Mass Reduction Methods for Energy Efficiency Improvement of Vehicles

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Abstract. Energy efficiency has become imperative in design of vehicles. Energy efficiency can be viewed from multiple aspects like economy to environmental (from cost of transportation to carbon emissions). There are many factors that have influence on energy consumption in any type of transportation (by land, water or air) and one of them is vehicle mass. In this paper the current methods for reducing vehicle mass will be shown.

Keywords: Energy efficiency · Mass reduction · Vehicle

1 Introduction

In the previous century widespread availability of fuel combined with its cheapness provided increase in mobility and great expansion in the transport system. Today, due to changing circumstances, such as future availability of required quantities of fossil fuels and growing concerns about environmental consequences of transport activity, the usage of alternate energy sources and reduction of energy consumption of transport system is becoming top-priority objective of public administrations at all levels [1].

Reduction of mass (weight) represents one of the most important strategies for lowering vehicle emissions and fuel consumption. In vehicles the design of engine, transmission, hybrid, and thermal management technologies have the purpose to reduce energy losses and increase energy efficiency. A part from that, weight reduction lowers the amount of energy needed for vehicle movement, regardless of the propulsion system efficiency [2].

Lightweighting is in especially high demand for products such as [3]:

- Automobiles
- Mass transit systems
- Airplanes
- Helicopters
- Portable tools

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Development of lightweighting technology brought to significant reductions in weight of the vehicle (as seen on Fig. 1), but even so, the total weight of vehicle and size increased (Fig. 2) due to integration of entertainment, safety features and a system for reduction of exhaust emission. The cause of this are safety regulations and consumer preferences for more spacious and comfortable cars [4].

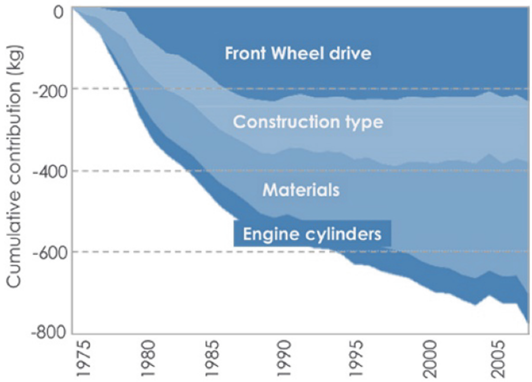

Fig. 1. Cumulative contribution of different approaches to weight reduction in vehicles [5].

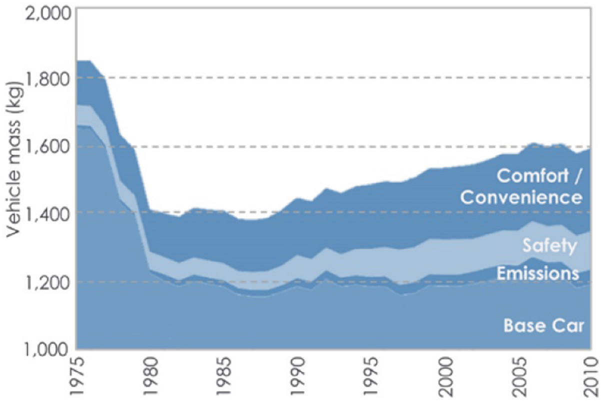

Fig. 2. The evolution of average passenger car mass between 1975 and 2010 [6].

There are several factors that influence on development of lightweighting technologies today (Fig. 3).

Of course, industries that maximize the lightweighting application are automotive and aviation. But due to mentioned drivers of change, it can be seen that lightweighting have its purpose in various applications, from construction (where the purpose of lightweighting is to decrease weight and amount of used materials without the sacrifice of structural integrity) to every vehicle from bicycles to drones.

In rest of the paper the methods for lightweighting will be described.

