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Review of Technical Literature and Trends Related to Automobile Mass-Reduction Technology

May 2010

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Acronyms, abbreviations, units

AHSS:	Advanced high-strength steel
Al:	Aluminum
CAFE:	Corporate Average Fuel Economy
CARB:	California Air Resources Board
CO_2:	Carbon dioxide
gCO_2/mi:	gram of carbon dioxide per mile
gallon:	gallon, equal to 3.785 liters
HSS:	High-strength steel
lb:	pound, equal to 0.4535 kilogram
kg:	kilogram, equal to 2.205 pounds
Mg:	Magnesium
mi:	Mile, equal to 1,609 meters
mpg:	Miles per gallon
PNGV:	Partnership for a New Generation of Vehicles
SMC:	Sheet-molded composite
ton:	U.S. ton, equal to 2,000 pounds
U.S. EPA:	United States Environmental Protection Agency

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Executive summary

Past automotive trends, ongoing technology breakthroughs, and recent announcements by automakers make it clear that reducing the mass of automobiles is a critical technology objective for vehicle performance, carbon dioxide (CO_2) emissions, and fuel economy. Vehicle mass-reduction technology offers the potential to reduce the mass of vehicles without compromise in other vehicle attributes, like acceleration, size, cargo capacity, or structural integrity. As regulatory agencies continue to assess more stringent CO_2 and fuel economy standards for the future, it is unclear the exact extent to which vehicle mass-reduction technology will be utilized alongside other efficiency technologies like advanced combustion and hybrid system technology. This report reviews ongoing automotive trends, research literature, and advanced concepts for vehicle mass optimization in an attempt to better characterize where automobiles – and their mass in particular – might be headed.

Several findings on mass-reduction technology trends emerge from this assessment. Automakers are deploying a wide variety of advanced materials in new vehicle models. The competition between alternative materials like high-strength steel, aluminum, magnesium, and plastic continues to result in a rich portfolio of options to reduce vehicle mass component-by-component (e.g., engine, beams, panels, etc). In addition, design approaches for the vehicle body structure that more heavily utilize higher-strength steels and aluminum are beginning to be embraced by some manufacturing companies, and this could substantially reduce the mass of vehicle models. Several major studies, as well as some automakers' announced plans, indicate that mass-reduction technology with minimal additional manufacturing cost could achieve up to a 20% reduction in the mass of new vehicles in the 2015-2020 timeframe. This incremental mass-reduction approach would, in turn, result in a 12% to 16% reduction in CO_2 emissions while maintaining constant vehicle size and performance.

Greater potential for future CO_2 emission reductions involves the commercialization of more advanced mass-optimization technologies that go beyond the near-term incremental approaches. Greater reductions in vehicle mass result from more comprehensive vehicle optimization designs that incorporate component-level mass reduction, a diverse mix of materials, secondary mass-reduction effects, new manufacturing techniques, and component integration to systematically make the whole vehicle more mass-efficient. These more advanced mass-optimization techniques could yield vehicle mass reductions of 30% or greater but would involve some additional costs and manufacturing process modifications. This scale of mass-reduction has been found to be feasible for introduction in model year 2020 vehicles. Beyond its direct CO_2 improvement, this scale of mass-reduction technology could involve powertrain cost improvements that could help enable affordable hybrid electric-drive vehicles.

Based on automakers' commitments to deploy mass-reduction technology, this study offers several policy implications. Automakers and suppliers are moving forward with advanced mass-optimization techniques apparently at a faster rate than regulators forecast or acknowledge. Several worldwide vehicle efficiency policies are directly indexed to the mass of vehicles (e.g., in Europe, China, and Japan), and therefore these standards stand to provide a lesser incentive for automakers to pursue and deploy emerging mass-reduction technologies in their new vehicle designs. Furthermore, U.S. regulators similarly have downplayed the importance of mass-reduction as a core efficiency technology to reduce new vehicle CO_2 emissions and increase fuel economy. Lack of recognition about the potential for vehicle mass reduction can run the risks of neglecting a major CO_2-reducing technology, ignoring a critical low-cost technology, and missing an opportunity to the set the stage for long-term electric-drive technologies that may very well require mass-reduced vehicles.

1. Introduction

Technology developments by the automobile industry, consumer preferences for vehicle performance, and societal pressures on vehicle efficiency will ensure that there will be a constant deployment of lower-mass vehicle concepts in new automobiles. This mass-reduction technology deployment occurs with the piece-by-piece introduction of new reduced-mass parts, the use of advanced materials in stronger designs, and the redesign of vehicle models that systematically optimize the use of materials and design in a more comprehensive manner. These types of mass-reduction technology can reduce the mass of vehicles, independent of the size, functionality, or vehicle class of automobiles.

