# Trend of Lightweight Vehicle Body Technologies

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**Abstract:** Lightweight automotive vehicle is becoming a trend because of the compelling need of environmental protection. Since the 1990s, in the US and Europe, it has prompted several large research initiatives in the automotive, steel and aluminum industries, as well as government sponsored programs. These projects and their major achievements are briefly described in this review paper. Technical approaches for making lightweight vehicle body, including advanced materials and manufacturing methods, are elaborated, and their technical advantages and issues are discussed.

**Keywords:** Lightweight, Vehicle Body, Vehicle Safety

## Introduction

There are three fundamental reasons for vehicle weight reduction: (a) reduce emission to protect environment; (b) reduce usage of natural resources such as petroleum and metal materials; and (c) improve a country's security by reducing dependence on oil import.

During the second half of the last century, the number of vehicles on roads increased dramatically as the economy grew. According to data by American Automobile Manufacturers Association [1], the US had 206.4 millions of vehicles in 1996, increased from 32.4 millions in 1940. During the same period, the number of vehicles in the world increased to 671.4 millions from 46.1 millions. Data of the US Bureau of the Census [2] shows that, in 2000, 38% of American families have two vehicles and 18% of US households own three or more vehicles.

In 2002 the US transportation sector consumed more than one-quarter of the total energy that the country consumed. Nearly 40% of the energy used in the US was from petroleum [3]. As a result, vehicle emissions have become a major source of air pollution.

A majority of the US oil consumption depends on import and about half of the import is from the OPEC countries. This has been perceived as a potential threat to the security of the US. In China, dependence on foreign oil is being accelerated. Due to the rapid economic growth in the past 20 years, China has turned itself into a net oil import country.

To increase vehicle fuel efficiency, development of alternative propulsion technologies is underway. It includes electric vehicle or full battery power, hybrid battery and internal combustion engine power, and fuel cell power. Three vehicle models using the hybrid power technology, Honda Insight, Toyota Prius, Honda Civic-Hybrid, have been on the US market. From July 2000 to December 2002, nearly 40,000 of Toyota Prius were sold in the US [4].

Weight reduction is a critical approach for reducing emissions. In particular, this review will focus on the weight reduction of vehicle body. Any reduction in the vehicle body can usually lead to

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additional reduction elsewhere on the vehicle. For example, for a lighter body, smaller engine power would achieve same performance. With a smaller engine, the car would only need to carry less fuel, which requires a smaller and lighter fuel tank. These weight reductions would lower the requirements on suspensions, wheels and tires, which would result in further weight saving.

Using advanced materials is a prominent approach for weight reduction. An equally important approach is to improve vehicle body manufacturing technologies. Advanced technologies in materials and manufacturing methods also enable further structural optimization.

**Major Research Initiatives for Lightweight Vehicle**

Facing the competition from the aluminum industry for reducing vehicle weight, the steel industry organized a research initiative called UltraLight Steel Auto Body, or ULSAB, and tried to demonstrate that, by using high strength steels, great weight saving can be achieved. The consortium included major steel companies in the world. In 1998, the consortium completed its study and announced a weight saving of 36% for mid-size car with the material and manufacturing cost comparable to those using regular steels [5].

The ULSAB vehicle body (Figure 1) employed ultra-high strength steel of 550 MPa yield for 90% of the body and the gauge thickness ranged from 0.65 to 2 mm. It also used tailored blanks to avoid structural discontinuities and provide smooth load flow. This not only allowed fewer parts and higher assembling efficiency but also enabled further structural optimization. The body was joined by mostly continuous laser welding with a total length of 18,286 mm for improved static and dynamic strength especially in torsion and crash loadings. The ULSAB body also used several other material and manufacturing technologies and they will be discussed in later sections of this paper.