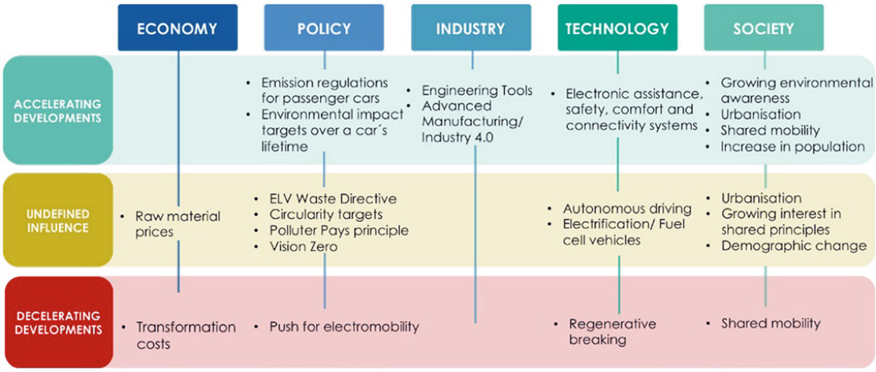

Fig. 3. Drivers of change and their impact on lightweighting development [4].

2 Methods for Lightweighting

2.1 Usage of Different Materials

One way to reduce vehicle mass is to replace traditional manufacturing materials that have high weight with lightweight materials. There are several performance factors that must be taken in consideration when choosing lightweight material: [4].

1. Technical performance – material must be in compliance with mechanical and thermal requirements.
2. Lightweighting potential – characteristics of materials (low density, high strength or their combination through weight-to-strength ratio).
3. Environmental impact – energy demands and emissions from obtaining raw material and manufacturing into application as well as usage of other consumables in these processes (water etc.).
4. Recyclability – possibility to gain materials from manufacturing scraps in order to reduce impact from extraction (economical and environmental impact).
5. Manufacturability – the ease with which material can be manufactured into components. Companies invests in infrastructure and manufacturing capacities, and with development of new materials with different properties there is need for different processing approaches.
6. Material compatibility – ability of material technology to be combined with other materials using existing joining technologies.
7. Cost of lightweighting – represents the additional cost required to reduce weight.

Materials for lightweighting can be viewed from two aspects: the material type and material structure (Fig. 4).

On Fig. 4 are shown the most relevant materials and structures but, depending on industry that uses them, there are more specific materials (for example, in aerospace industry, besides mentioned, materials used for lightweighting are also titanium, ceramics etc.).

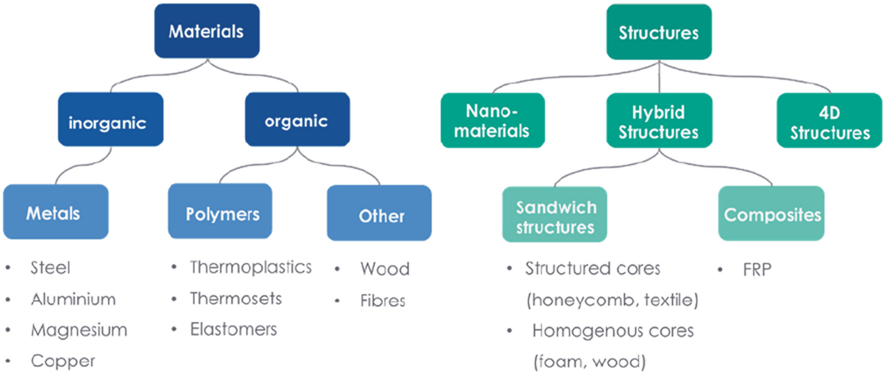

Fig. 4. Overview of the most relevant lightweight materials and structures [4].

On Fig. 5 is diagram that show the usage the materials in automotive industry in year 1995. compared to year 2008. From the figure it can be seen that usage of iron castings is declining. Usage of steel is rising because of development of steel grades (Fig. 6) that provides better strength-to-weight ratio.

