the development time of new models and the proximity of the date of introduction of the new legislation means that a decision is urgently required.

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