A primary driver for reducing the mass vehicle designs will be the consistent regulatory push for increased vehicle efficiency in major automobile markets. Standards that regulate the fuel efficiency or carbon dioxide (CO_2) emissions of light duty vehicles have become the norm around the world. The goals of the standards generally are to reduce petroleum use and the CO_2 emissions associated with automobiles. These standards take on many different forms, involve different ways of categorizing vehicles, require different levels of stringency, and have different timelines for their implementation. There are regulatory standards in Europe (gCO_2/km), United States (gCO_2/mile, mile/gallon), China (km/L), Japan (km/L), Canada (gCO_2/mile), South Korea (km/L, gCO_2/km), Taiwan (km/L), and Australia (L/100km) (ICCT, 2009). Together, these programs encompass about 70% of 2009 world automobile sales. These efficiency initiatives – or at at least those that do not index their standards to mass – will drive the development of vehicle mass-reduction techniques along with a variety of engine, transmission, and other vehicle efficiency technologies.

This study investigates trends and technical research related to the development of reduced-mass vehicle designs and their potential importance for the efficiency of future vehicles. The report is structured as follows. After this introduction section, Chapter 2 reviews a number of basic weight-related trends in the U.S., including a summary discussion of a number of fundamental relationships in vehicle attributes of weight, performance, and CO_2 emissions. Chapter 3 analyzes trends related to materials and vehicle structural changes that allow for the reduction of vehicle weight, highlighting a variety of mass-reduction concepts that are now emerging in production vehicles. Also within Chapter 3, technical literature on the potential for mass-optimized vehicle designs is examined and findings from a number of major engineering design studies are reviewed. Chapter 4 provides a discussion of the implications of these vehicle mass reduction trends for future policy. Chapter 5 briefly summarizes major findings.

2. Background

Some background is provided in this section to put the rest of this report on vehicle mass reduction in context. This section outlines basic vehicle mass trends in the U.S., the relationship between mass and other vehicle attributes, the distinction between mass-reduction technology and downsizing, and the basic breakdown of vehicle mass by the various components of the vehicle.

Vehicle mass, or more typically measured as weight in the U.S., has changed substantially in various automotive markets over different time periods. Light-duty vehicles sold in the U.S. over the past 35 years exhibit how weight trends can shift under different market and regulatory situations. Figure 1 shows the weight trend for light-duty vehicles, as well as for the two major categories within light duty vehicles (based on data from U.S. EPA, 2009a). The historical shifts in the U.S. auto market over this period show both periods of decreasing and increasing weight. From 1975-1980, the time period of the onset of federal fuel economy standards, as well as higher fuel prices and drastic world oil price fluctuations, there was a 21% decrease in average new light duty vehicle weight (with a 25% decrease for cars and 9% for light trucks). However, following that time period was a period of stable fuel economy standards and relatively low or stable fuel prices, resulting in rather different vehicle attribute trends. During the period from 1987-2009, the shift has been toward heavier vehicles, with a 28% weight increase for new light duty vehicles over that span (27% weight increase for cars, 17% for trucks). During that span, the highest year-on-year increase in vehicle weight was 3%, and the annual average increase was 1.1%.

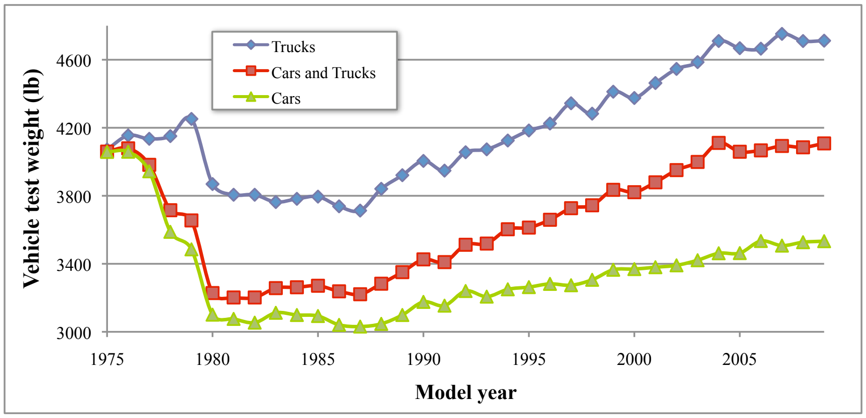


Figure 1. Light duty vehicle weight trends for model years 1975 to 2009 (U.S. EPA, 2009a)