**Figure 1**. The vehicle body developed by ULSAB with mostly ultra-high strength steels.

In September 1993, the US government and the US Council for Automotive Research (USCAR), a consortium of the three largest US automobile manufactures, formed a cooperative research and development partnership aimed at technological breakthroughs to produce a prototype "super-efficient" car. The "Big Three" (Ford, General Motors and then Chrysler), eight federal agencies, and several government national defense, energy and weapons laboratories joined in this Partnership for a New Generation of Vehicles (PNGV). It was intended to strengthen US auto industry competitiveness and develop technologies that provide cleaner and more efficient cars. The goals included production prototypes of vehicle capable of up to 80 miles per gallon gasoline (34 km per liter) for a mid-size car – three times greater fuel efficiency than the average car of 1994. This initiative promoted using advanced materials and manufacturing technologies for vehicle weight reduction and also started research and development of propulsion technologies such as hybrid power and fuel cell power.

In response to both the US PNGV program and accelerated vehicle development in Japan, the European Union (EU) formed the European Council for Automotive Research and Development (EUCAR). The objective was to increase competitiveness of the European automotive industry and environmental improvements. EUCAR requested a budget of over $2.3 billion from the EU over five years, representing a 50% EU government cost share. This included $866 million for vehicle technology, $400 million for materials R&D, $400 million for advanced internal combustion engine, $333 million for electric/hybrid propulsion, and $333 million for manufacturing technology and processes.

Japan took advantage of its Ministry of International Trade and Industry as the focus of industry-government cooperation to execute a similar activity with funding about $250 million per year. Its strategy was focused on market share and electric/hybrid vehicles for the California market. Reduction of nitrous oxide emissions was also an environmental goal of the program. Industry manufacturers gearing up for the 1998 California zero emission vehicle program included Honda, Mazda, Nissan and Toyota. Other Japanese manufacturers participating in the cooperative activity included Daihatsu, Mitsubishi, Isuzu and Suzuki.

In 2002, the US Department of Energy launched FreedomCAR, a partnership with automakers to advance high-technology research needed to produce practical, affordable hydrogen fuel cell vehicles that American consumers will want to buy and drive. FreedomCAR is neither a car nor a prototype – instead, it represents a new approach to powering the vehicles of the future. The "CAR" in FreedomCAR stands for Cooperative Automotive Research between the US Department of Energy and the US Council for Automotive Research. FreedomCAR focuses government support on fundamental, high-risk research that applies to multiple passenger-vehicle models and emphasizes the development of fuel cells and hydrogen infrastructure technologies.

In parallel, announced by President Bush in January 2003, the US government also launched The Hydrogen Fuel Initiative with a $1.2 billion investment in related technologies to reverse America's growing dependence on foreign oil by developing the technology needed for commercially viable hydrogen-powered fuel cells – a way to power cars, trucks, homes, and businesses that produces no pollution and no greenhouse gases. Through partnerships with the private sector, the Hydrogen Fuel Initiative seeks to develop hydrogen, fuel cell, and infrastructure technologies needed to make it practical and cost-effective for large numbers of Americans to choose to use fuel cell vehicles by 2020. The goal of the initiative was to dramatically improve America's energy security by significantly reducing the need for imported oil. At the same time, it is a key component of the US clean air and climate change strategies.

Most advanced automotive technologies (for example, lightweight materials and batteries) developed under the FreedomCAR Partnership can be used to accelerate deployment of gasoline-electric hybrids as well as advance development of fuel cell vehicles. These two US government programs are largely the continuation of the PNGV program.

**Advanced Materials for Weight Reduction**

The substitution of lightweight materials (such as aluminum, magnesium, titanium, advanced high-strength steels, and polymer matrix composites) for mild steel in automotive applications can have a positive impact on fuel efficiency and emissions.

The amount of high and medium strength steels, aluminum, and plastics used in automobiles has been growing (Figure 2) while the amount of regular steel and iron has declined. The change to lighter weight materials has helped the average automobile to be about 110 kg lighter in 2004 than in 1977. Steel (all kinds combined) makes up over half of the weight of an automobile.

