REVIEW ON WEIGHT REDUCTION IN AUTOMOBILE

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ABSTRACT

Vehicle weight reduction is a known approach to address growing concerns about greenhouse gas emission and fuel use by passenger vehicles. We find that every 15% reduction in vehicle weight can cut fuel utilization by about 7%. In modern era vehicle weight cutback is essential for meeting future, more stringent fuel economy standards. New vehicles are required on average to achieve at least 80 KM per LIT, by year 2016, up from 28.8 MPG today. The values of future vehicle description and sales mix indicate that the target is aggressive. New vehicles must not only become lighter, but also forgo kilowatt improvements, and progressively use advanced, more fuel-efficient power trains, such as hybrid-electric drives.

We can decrease weight by substitute some of the iron and steel used in vehicles with lighter-weight high-strength steel or aluminium, redesigning the vehicle, and/or downsizing the vehicle. Using these specifications, it is possible to achieve up to 40% (690 kg) vehicle heaviness reduction. However, the cost associated with manufacturing less weighted vehicles is a nontrivial $3 to $4 per kilogram of total weight saved. In addition, the properties of materials impacts of using alternative lightweight materials, which tend to be more energy-intensive to process, must also be considered. In this paper, the energy implication of pursuing this light weighting strategy are explored on a vehicle life-cycle- and vehicle fleet system-level basis. A model of the energy and material flows through the evolving vehicle fleet system over time has been developed, which accounts for potential changes in future vehicle weight and material composition. The resultant changes in material production energy and fleet fuel savings, which are the main energy burdens for the entire product system – the vehicle fleet –, are estimated. The new 2016 fuel economy standards and more stringent standards beyond can become conscious significant fuel savings of 1,550 billion liters through year 2030. However, the advanced power trains that are expected to enter the marketplace are heavier and require more energy to produce. Their production efforts may be offset by efforts to use less energy-intensive high-strength steel to lightweight new vehicles, as well as efficiency profit with respect to efficiency in material processing.

KEYWORDS

Historical vehicle weight trends
Effectiveness of vehicle weight reduction
How vehicle weight reduction can be achieved
Vehicle weight reduction by lightweight material substitution
Vehicle weight reduction by redesign and secondary weight savings
Cost of vehicle weight reduction.

I. INTRODUCTION

Vehicle weight reduction is a well-known strategy for improving fuel consumption in vehicles, and presents an important opportunity to reduce fuel use in the transportation sector. By reducing the mass of the vehicle, the inertial forces that the engine has to overcome are less, and the power required to move the vehicle is thus lowered. In this section, weight reduction as a strategy to reduce fuel consumption will be explored, primarily on the vehicle level. The effects of weight reduction on fuel use on the light-duty vehicle fleet level will be examined in Section 7.

1) Historical vehicle weight trends

In the United States, the sales-weighted average new light-duty vehicle weight is 1,880 kg (4,144 lb) today, and has been increasing slowly but steadily at a rate of about 1% per year since the early 1980s (see Figure 10 (a)). Since the mid 1980s, the popularity of larger and heavier light trucks, especially sport utility vehicles (SUVs), was partly responsible for the upward weight trend. The market share of SUVs has increased by more than a factor of 10, from less than 2% of the new light-duty vehicle market in 1975 to 27% of the market today. Conversely, the market share of new passenger cars and station wagons has decreased by more than 30%

2) Effectiveness of vehicle weight reduction

It is clear that vehicle weight reduction has the potential to reduce fuel consumption, but the precise relationship is not so obvious. Figure 12 plots the adjusted, combined city/highway (55/45) fuel consumption and curb weights of all model year 2005 light-duty vehicles offered in the United States, revealing a general positive correlation. On average across all available vehicle models, every 100 kg weight reduction will achieve a reduction of 0.69 L/100km in fuel consumption. While these figures are useful to detect a general trend, they are not normalized for performance, size, or other attributes.