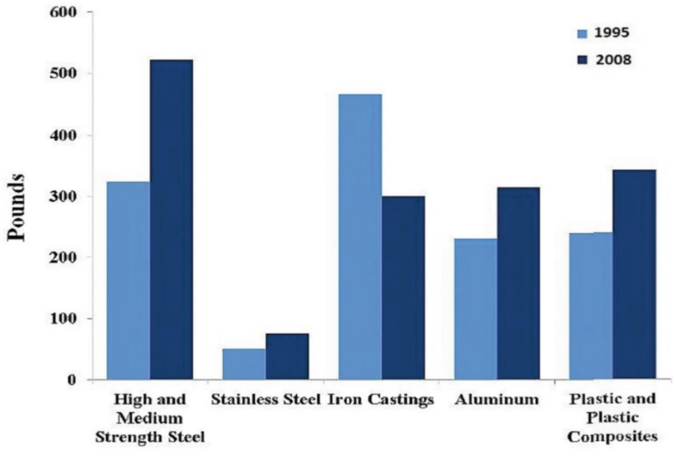

Fig. 5. Growth of advanced materials in automotive for lightweighting and Safety [7].

On Fig. 7 it is shown the percentage usage of lightweight materials in aviation an automotive industry.

Lightweight materials (light metals, aluminum, plastics and composites) already makes around 80% of airplane. The purpose of lightweighting in airplane has two parts: reducing the fuel consumption and increasing the number of passengers and amount of luggage that airplane can carry. Lightweighting in heavy transport have the same purpose.

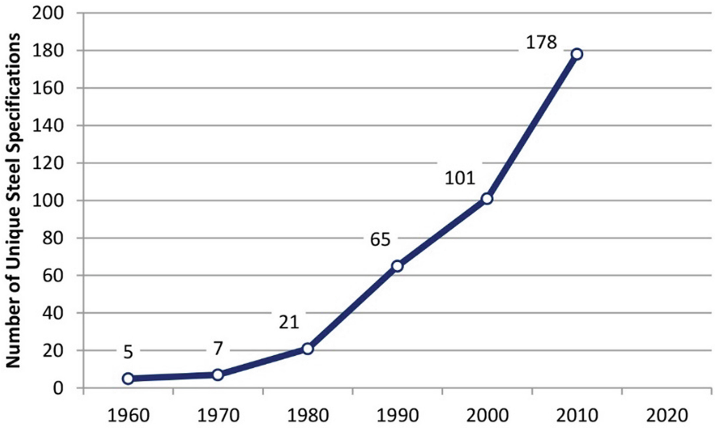

Fig. 6. Growth in steel grades – higher strength steels [8].

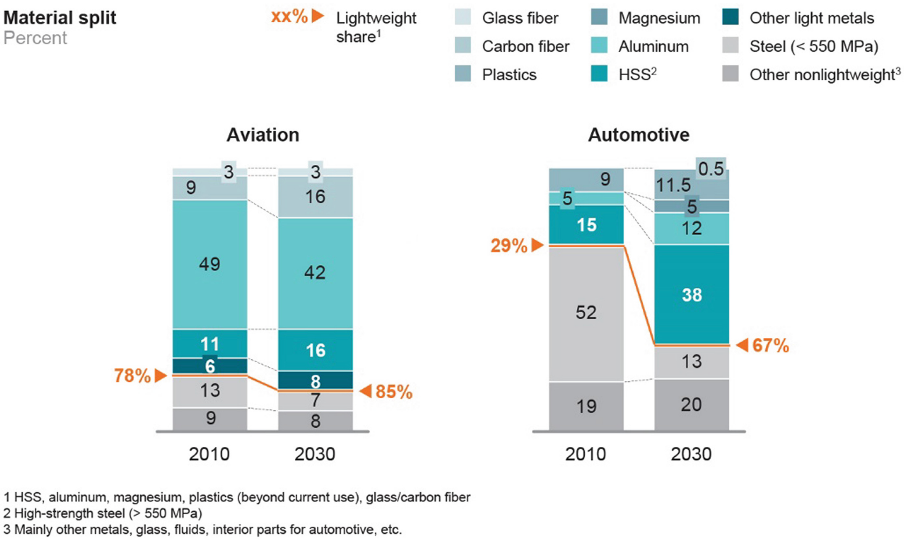

Fig. 7. Usage of lightweight material in aviation and automotive industry [9].

