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[1.] Giovanni BELINGARDI

LIGHTWEIGHT DESIGN OF VEHICLE BODY A CONTRIBUTION TOWARD GREENER ENVIRONMENT

[1.] Politecnico di Torino, Department of Mechanical and Aerospace Engineering, Torino, ITALY

Abstract: *The vehicle mass experienced a period of progressive increase. Nowadays as it is essential to decrease both the fuel consumption and the CO_2 production, lightweight design becomes a relevant target for car manufacturer. One of the considered strategy toward lightweight is the substitution of the material used for manufacturing the different parts of the car body. Together with the new developed HSS steels, aluminium and magnesium are considerded. Recently composite material solutions have gained a lot of attention due to their very interesting characteristic. The paper discusses some the relevant aspects when developing a new material solution from the material production to the end-of-life. The paper includes one example of results that can be achieved with properly oriented light weight design procedure.*
Keywords: *lightweight design, car body, HS steel, light alloys, composite materials*

INTRODUCTION

The design of modern cars must meet many requirements in terms of transport performance, comfort, active and passive safety, fuel consumption and costs, quality and reliability, environmental impact and end-of-life destination. To satisfy these goals and to match legislation prescriptions and costumer expectations, continuous evolution of technology and multidisciplinary approach to the design are required. Most of these design aspects intersect each other in a number of even more complicated multidisciplinary views. This complexity asks for anticipation of the design choices at the very beginning of the design process, when the alternatives are explored and compared in order to define the solutions to be implemented in the new vehicle.

Nowadays, one of the main concern about automotive industry is related to the reduction of fuel consumption and exhaust emissions. In the last years, vehicle weight has progressively increased in order to guarantee higher vehicle performance, passenger comfort, safety and emission standards but, on the other hand, this has penalised the fuel consumption and the CO_2 emissions. In Europe as well as in US and in the far east countries governments have decided to force a change in this trends and new generation cars need to ensure lower emission levels. Particular attention is devoted to the Greenhouse Gas (GHG) production as they are considered the main responsible for the climate changes and the progressive world heating.

The EU government has put ambitious reduction targets and lightweight design can give an important contribution to achieve these targets.

The carbon dioxide production is directly related to the fuel consumption of the vehicle because it is a product of combustion chemical reaction. Therefore, taking into account that the combustion efficiency has already reached very high values, the only way to limit the CO_2 production is to decrease the fuel consumption. Even little reductions of the fuel consumption of each car would result in an overall big reduction of CO_2 emissions. A weight reduction of 100 kg, including secondary effects, leads to a reduction in fuel consumption of approximately from 0.3 to 0.5 litres per 100 km. This goes along with a reduction of CO_2 emission *of from 8 to 11 grams per kilometre [1]. If all cars in Europe (210 million vehicles) would save a quarter litres per 100 kilometres, the CO_2 emissions would be reduced by 17,344 million tons each year [2].*

In the last decades of the previous century, the rate of weight increase was steeper (figure 1). This high gradient can be explained by evident market trends toward larger vehicle and engine dimensions as well as higher performance requirements. At the same time, even enhanced vehicle features are responsible for the weight increase. In particular, safety and pollution control subsystems as well as comfort-related subsystems and equipments provide important contributions. The Figure 1 shows the tendency of weight increase for B-segment vehicles over the model years. In 40 years, weight increase is about 700 kg.

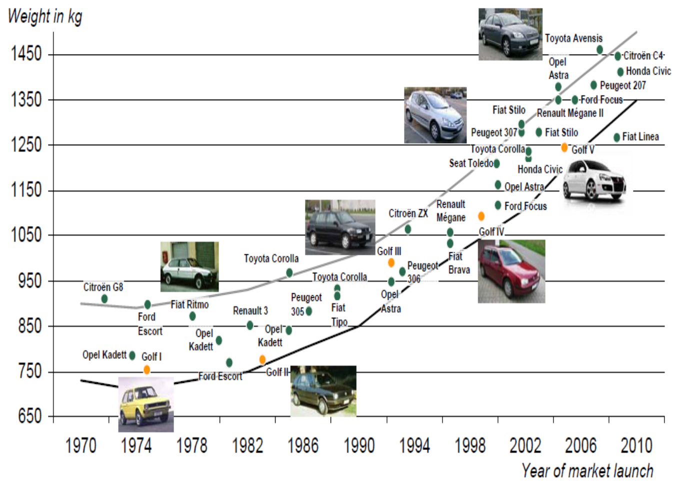

Figure 1. Comparison of curb weight trend of common B-segment vehicles [3]