The presentation of data in the above Figure 1 involves aggregated data on the weight trend in the new vehicle fleet. Underlying the overall vehicle weight trend is a handful of factors related to consumer shifts in vehicle category and size, as well as differences in the content of the vehicles. Just as the average light duty vehicle weight increases due to consumer shifts from cars to trucks, so to do the car and truck average weight increase due to the increased purchase of existing models that are in heavier vehicle classes within those categories (e.g., compact sedan to mid-size sedan shift). These fleet composition sales shifts are separate trends from the concurrent general increases in vehicle weight that come from vehicle model redesign changes that tend to see increases in vehicle content (e.g., air conditioning, safety equipment). Based on a General Motors study, the content increases due to such equipment changes on a vehicle could amount to approximately 300-400 lbs (Glennan, 2007). This would imply that equipment changes represent a smaller portion – about 20-40% – of the overall light duty vehicle weight trend shown in Figure 1 (see also Corus, 2009).

The remainder of the overall mass increase would then come primarily from the shifts toward vehicles of larger size and mass characteristics (i.e., independent of vehicle content). Due to the relatively recent development of U.S. size-indexed standards and the related tracking of size variables, there are not comparable historical model year data for vehicle size to compare with the above vehicle mass weight data. It is highly likely that data on vehicle size (as measured by the footprint metric) has followed approximately the same trend as vehicle mass on a percentage basis, due to the close statistical correlation between vehicle size and mass variables. Vehicle size and mass relationships are investigated further later in this report (See, for example, Figure 10 for how current vehicle models' size and mass are related).

To understand vehicle efficiency improvements that occur over time, multiple vehicle attributes must be examined at once. The trade-offs that are involved with efficiency technologies and their potential use toward vehicle performance (e.g., maximum power, greater acceleration), vehicle size and mass, and fuel economy have been analyzed extensively in the research literature. Vehicle designers and powertrain engineers have continued to bring forth incremental efficiency improvements in vehicles' aerodynamics, engines, and transmissions through redesign phases of vehicle models. However, how this technology budget is utilized in the U.S. light duty vehicle fleet tends to differ over time, due to the level of regulatory pressure to increase fuel economy, the changes in the price of petroleum, and consumer reactions to market factors and automaker offerings.

Figure 2 shows vehicle attribute trends from the onset of U.S. Corporate Average Fuel Economy (CAFE) standards in 1975 through model year 2009. In the figure, average new light duty vehicle weight, acceleration performance, fuel economy, and weight-adjusted fuel economy are shown, with data from U.S. EPA (2009a). The vehicle weight variable is the loaded test weight of vehicles. The acceleration performance is U.S. EPA's estimate of the time it takes to accelerate vehicles from rest to 60 miles per hour (mph) in seconds. The fuel economy variable is the combined (city and highway), adjusted (for on-road conditions) measure of miles per gallon traveled. The "efficiency" variable is the weight-adjusted fuel economy of vehicles (weight multiplied by fuel economy), and is a measure of the distance that a vehicle can transport a ton, or 2000 lbs, of loaded vehicle weight on one gallon of fuel. This ton-mpg measure is used here as a simple measure for overall vehicle efficiency, due to data difficulties in attempting to more accurately portray the more true technical efficiency of engines, transmissions, aerodynamics, vehicle weight, etc. All of the variables are sales-weighted average values for new vehicles of the model year specified.