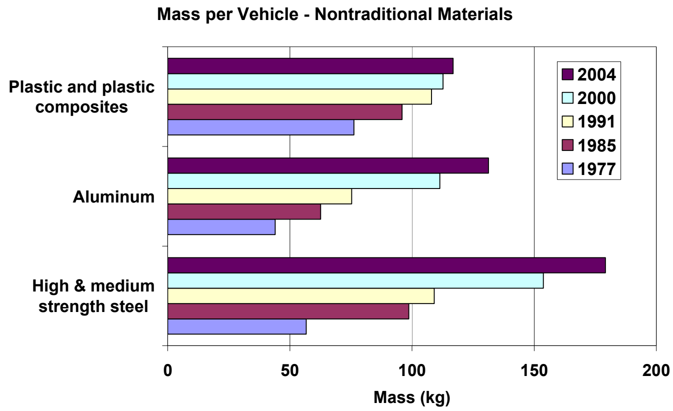


**Figure 2**. Nontraditional materials used in vehicles (Source: American Metal Market. 2004 data are projected).

Aluminum

As shown in Figure 2, average usage of aluminum in vehicle increased steadily from 44 kg of 1977 to 131 kg projected for 2004. There have been several full aluminum-body vehicle models on the market such as Audi A8 and Jaguar XJ. Given the fact that the vehicle weight decreased during the same period, the percentage of aluminum usage increased even faster.

The material properties (density, modulus, yield strength) determine that aluminum alloys can provide higher structural performance per unit mass than steel. This is why airplanes are made of aluminum. However, aluminum has higher material cost mainly due to high electricity usage in the production. Some of its physical properties such as low melting point, high electrical and thermal conductivity and large thermal expansion are also disadvantageous compared to that of steel.

Aluminum is less formable than carbon steel, in the sense that parts made from them lack dimensional control because the materials spring back into altered shapes after the binding force applied during the stamping operation has ceased. Spring back can be held in check through the application of binder forces that vary in response to part-surface and process variations. Traditional stamping methods, however, lack the flexibility to provide optimal forming trajectories for difficult-to-form materials. What is needed is an optimized, closed-loop, flexible binder force control system that can be installed in stamping presses to improve part quality, reduce variability, and maintain the accuracy of stampings made from aluminum alloys and ultrahigh-strength and stainless steels.

Many aluminum alloys are more brittle than mild steel. Also due to its lower stiffness and strength than steel, aluminum parts usually have thicker gauge thickness, which results in larger strain in bending. These factors make aluminum parts tend to fracture under impact loading [6]. For crash energy management, the fracture itself is not important and the fracture process does not absorb as much energy as bending and membrane stretch. However, fracture development affects other energy absorbing modes including bending and membrane stretch (Figure 3). Therefore, it is critical to accurately predict fracture development of aluminum parts under impact loading. This is a challenging technical issue.

**Figure 3**. Fracture development of 4-cell aluminum tube under axial impact loading [7].

Plastic and Composite Materials

Composite materials, such as metal-matrix, glass- and carbon-fiber reinforced thermosets, and thermoplastics, are promising materials. Polymer-matrix composites have been used as replacements for steel pickup truck beds and show excellent dimensional stability, high strength, and increased corrosion and wear resistance.

Advanced carbon-fiber composites offer great potential for weight reduction without sacrificing vehicle crashworthiness. For this reason, there is an extensive research program underway aimed at designing and developing a composite-intensive high-volume manufacturing process for the primary structure of vehicles. The targeted body-in-white structure will need to offer a minimum of 60% weight savings over steel while being close to steel in cost and meeting various manufacturing, assembly, and performance criteria.

Using lightweight core as spacing material to form a sandwich composite material can increase bending and torsional stiffness while achieving a weight saving. Figure 4 shows a sandwich plate with metal form core [8]. For better interface strength, it is preferred that the two surface plates are made of the same metal material as the metal foam core. Another example is hybrid metal/plastic (stabilized core) systems shown in Figure 5 and this type of sandwich plates was used in the ULSAB vehicle body [5].