The vehicle mass (m_F) is the dominant driving-resistance since it is present in three of four parts of the power demand equation (Eq. 1) and thus has direct influence on the fuel consumption. The benefits of weight reduction in this regard become clear by a simple analysis of the power demand P for vehicle riding:

$$
\begin{aligned}
&P = P_{ac} + P_{cl} + P_{roll} + P_{aer} = \\
&(e_i + m_F + m_{Zu}) \cdot a \cdot v + (m_F + m_{Zu}) \cdot g \cdot \sin(\alpha_{St}) \cdot v + \\
&(m_F + m_{Zu}) \cdot g \cdot \cos(\alpha_{St}) \cdot f_R \cdot v + 0{,}5 \cdot \rho_L \cdot c_w \cdot A \cdot (v - v_w)^2 \cdot v
\end{aligned} \qquad (1)
$$

Except for the aerodynamic drag resistance, every addend of equation 1 contains the mass of the full vehicle. In city traffic, the drag resistance and climbing resistance contributions are quite low while the acceleration phases are considered to cause up to 40 % of the total fuel consumption.

Specific studies demonstrated that gains in terms of CO_2 emissions can be achieved by acting in particular on lightweight design and by adopting all the strategies and devices that lead to an increment in the internal combustion engine efficiency, in order to pursue the objective values of about 4,7 l/100km in fuel consumption, on the basis of fleet average [4].

A decrease in vehicle weight can be obtained by architectural and structural measures and by the use of alternative materials with better weight-specific properties than conventional mild steel. These two paths of lightweight design cannot be strictly separated, as changes in component material usually requires changes in the component design, too. In the following sections some perspective and results will be briefly presented and discussed for both the above mentioned paths.

TRENDS OF LIGHTWEIGHT MATERIALS FOR CAR BODY CONSTRUCTIONS

The use of unconventional materials offers a vast number of alternatives and at the same time proposes big challenge to designers, which, to meet the various, sometimes contradictory, requirements and goals, must face puzzling problems: new manufacturing technologies for parts production, different assembly methodologies, mounting techniques, compatibility issues, recycling deeds, always paying the attention to a problem of paramount importance: cost. Material costs, design development and prototype testing costs, production costs, tooling costs and whatever operation costs affect the cost of every single vehicle.

A simple evaluation of the advantages of substituting the universally adopted deep drawing mild steel with other materials can be performed by using simple engineering formulas for structural parts behaviour. There are many criteria with which it is possible to rank the material for specific application and target. An efficient practice is to plot one property versus one or more competing properties (for instance Young modulus or strength versus density and cost) to get bi- or tri-dimensional maps [5,6].

A multi material structure is the outcome of the best possible design able to meet the environment and legislation conditions, but also able to mantain the costs at acceptable levels. This problem has been widely studied in a number of EU-Projects, we would like to mention one of these projects: Super Light Car (SLC) with the example of a vehicle of the B-class segment.

The aim of the SLC-Project was the development of lightweight body structures in multi material design, which could be 30% lighter than the actual reference vehicle that is based on a extensive steel construction. This aim was only achieved with the exact evaluation of different material combinations, the development of new designs, simulations methods and joining techniques. In order to obtain in a credible way the evaluation of costs and the sustainability of innovative multi material design, appropriate methods for lightweight vehicles have been used.

The multi disciplinary analysis within the SLC-project deals with the manufacturing of new solutions based on hybrid, multi-material compounds (see figure 2a). The design of these innovative solutions asks also for innovative joining technologies (particularly in the case of multi material design) and innovative manufacturing process [5,8].

The SLC project leaded to a body concept (as shown in figure 2a) with a decrement of 82 kg (about 29% of that of the reference vehicle), with an estimated increment of costs of less than 5 € / kg.

In Figure 2b, it is possible to see paths related to material use for car body concepts, as defined by Audi [7]. The steel unibody is the reference design solution. According to the first path, the evolution of the traditional steel construction will include some innovative production technologies such as roll forming and thin casting technology, which lead to steel spaceframe and stainless steel spaceframe. The aluminium construction is the second path which has already been used for the production of aluminium shell construction and aluminium spaceframe (the typical example is Audi R8, completely made of aluminium with small use of carbon fibre reinforcements). The third path is the plastic material construction, mainly described by use of fibre reinforced plastics which leads to the so-called body-in-black. The mixed construction is considering the multi-material design. As shown in figure 2a, the final choice has been defined as a hybrid structure which includes mostly steel, aluminium, magnesium and fibre reinforced plastics.