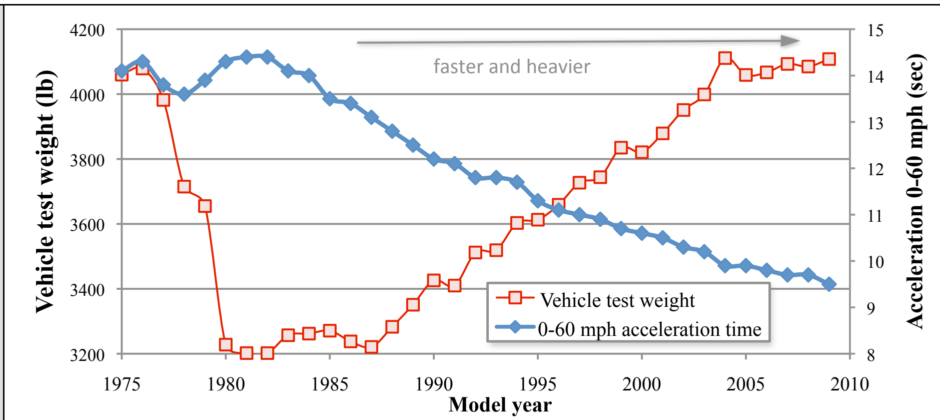
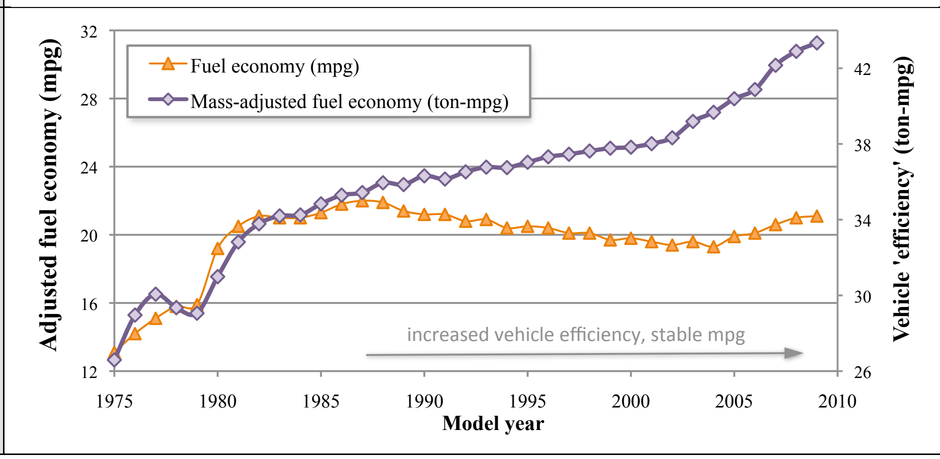
Vehicle weight and acceleration trends	
Fuel economy and weight-adjusted efficiency trends	

Figure 2. U.S. light duty vehicle trends for weight, acceleration, fuel economy, and weight-adjusted fuel economy for model years 1975-2009 (U.S. EPA, 2009a data)

By showing the acceleration, weight, fuel economy, and the efficiency variables together, Figure 2 demonstrates the historical trade-offs that have occurred between these factors. Within that 1975-2009 period, the only period for which major fuel economy increases were mandated was from 1975 to 1987. During this early CAFE time period, when there was an increasingly stringent fuel economy standard, vehicle weight was constrained – to either be held steady or be reduced on average – to aid in automaker compliance with the fuel economy standards. Also during this time period, vehicle acceleration was approximately stable. With these weight and acceleration variables constrained, new efficiency technology was fully devoted to fuel economy improvement. As a result, average fuel economy improved rather dramatically from about 13 mpg to about 22 mpg in those first twelve years of CAFE. However since 1987, vehicles have, on average, become heavier and faster while fuel economy has not shown marked or consistent increases. By showing the combined impact of vehicles getting heavier while having approximately stable fuel economy from 1987 to 2009 in ton-mpg terms, the improvement in vehicles' technical efficiency is illustrated. This steady efficiency improvement from 1987 to today went toward the production of heavier and faster vehicles – instead of toward increased fuel economy.

Such trade-offs with vehicle mass, performance, fuel economy, and efficiency are discussed and analyzed in detail in a number of research studies (Lutsey and Sperling, 2005; An and DeCicco, 2007; Knittel, 2009; U.S. EPA, 2009a). Generally, these types of studies suggest how fuel economy could have improved if other vehicle attributes were held constant. Some of these studies suggest that, due to the technology advances of automakers' engineering efforts, improvements in new vehicles' technical efficiency occur at a rate of about 1% to 2% per year, even in the absence of regulatory pressure to sell a fleet of vehicles with higher fuel economy. However, as indicated from the Figure 2 trends, increases in the overall average vehicle mass tend to consume any efficiency improvements that do indeed occur, and therefore the fuel economy level does not reflect all of the naturally occurring efficiency improvements. Included in these efficiency technologies that are "unseen," or not directly in evidence, are numerous mass-reduction techniques that are incrementally introduced into vehicle models over time.

The average mass of the existing fleet of vehicles is directly linked to the energy consumption of vehicles, due the physical requirement of the vehicles' powertrain systems to accelerate and maintain various speeds for the inertial mass of the vehicle. Due to the oxidation of carbon in the combustion of hydrocarbon gasoline and diesel fuels, vehicle CO_2 emissions are, in turn, closely linked to the mass of vehicles. Based on the model year 2008 vehicle fleet, Figure 3 shows this relationship between vehicles' weight and CO_2 emission rate on the combined city-highway U.S. Federal Test Procedure (FTP). In addition to the new 2008 vehicle fleet on the plot are the fourteen sales-weighted corporate averages CO_2 emission rates and vehicle weights for major automakers. Based on the linear relationship between vehicle models' curb weight and CO_2 emission rates shown, a 10% change in vehicle weight within the existing fleet of vehicles is associated with an approximate 8% change in vehicle CO_2-per-mile emissions.