3) How vehicle weight reduction can be achieved

There are several ways to reduce the sales-weighted average weight of new vehicles sold in the United States. Weight reduction can be achieved by a combination of: 1) lightweight material substitution; 2) redesigning the vehicle to minimize weight; and 3) downsizing the new vehicle fleet by shifting sales away from larger and heavier vehicles. These approaches will be discussed in turn.

4) Vehicle weight reduction by lightweight material substitution

For an average vehicle, about three-quarters of its weight is incorporated in its powertrain, chassis, and body (Figure 14), and the bulk of this is made of ferrous metals. Other major materials found in an average automobile in the United States include aluminium and plastics or composites, as shown in Figure 15. This figure also shows how the use of aluminium and high-strength steel (HSS) as a percentage of total vehicle mass has been increasing over the past two decades, while the use of iron and mild steel has been declining. Aluminium and high-strength steel are two of several alternative lightweight materials that can be used to replace heavier steel and iron in the vehicle. Other material candidates include magnesium, and polymer composites such as glass- and carbon-fibre-reinforced thermosets and thermoplastics. The relevant properties of these materials are summarized in Table 13 below, and are discussed in turn. More costly and rarer alternative materials, such as metal-matrix materials and titanium, are not considered.

Aluminium. Nine percent of the mass of the average automobile in the United States is aluminium. Most of the aluminium is cast, and used mainly in the engine, wheels, transmission, and driveline. The stamped-sheet aluminium body of a car is more difficult to form than steel, and has to be handled with care to prevent scratches, because it is softer. Aluminium is a better conductor than steel, making it more difficult to spot weld, so it is more likely to use more laborious adhesive bonding rather than spot welding. Ducker Research projects that aluminium use in automotive applications will reach 144 kg per vehicle by 2010, but is unlikely to overtake steel, due to the higher cost of aluminum.

Magnesium. Magnesium alloy is 30% less dense than aluminum and 75% lighter than steel components. It is also easier to manufacture, having a lower latent heat (it solidifies faster, and die life is extended), and being easier to machine. However, it has a lower ultimate tensile strength, fatigue strength, modulus, and hardness than aluminum. Promising automotive applications include structural components in which thin-walled magnesium die castings may be used. About 40% of magnesium in vehicles today is cast into instrument panels and cross car beams. Other applications include knee bolsters, seat frames, intake manifolds, and valve covers.

Magnesium content in vehicles is expected to grow from 3.5 kg today to 7.3 kg in 2010 [Ducker 2002]. The U.S. Automotive Materials Partnership (USAMP) announced an ambitious goal of raising this to almost 160 kg by 2020. However, factors limiting the growth of magnesium by the automotive industry include the development of creep-resistant alloys for high-temperature applications, improvements in the die casting quality and yield, corrosion issues, and the production of magnesium in sheet and extruded forms. **Polymer composites**. Plastics and polymer composites currently make up about 8% of a vehicle by weight and 50% by volume, and these numbers are expected to increase slowly. The main factors restricting the growth of polymer composites in vehicles today are the long production cycle times and the cost of the fibers. The most common type of automotive composites is glass fiber reinforced thermoplastic polypropylene, which is applied to rear hatches, roofs, door inner structures, door surrounds, and brackets for the instrument panel. Other types include glass mat thermoplastics, sheet molding compounds made of glass fiber reinforced thermoset polyester, and bulk molding compounds or glass fiber reinforced thermoset vinyl ester. Carbon fiber reinforced polymer (CFRP) composites are more expensive and less popular, although they offer significant strength and weight-saving benefit. The Rocky Mountain Institute's mid-size concept Hypercar used CFRP to achieve a body-in-white weight that is 60% lighter than a conventional steel one [Lovins and Cramer 2004]. However, carbon fibers cost an inhibiting $13–$22 per kilogram, compared to $1–$11 per kilogram of glass fibers [Das 2001]. Use is typically restricted to low-volume applications in high-end luxury vehicles. One successful application in production vehicles is the carbon fiber drive shaft. Other technical challenges of using CFRP include the infrastructure to deliver large quantities of materials and the recycling of composites at the vehicle's end of life.