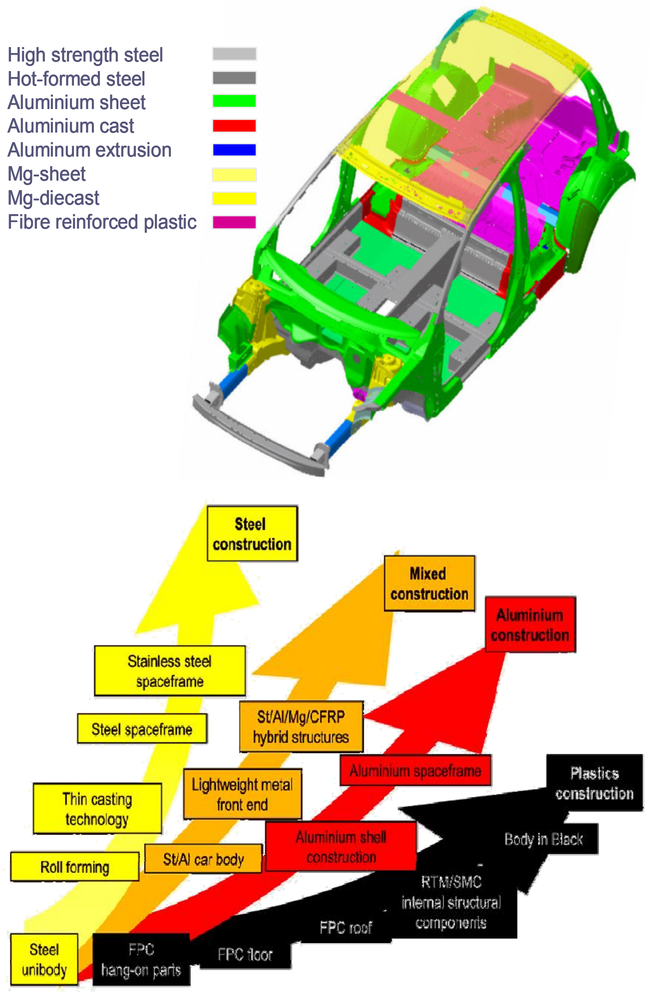

Figure 2 a) final concept for the SLC multimaterial body; b) paths for car body concepts [4]

ONE EXAMPLE OF LIGHTWEIGHT STRUCUTRAL SOLUTIONS

In this paragraph one example is presented of possible structural solutions aimed to lightweight but, obviously, able to match all the other structural requirements so that a full substitution of the normal production subassembly with newly designed one could be possible. The application is related to a front bonnet of a medium/high class car [8]. Different solutions in terms of material and shape of the inner structure have been studied by means of virtual analysis. The most interesting solution in terms of weight and performance has *been prototyped [8]. Validation has been made by experimental tests, in particular to confirm the pedestrian head impact performance. The other types of performance of the bonnet (different type of stiffness and denting resistance) have to be maintained unchanged as they were in the original solution.*

The reference bonnet is completely made of steel. The external shape of the skin could not be changed because it was defined by aesthetic style. For this reason, only the material and not the shape of the skin could be changed, while for the inner structure variations of both shape and material were possible. The structure of the reference bonnet is shown in figure 3.

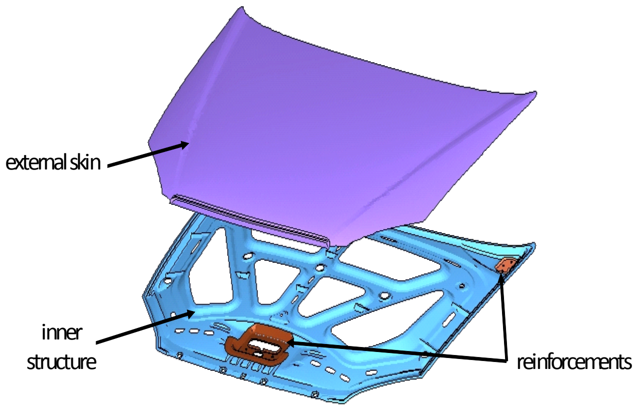

Figure 3. Structure of the reference steel bonnet

To reduce the weight of the bonnet the use of thermoplastic materials has been considered; their low density and good recyclability have been taken into account. The Noryl GTX has been selected as a possible solution, its quite good mechanical properties are reported in table 1.