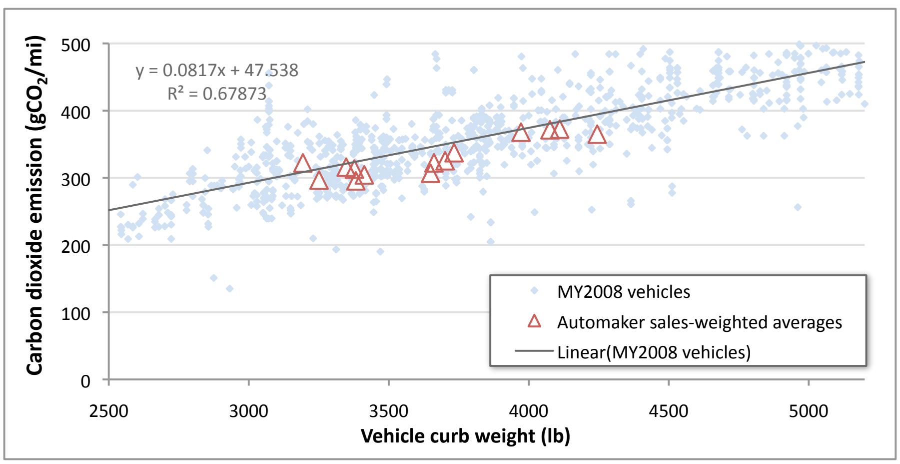


Figure 3. U.S. automobile weight and CO_2 emissions

Although Figure 3 shows an important fundamental relationship between a fleet of vehicles' weight and CO_2 emissions, an important distinction must be made between this current fleet relationship and the potential for "mass-reduction technology" that exists on all vehicles of all sizes. A shift in sales within an existing fleet is generally referred to as downsizing and it involves a shift in fleet composition toward vehicles that are both smaller and have reduced weight, but does *not* involve a redesign of existing vehicle models. Mass-reduction technology, on the other hand, involves the use of higher strength materials and mass-optimized vehicle structures to redesign vehicle models to have lower mass but without change in vehicle size or functionality.

Based on a number of studies, the physical relationship between vehicle mass and its technical efficiency (measured approximately as either in CO_2 emission rate or fuel consumption) is well established. Often the relationship is expressed as an elasticity between mass and fuel economy to define the effect in percent fuel economy increase that results from a percent vehicle mass reduction. The research consistently shows elasticities whereby a 10% decrease in the mass of a conventional vehicle results in a 6% to 8% decrease in the fuel consumption rate (on standard regulatory test cycles) if the vehicles' performance is kept constant (see, e.g., Casadei and Broda, 2008; Bandivadekar et al, 2008; FKA, 2007; Pagerit, et al, 2006). The range in the estimated elasticity is primarily related to which performance variables (e.g., 0-60 mph acceleration) are kept constant and which drive cycles are examined. When other factors like towing requirements and hybrid drivetrains are considered, the relationship can change somewhat. Figure 4 shows this vehicle mass-to-CO_2-emission relationship for vehicle mass reductions up to 35%. As shown, a 30% mass reduction is equivalent to an 18% to 24% CO_2 emission rate (and fuel consumption) decrease.