Current research, especially in automotive industry go in the direction of development of composite materials. Composite materials have the greatest strength-to-weight ratio in comparison to other lightweight materials.

2.2 Technology Used in Lightweighting

In the next segment the some of the specific technologies used in lightweighting process will be mentioned. They can be divided in two sections: first represents the technologies in order to manufacture part using lightweight materials and the second represents the ways of joining parts made from lightweight materials [10].

Shaping/Fabricating Technologies
Some specific technologies form manufacturing parts from lightweight materials are [10]:

- Warm forming – is process used in forming parts while sheet is warm in order to improve formability (strain rate sensitivity of the material is much greater allowing enhanced formability including superplastic deformation). This technology provides the means to form part from materials that lacks formability of steels. One of the application is quick plastic forming process for car parts.
- Hot stamping – is similar to warm forming process with the difference that is used to form parts from steel. Using this process parts with exceptional strength level can be produced using specially designed alloys, that influences on vehicle safety.
- Impulse forming – is process where very high forming velocity (50–500 m/s) is used. Achieved improvement using this process, from conventional forming, is improved formability, attained precision shape control, high fidelity embossing and possibility of precision shearing with high quality.
- High-integrity casting of light alloys – is process that offers inexpensive mass production of complex shaped components. In the past, the problem with this process was that parts had poor ductility, toughness and sometimes strenght. But, with the improvement made in evacuating the die-casting chamber prior to casting and using pressure to eliminate porosity, characteristics of parts increase significantly.
- Additive manufacture – is process providing creation of part layer by layer (in contrast to subtractive technologies such as milling etc.). Additive manufacturing enables creation of complex parts with defined infill structures using materials such as thermoplastic, ceramic and metal. It also enables reinforced structures with carbon fiber.
- Beam structures – usage of beam structures (through different materials and shapes) that are joined in order to achieve stiff and strong structural parts of vehicle.

Joining Technologies
Joining technologies in lightweighting are necessary in order to connect special materials or different materials. Some of these technologies are [10]:

- Friction stir welding - is based on the solid state intense mixing of the metals of two components and can join materials in lines or spots. This technology is used in automotive industry.
- Impact welding – consists of metal impact with high velocity and under certain angle generated by explosive or magnetic pulse.
- Self-piercing rivets – technology used for joining two very different materials (for example metal with plastics). Rivets in this technology can be made from aluminium.

- Structural adhesives – adhesives are also used for joining two dissimilar materials, but often used as addition to rivets or similar joining technologies. It can be used as individual joining method but there are concerns with joining parts that needs to be in fixed position until adhesive dries.
- Conformal joining – is technology that uses part design such that features abut one another and eliminate motion. Structures that provide great strength can be made by adjoining of interfering structures

2.3 Design and Optimization in Lightweighting

In design process of vehicle, parts and assemblies are optimized while retaining their functionality and demanded characteristics. The design and optimization of parts, through development of Computer Aided Design/Computer Aided Manufacturing/Computer Aided Engineering (CAD/CAM/CAE) technologies have great impact on lightweighting. Reducing weight and improving mechanical properties can now be done through simulation with usage of Finite Element Analysis and variety of optimization types.

Structural Optimization Types

There are several types of structural optimization methods that is used in design of lightweight parts. One of the classification is by the type of design variables [11]:

- Topology optimization – design variables correspond to the element volume fractions that designs simultaneously the material properties (modulus of elasticity) and density in order to identify what elements to keep and what to discard.
- Sizing optimization – design variables are the element of cross-sectional dimensions, where all elements associated to a property data entry are designed with the same value.
- Topometry optimization – represents a generalization of sizing optimization where each element is designed independently.
- Shape optimization – design variables are scale factors of perturbation vectors that are input directly or by providing basis vectors (containing alternative grid locations) that can be internally converted into perturbation vectors (vectorial difference between basis vector and the original grid locations).
- Topography optimization – special case of shape optimization where perturbation vectors are either perpendicular to the designable region or in a given direction.
- Freeform optimization – special case of shape optimization where program splits any given perturbation into multiple perturbations on a grid by grid basis which increases the variability of design space.