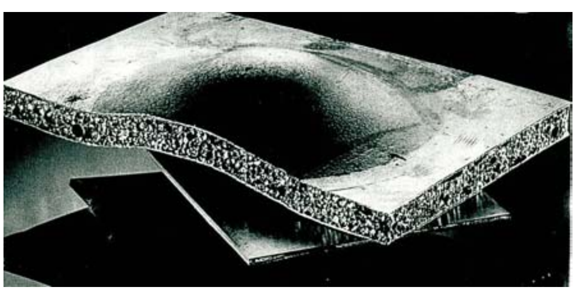

**Figure 4**. Metal foam sandwich plate [8].

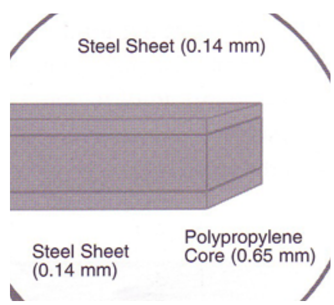


**Figure 5**. Metal/plastic sandwich plate [5].

Plastic materials were first used to manufacture non-load bearing parts of vehicle body such as fenders, bumper facial and door panels. As thermoplastics technology advanced, some of them have been used as non-critical load bearing components such as instrument panel. Figure 6 shows an instrument panel of the 1995 Lincoln Continental, made of an injection molded from ABS [9]. It consists of two adhesively bonded plastic parts. It replaced the steel cross-car beam of 18 parts used in its prior model and achieved 4.5 kg mass saving.

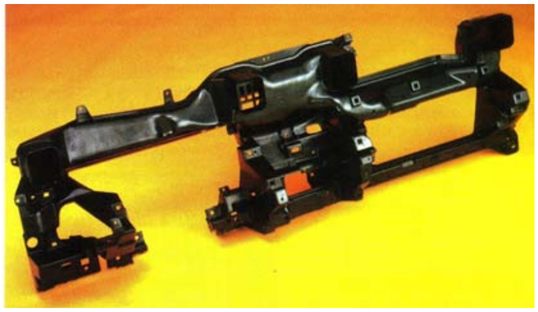

**Figure 6**. An injection molded plastic instrument panel [9].

**Manufacturing Technologies for Weight Reduction**

The traditional method for vehicle body manufacturing, stamped steel panels joined by spotwelds, has been proved efficient and cost effective. However, it also has several drawbacks compared to some advanced manufacturing methods.

Continuous Bonding and One-Piece Tube

For a given thin-wall tube such as vehicle frontal rail, it is apparent that continuous bonding renders greater structural stiffness and strength over spot-welding. In other words, for required stiffness and strength, the tube with continuous bonding may have smaller gauge thickness than that with spot-welding, and thus achieving a mass saving. Two examples of continuous bonding are laser welding and adhesive bonding. With the current adhesive bonding technology, it may still be necessary to combine it with the spot-welding for achieving required performance under impact loading.

Alternatively, one-piece tube, which does not need bonding at all, would have the same structural effect achieved by the continuous bonding. Tube hydroforming and aluminum tube extruding are two methods for making one-piece tubes and they are entering the main stream of vehicle body manufacturing. One-pieced tubes also have a smaller number of assembly operations.

Hydroforming consists of bending tubes in a rotary draw bender and then expanding them by fluid pressure in a die until they take on the die's shape. This process is well understood for steel, but not so for aluminum. As a consequence, hydroformed aluminum tubes are not yet used by the US automobile industry. It is a research project under the US FreedomCAR initiative, in which material data, design rules, and a computer model of the hydroforming process to enable the design and manufacture of hydroformed aluminum tubes for use in automotive bodies will be developed.

Joining of Dissimilar Metals

Aluminum alloys are among the many new materials making their way into automobile construction. A technical challenge is to find ways to effectively join these lightweight metals and more traditional automotive materials such as steel. One program by USCAR is to develop and evaluate different technologies for joining dissimilar aluminum alloys to one another and for joining aluminum to steel. A unified modeling procedure to represent these joints in computerized vehicle structural simulations will need to be developed.

The candidate techniques for joining together dissimilar aluminum alloys are spot welding and self-piercing rivets, with or without adhesives; for aluminum-to-steel joints, they are self-piercing rivets with or without adhesives. These methods are not yet in wide use because there is not sufficient performance data showing that they are safe and durable.