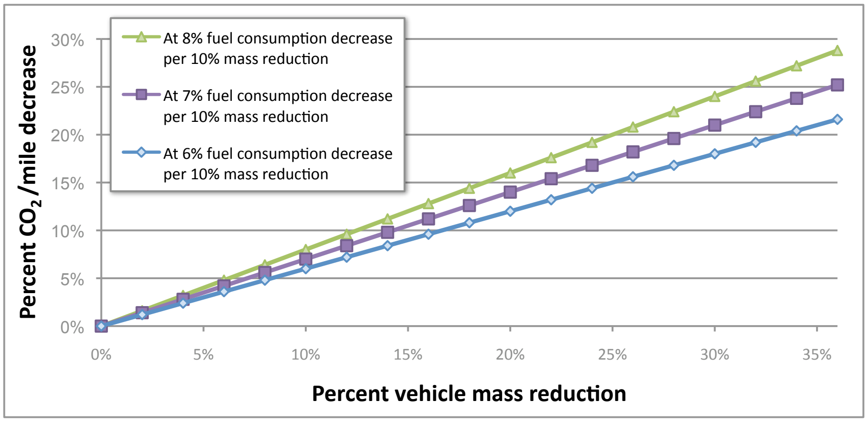
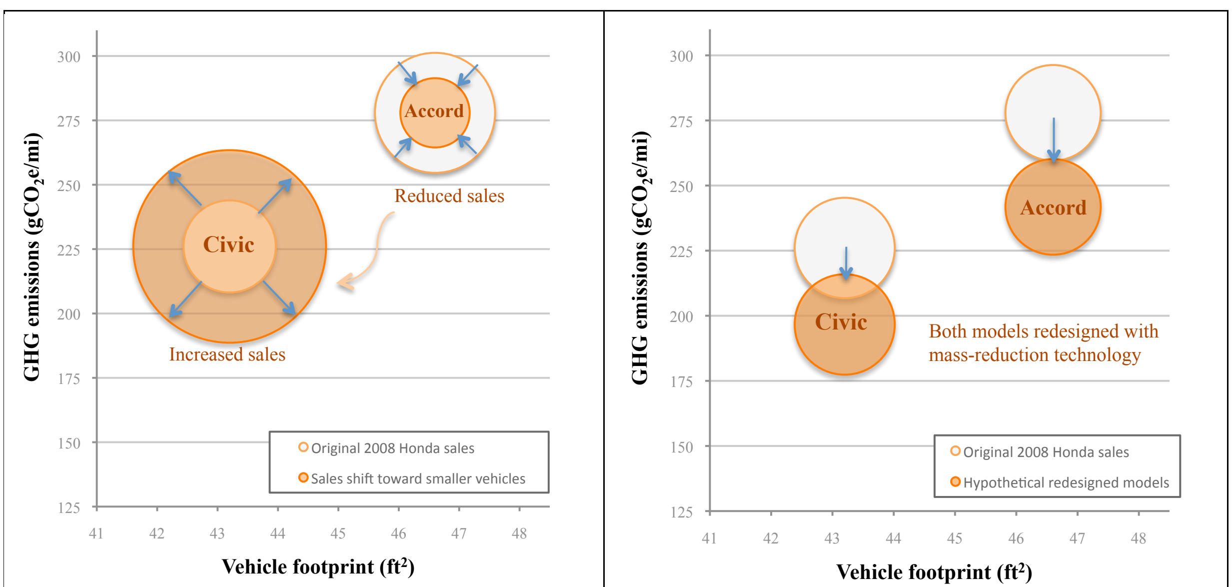


Figure 4. Effect of mass-reduction technology on CO_2 emission rate for constant performance

Because this report is focused exclusively on mass-reduction technology it is important to emphasize the distinction between technologies for improved mass-optimization and downsizing. Figure 5 illustrates this distinction by showing hypothetical examples of fleet downsizing and mass-reduction technology. In the left side of the figure, the example of Honda selling more Civics and less of the larger Accord models shows *fleet downsizing*. On the other hand, the hypothetical example of *mass-reduction technology* example of Honda, using higher strength materials and mass-optimized designs to reduce the mass of each model by 10%, is shown on the right. Sometimes downsizing (or increased size trends, too) can confuse or confound the analysis of mass-reduction technology trends; however these are distinctly different factors. Both of these approaches yield lower CO_2 emissions and a lower average vehicle mass, but the fleet downsizing approach requires a shift in consumer purchasing. The focus of this technology review is exclusively on the mass-reduction technologies of vehicle models through advanced material substitution and optimized redesign – not on fleet or per-vehicle downsizing.

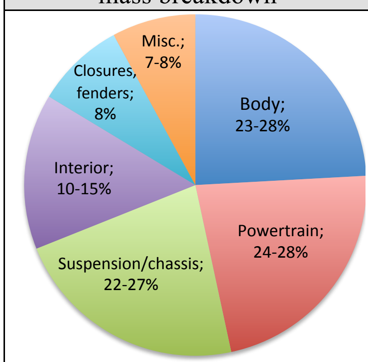


Fleet downsizing: Shift in fleet composition toward smaller vehicles (without redesign of vehicle models for lower mass)	*Mass-reduction technology*: Redesign of vehicles to have the same size but lower mass (without vehicle sales shift or models getting smaller)

Figure 5. Distinction between fleet "downsizing" and vehicle "mass-reduction technology"

As further background for this report on concepts for reducing vehicle mass, a breakdown and description of vehicles' mass characteristics is provided here. The weight of a given vehicle can be partitioned by its material composition or by its functional vehicle systems. Because much of mass-reduction technology research revolves around particular systems, conventional system categories are summarized and defined here. Table 1 shows an approximate breakdown of vehicle systems, with ranges to show the approximate variation seen in various existing vehicle designs. One of the major systems of the vehicle is the body, or sometimes referred to as the "body-in-white." The body represents about a quarter of the overall vehicle mass and is the core structure and frame of the vehicle. The body is so fundamental to the vehicle, that sometimes it is the only portion of the vehicle that is researched, designed, and analyzed in mass-reduction technology studies, because the other systems are not as sensitive to the structural integrity of the vehicle. The other two most prominent vehicle categories are the powertrain and the suspension systems; each of these typically makes up about one-fifth to one-quarter of the vehicle mass. After these systems, the interior, closures, and miscellaneous (including electronic, lighting, thermal, etc) make up the remaining vehicle systems.