Application of structural optimization can be seen on Fig. 8. There is shown the optimized design of plate. Goal in this example was to improve the stiffness and reduce weight of the component.

With development of additive manufacturing technologies, the design and manufacturing of complex parts has made possible. Optimization provided through additive

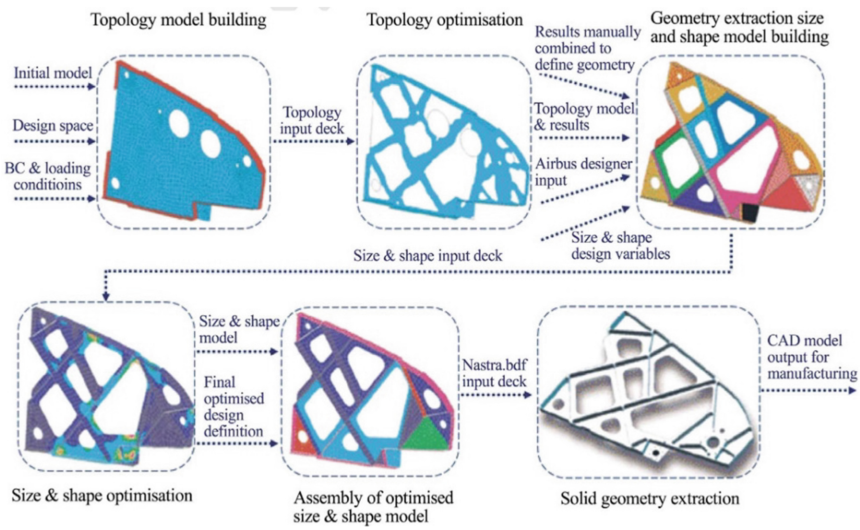

Fig. 8. Example of combination of topology, sizing and shape optimization methods on the design of plate component [12].

manufacturing have one more step and that is creation of infill structures in different configurations in order to decrease the amount of used material without the degradation of part mechanical properties.

From that the multi-scale optimization found its purpose. Additive manufacturing provides realizations of parts with topological optimization in macro-scale and lattice structure in meso-scale, and structural elastic properties can be made with designed gradients by lattice structure optimization [13].

On Fig. 9 can be seen the optimized structures of automotive bracket and lightweight titanium seatbelt buckle used in airplanes made by additive manufacturing.

Further improvement of lattice structures is through usage of bionic and mathematical inspirations seen on Fig. 10.

Fig. 9. Examples of optimized structures for manufacturing by additive technologies: a. optimization of automotive bracket; b. 3D printed lightweight titanium seatbelt buckle used in airplanes [13–15]

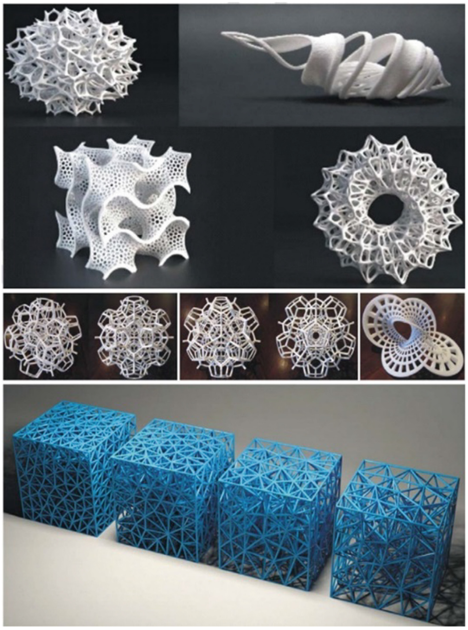

Fig. 10. Examples of AM lattice structures inspired by bionic design and mathematic [13, 16–18].

3 Conclusion

Application of lightweighting technology on transportation have great impact on energy efficiency, environmental protection and also economy. The methods shown in this paper are intertwined. Reduction of mass is achieved through optimized design using lightweight materials. Further development of lightweighting in transportation will reflected through transportation end environmental policies and through development of other technologies for increase of energy efficiency (such as alternative fuels etc.)

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