Table 1: Properties of the Noryl GTX thermoplastic material

Property	Value	Property	Value
Density (g/cm³)	1.20	Flexural modulus (GPa)	4.00
Ultimate tensile strength (MPa)	80	Flexural yield strength (MPa)	135
Yield tensile strength (MPa)	85	Izod impact (unnotched, 23°C, kJ/m²)	45
Elongation at break (%)	6	CTE linear (μm/m/°C)	55
Elongation at yield (%)	3	HDT (66 psi, °C)	190
Tensile modulus (GPa)	4.30	Vicat softening point (°C)	230

Two different designs for the inner structure have been proposed [8] as shown in figure 4. Both are characterized by a regular structure with local ribs. They are aimed to reduce the weight and to distribute in a more efficient way the energy in case of impact against a pedestrian head, and at the same time to ensure sufficient bending and torsional stiffness. The studied solutions have been completed by an external aluminium skin and reinforcements still made of steel.

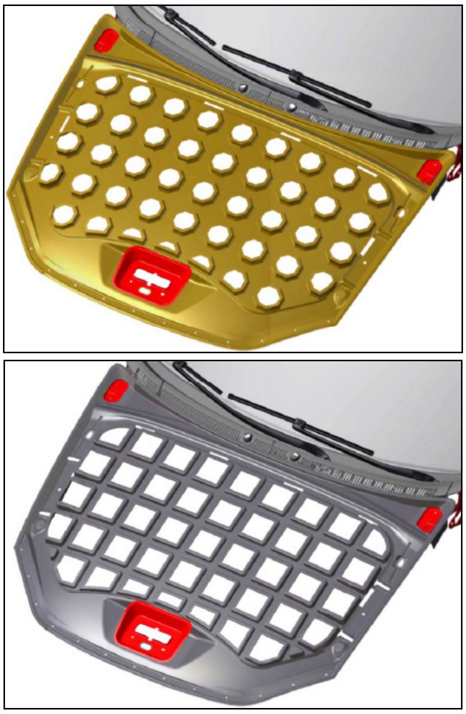

Figure 4 . Different designs considered for the thermoplastic inner structure [8]

Table 2: Numerical results of the pedestrian head impact test. [8].

Solution	Weight (%)	HIC_{15} (%)	Deformation (%)
Aluminium	-32.5	-10.0	14.7
Noryl (skin 2.5 mm)	-27.8	0.5	-3.8

Table 3: Numerical results of the stiffness tests. [8].

Solution	Weight (%)	K_t side (%)	K central (%)
Aluminium	-32.5	26.1	20.1
Noryl (inner structure 3.5 mm)	-31.1	-70.0	-61.5

A third solution has been developed with the same geometry of the reference one, but completely in aluminium (6016-T4 for the skin; 6181-T6 for the inner structure). Both lightweight solutions, with aluminium and thermoplastics, allow for a weight *reduction of about 30% if compared to the reference solution in steel.*

The results of the numerical tests are summarized in tables 2 and 3, where the HIC_{15} for the pedestrian impact test and the vertical deformation have been reported as variation with respect to the reference (steel) solution. Both the aluminium and the Noryl solutions show good potential to obtain the same improved performance for the pedestrian head impact.

CONCLUSIONS

The lightweight design is becoming rapidly one of the main targets in the development of a new car. This is countertendency with the trend of the last decades, when the mass of the vehicle has increased progressively.

The reduction of the mass of the vehicle is of great importance from two linked points of view: the reduction of the fuel consumption and the reduction of the CO_2 production. The reduction of the mass of the vehicle can be obtained by optimising the structure of the vehicle, in particular the body, by substituting the commonly used deep drawing steel with other materials such as aluminium or magnesium. This alternative is asking for relevant changes in the manufacturing process and there are also some questions related to the technologies to be adopted for joining parts made of different materials.

Another possibility is the use of composite materials. This is the clear trend in the aeronautical industry and this can be the near future also for the automotive industry, although a number of problems are still open and ask for practicable answers. Some new results have already been published and ask for verification of their practicability.

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