Table 1. Vehicle mass breakdown by system and components

<table>
<tr><th>Approximate vehicle mass breakdown[a]</th><th>System</th><th>Major components in system</th></tr>
<tr><td rowspan="6">
</td><td>Body-in-white</td><td>Passenger compartment frame, cross and side beams, roof structure, front-end structure, underbody floor structure, panels</td></tr>
<tr><td>Powertrain</td><td>Engine, transmission, exhaust system, fuel tank</td></tr>
<tr><td>Chassis</td><td>Chassis, suspension, tires, wheels, steering, brakes</td></tr>
<tr><td>Interior</td><td>Seats, instrument panel, insulation, trim, airbags</td></tr>
<tr><td>Closures</td><td>Front and rear doors, hood, lift gate</td></tr>
<tr><td>Miscellaneous</td><td>Electrical, lighting, thermal, windows, glazing</td></tr>
</table>

[a] *Based on Stodolsky et al, 1995a; Bjelkengren, 2008; Lotus Engineering, 2010; the actual system definitions and system component inclusion can vary, and percentage weight breakdown can vary substantially by vehicle*

There are not perfect definitions or conventions that are applied in the literature for the vehicle system categories and the components included within each category. For example, sometimes the general term "body" can more broadly refer to all vehicle parts but the powertrain and the chassis, and therefore this definition makes the body about half of the overall vehicle mass. Often times the term "glider" is used to include all of the vehicle parts except for the powertrain of the vehicle. This report references and summarizes many different studies on vehicle mass characteristics. As a rule, this report tries to adopt the Table 1 definitions and make note when other conventions are applied in the various studies that are referenced.

3. Vehicle mass reduction: Survey of trends and technologies

There is a diverse array of mass-reduction techniques that have been and are being used in automobiles to improve efficiency and performance. The mass-reduction techniques can be seen through historical trends in vehicle designs, new vehicle designs that are currently emerging in vehicles, and concepts for future vehicle model redesign. Mass-reduction can occur in smaller incremental ways, for example reducing the mass of vehicle parts piece-by-piece, or through a more fundamental whole-vehicle redesign. This chapter provides a survey of mass-reduction technology trends, vehicle mass characteristics among the existing vehicle fleet, production vehicle models with advanced mass-reduction techniques, and vehicle concepts for the future.

3.1. General technology trends

Historical vehicle mass reduction trends include major transformations in the materials used in the design and construction of vehicles. Figure 6 shows the progression of vehicle materials from a long-term historical perspective (from Taub et al, 2007). The first mass-produced vehicles were primarily constructed from wood, but quickly the primary dominant vehicle material became steel due to its greater durability and higher strength. As vehicle designs and the available materials evolved, a greater diversity of materials has been utilized for the more specialized parts of increasingly complex vehicles. Over the years the modern automobile has seen a fundamental shift its composition toward higher strength steels, aluminum, plastics (including various polymers and composites), and other materials.

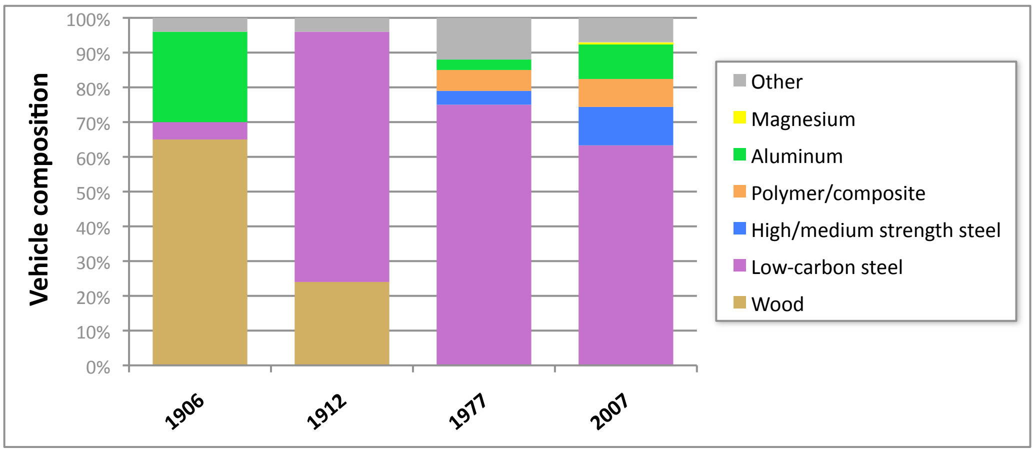


Figure 6. Historical shift in vehicle composition by mass (based on Taub et al, 2007)