To summarize the lightweight material candidates, a comparison of these options is given in Table 14. Of the candidates, aluminum and HSS are more cost-effective at large production volume scales, and their increasing use in vehicles is likely to continue. Cast aluminum is most suited to replace cast iron components, stamped aluminum for stamped steel body panels, and HSS for structural steel parts. Polymer composites are also expected to replace some steel in the vehicle, but to a smaller degree given high cost inhibitions.

5) Vehicle weight reduction by redesign and secondary weight savings

Redesigning or reconfiguring the vehicle is another strategy to achieve weight savings. For example, a marked decline in vehicle weight in the early 1980s was partly achieved by changing some vehicles from a heavier body-on-frame to lighter-weight unibody designs. Although most cars already have a unibody design, the potential exists for smaller sport-utility vehicles to follow suit. Another way to minimize weight with creative design and packaging is to minimize the exterior dimensions of the vehicle while maintaining the same interior space, or to remove features from the vehicle. Figure 16 plots the interior volume of various midsize sedans offered in model year 2007 with their curb weights, illustrating the potential weight savings using this approach. However, it is acknowledged that the need for safety features, either by regulation or consumer demand, may hinder lightweight vehicle design using this approach. Secondary weight savings can also be realized by downsizing subsystems that depend on the total vehicle weight. As the vehicle weight decreases, the performance requirements of the engine, suspension, brake subsystems and others are lowered, and these can be resized accordaccordingly. Recently, researchers at the University of Michigan estimated a 1.25 factor for secondary, compounded weight savings by observing the mass of all subsystems in 35 different vehicle models. [Malen and Reddy 2007] That is, for every 1.00 kg initial mass change, an additional 1.25 kg of mass savings will be realized by resizing subsystems accordingly. It is acknowledged in this report that their approach does not normalize the data for other parameters, such as vehicle size or acceleration performance, which could lead to less optimistic weight savings. For example, simulations of the Toyota Camry reveal that if the car's body weight is reduced by 100 kg using material substitution, the engine weight can be lowered by only 9 kg while delivering the same vehicle acceleration performance.43 Reviewing these novel design options, it is clear that the amount of weight savings using this approach is not easily quantified and depends on the final designs of subsystems and the entire vehicle. The amount of secondary weight savings possible by vehicle redesign was moderated; we assumed it to be half the benefit achieved with material substitution. So, for every incremental kilogram of weight reduction from material substitution, one can expect to achieve a further 0.5 kg weight savings with weight-minimizing redesign.

6) Vehicle weight reduction by size reduction

Vehicle size reduction, the third way to reduce vehicle weight, is distinguished from the two weight-reduction approaches already discussed. Vehicle size generally correlates with weight. This can be seen in Figure 17, which shows vehicle size in terms of a modified footprint—its wheelbase multiplied by overall width—and curb weight of all model year 2005 light-duty vehicle models offered in the United States.

7) Brief discussion on safety

The discussion of vehicle lightweighting is not complete without some mention of safety implications. There is much debate on this topic, and there are studies that indicate how drivers and occupants of smaller and lighter vehicles are at a greater risk in crashes than those in larger and heavier vehicles. The question of how vehicle weight reduction affects overall traffic safety is not as straightforward, however, and is confounded by other driver-, road-, and accidentrelated factors. We believe that there will be little compromise in safety standards when reducing the weight and size of the vehicle, for two reasons. First, it is possible to design and build quality small vehicles with similar crashworthiness as larger and heavier ones. Use of new materials, such as aluminum and some composites designs, can offer superior cash energy absorption. By reinforcing the structural stiffness of the vehicle at critical points, including safety features such as side airbags, and introducing crumple zones to absorb energy in case of a collision, automakers are already making smaller cars that protect their occupants better. For example, the MINI Cooper scored 4 out of 5 stars in the U.S. National Highway Traffic Safety Administration frontal and side crash ratings. Second, aside from the crashworthiness of the vehicle and driver safety, there are other facets of the traffic safety discussion to be considered, including rollover risk, aggressiveness of vehicles to other road users, and vehicle crash compatibility. Considering net or overall traffic safety, some of the larger and heavier SUVs and pickups can actually pose greater safety risks for their drivers and other road users [Ross et al. 2006]. Hence, there is little compromise in safety as vehicle weight and size is reduced, and safety for all might actually improve if the heaviest vehicles could be made lighter.