As the list of potential materials for automobile construction grows, manufacturers also need ways of joining new composite materials to more traditional automotive construction materials, such as steel and aluminum. Because these are dissimilar materials, traditional welding techniques will not work. The automotive industry has been slow to adopt joining methods that rely on bolts, rivets, and adhesives (techniques known collectively as hybrid joining), because there is not enough data yet showing whether they are strong enough to withstand the stresses associated with automotive applications.

**Lightweight Vehicle and Safety**

Lightweight vehicles will pose a new challenge to vehicle safety. About the most firmly established vehicle safety effect is that the heavier the vehicle, the lower are the risks to its occupants. Passengers in lighter vehicle will endure greater deceleration when colliding with heavier vehicle and thus greater injury risks. When the vehicles become lighter and lighter, there will evidently be an extended transition period of mix traffic of heavy and light vehicles on roads. Mix heavy and light vehicles have already been observed on roads, but due to an opposite reason: heavy vehicles such as SUVs increased significantly during the past 10 years.

In two-vehicle crashes, an increase in mass of one vehicle exposes the occupants of the other vehicle to increased risk. Interestingly, according to a recent study by Evans [10], increased size of a vehicle also protects its own occupants, but without any adverse effect on occupants of vehicles into which it crashes. This finding was based on a statistical study of 3118 crashes. The data was extracted according to certain criteria from the US Fatality Analysis Reporting System (FARS) data for 1975-1998. The finding manifests that, to make a lighter vehicle safe, it should be designed larger. Using advanced lightweight materials will enable this approach. A straightforward design option, although may not be optimal, is to make vehicle crumbling zone larger.

Weight reduction is a double-edged sword to vehicle stability and safety. It would be easier to maneuver a lightweight car and make it stop in active safety control. Its lower location of the center of gravity makes it more difficult to rollover. However, when driving a lightweight vehicle, it may be difficult to maintain heading and frequent course corrections would increase driver fatigue. Lightweight vehicles will also be more sensitive to lateral wind force.

**Concluding Remarks**

Developing lightweight vehicle technologies is driven by the need of environmental protection. Several large research initiatives in the western world have promoted great technology advancement. High strength steels, lightweight metal alloys such as aluminum and magnesium, and composite materials are competing in the course of dominating lightweight vehicle design. Manufacturing methods for weight reduction, including sheet metal hydroforming, aluminum extruding, continuous bonding, etc., may soon enter the main stream of vehicle body manufacturing. As cars get lighter, more technical challenges in vehicle safety will be encountered. Great engineering efforts will be required in designing light and safety vehicles.

## References


1. American Automobile Manufacturers Association, “World Motor Vehicles Data”, 1998 Edition, 1998.
2. US Bureau of the Census, “American Fact Finder”, August 2001.
3. US Energy Information Administration, “Monthly Energy Review”, July 2003.
4. Crain Communications, “Automotive News”, December 23, 2002.
5. American Iron and Steel Institute, “UltraLight Steel Auto Body Final Report”, 1998.
6. McGregor IJ, Meadows DJ, Scott CE, and Seeds AD, “Impact Performance of Aluminum Structures”, in book “Structural Crashworthiness and Failure”, edited by Norman J, and Wierzbicki T, Elsevier, 1993.
7. Mayer RR, Peterson B, Mishra R, and Sachdev A, “The Effect of Tempering (Artificial Aging) on the Crashworthiness Performance of Mass-Efficient Extruded Aluminum Structures”, Proceedings of Design Engineering Technical Conferences, ASME, Chicago, Illinois, September 2-6, 2003.
8. Kimberley W, and Rogers K, “Materials”, Automotive Engineer, Volume 24, 1999.
9. Florence R, and Sherman K III, “Instrument Panel Trends and Engineering Thermoplastics”, Automotive Engineering, May 1997.
10. Evans L, “How to Make a Car Lighter and Safer”, SAE 2004-01-1172, SP-1878, SAE World Congress, 2004.