8) Cost of vehicle weight reduction

Cost is an important consideration, because we are interested in detailing the benefits associated with vehicle weight reduction at an acceptable cost of implementation. For weight reduction using lightweight materials, automakers have been reluctant to adopt new materials and manufacturing processes, in part because of the established infrastructure, capital equipment, and knowledge base to promote use of conventional materials, and also because of the cost of substituting these alternative lightweight materials. Cost estimates of using lightweight automotive materials in the literature vary widely, from $1.20 to $13.70 per kilogram of weight savings. This is not surprising, since much depends on the type of lightweight material proposed, the vehicle component, assumptions made on the processing of the materials, and the production volume. When comparing the use of lightweight materials in different vehicle components, we reiterate that the weight reduction benefit depends very much on the intended use and design. So the substitution of a lightweight material, say aluminum, for steel brings about a wide possible range of weight reduction for different components. To get a sense of potential applications of lightweight materials in vehicles and their corresponding manufacturing (OEM) costs,44 results from different case studies available in the literature are summarized in Table 16. Most of the case studies examined lightweight material applications in the body-in-white. In general, the cost of alternative lightweight automotive material technology per unit weight savings is lower for high-strength steel (HSS), and is followed by aluminum and polymer composites. Automotive composites remain prohibitively expensive given high raw material prices and long production cycle times. HSS and aluminum are likely to remain popular substitutes for steel in passenger vehicles in the near-term. Given this review, we will assume a mid-range estimate of $3.00–$5.00 per kilogram of weight savings by material substitution. Costs will be on the lower end for early weight reduction, and increase as more aggressive weight reduction is sought. Vehicle redesign and size reduction are simply assumed to be cost-neutral with respect to manufacturing costs. We assume that design costs are already incorporated in the development of new vehicle models and the manufacturing costs of producing a smaller or larger vehicle do not differ much. As a result, the net cost of weight reduction by all three approaches would be $2.00–$3.50 per kilogram shaved off the average vehicle.

II. CONCLUSION

Reduction in vehicle size and weight can significantly reduce fuel consumption. Every 10% of weight reduced from the average new car or light truck can cut fuel consumption by around 7%. The three strategies to reduce weight are (1) lightweight material substitution, (2) vehicle design changes, and (3) vehicle downsizing. When alternative materials are used to perform light weighting, aluminium and high strength steel are more cost effective at large production scales. Plastics and polymer composites, which cost more, will likely take a smaller role. With aggressive material substitution, up to 20% of vehicle weight can be cut. Secondary weight savings can be realized by downsizing subsystems. It is also possible to reduce weight by redesigning or reconfiguring the vehicle. Creative designs can minimize the exterior dimensions of the vehicle while maintaining the same interior space. Average vehicle weight can also be reduced by downsizing vehicles. That means selling more small vehicles and fewer large ones, both across and within vehicle segments. If a buyer were to choose a small car instead of a midsize, or a midsize instead of a large car, the vehicle's weight could be reduced by 9% to 12%. For SUVs, minivans and pickups, the weight savings can reach 26%. Based on these assessments of material substitution, vehicle redesign, and downsizing, weight reduction of 20-35% is possible by 2035. We estimate that weight reduction by all three approaches would cost $2 to $3.50 per kilogram of weight saved in the average vehicle.

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