Within the vehicle composition shift, the most dramatic increases by mass in recent years are for high strength steels and aluminum. Generally many of the milder, low-carbon steel parts of vehicle powertrains and body structures have increasingly and incrementally moved toward higher strength steels. The higher strength steels in turn bring forth structural designs that are simultaneously stronger and lower in mass (because they use less overall steel material). High strength steel (HSS) alloys continue to be more widely used across almost every vehicle system, including various powertrain components, steering wheels, front-end structures, chassis, beams, and closure body panels. The above figure and other data show how on average, high-strength steel content has about doubled in the past two decades to make up 13% of 2007 vehicles (Taub et al, 2007; Ward's Automotive, 2009). Within this trend, there are particular advanced high strength steel (AHSS) alloys that have seen particularly fast growth (Keith, 2010). Such prominent AHSS materials include dual phase, martinsitic, and boron steels. Individual vehicle models and some companies have incorporated these advanced steels much more quickly than the fleet average. For example, the body of the Honda Civic went from 32% to 50% HSS when redesigned for 2006 (Krupitzer, 2009), the Mercedes C-class jumped from 38% to 74% HSS in its body redesign (Gildea, 2007), and the BMW X6 has 32% of its body and closure structures composed of AHSS (Steelworks, 2009). Estimates from Ducker Worldwide indicate that the automobile industry will see an annual increase in AHSS of about 10% through 2020 (AISI, 2009). Looking at automaker-by-automaker average material composition, there are considerable differences in the use of high-strength steels. Compared to the average 2009 usage of about 14%, some automakers have greater than 20% AHSS while others have less than 10% AHSS (Schultz and Abraham, 2009).

Similarly, lower density aluminum alloys continue to replace the milder, lower carbon steels. Much of the overall vehicle composition shift toward aluminum has come with increasing use of aluminum in engine cylinder heads and blocks, transmission parts, and wheels. Aluminum has gone from about 5% of light duty vehicles in the late 1980s to about 9%, or over 325 lbs per vehicle today (Stodolsky et al, 1995; Brooke and Evans, 2009). Most cylinder heads are aluminum, and now engine blocks made from aluminum in U.S. light duty vehicles passed 50%, surpassing steel in this area for the first time (Simpson, 2006). Along with engine cylinders heads and blocks, aluminum is competing to replace many traditional steel components in vehicles, including valve covers, torque converter and transmission housings, crankcases, control arms, suspension links, cradles, steering wheels, door frames, dashboards, sheet panels (e.g., roof, door, hood), and beams (Caceres, 2007). Along with these areas, relatively new areas being explored for aluminum include all aluminum bodies, bumpers, crash-management systems, and unibody construction (Keith, 2010).

Other than increased use of high-strength steel and aluminum, there are also substantial increasing trends for the use of magnesium. Magnesium is least dense of the primary automotive metals, at about 30% lower density than aluminum and 75% lower density than steel and is therefore seen as a promising potential lower mass metal substitute (Kulekci, 2008). However, currently magnesium only makes up about 10 lbs, or 0.2%, of the average new U.S. vehicle (Ward's Automotive, 2009). New magnesium parts have been commercialized in a number of vehicle models for several years now. For example, Volkswagen applied 20 kg of magnesium in its cars in the 1970s and refers to the more recent expanded magnesium application into instrument panels, driveline components, and the gearbox housings as a magnesium renaissance (Friedrich and Schumann, 2001). Although current magnesium use in vehicles is low, some forecasts suggest that magnesium could become a major automotive component in the near future. The same Volkswagen engineers suggest that 60 kg magnesium per vehicle is realistic and 100 kg per vehicle of magnesium is conceivable in the 2010-2020 timeframe (Friedrich and Schumann, 2001). A study by the U.S. Council for Automotive Research indicates that vehicle magnesium content could increase to 350 lbs by 2020 (U.S. AMP, 2006). Ford forecasts the use of about 250 lb of magnesium components per vehicle by around 2020 (AEI, 2010b). Some early magnesium applications are seen in roof frames, cross beams, interior components like the instrument panel, steering column, steering wheel, and engine cradle (e.g., see Gerard, 2008).

Outside of the above three metal groups, there is also potential for automobile mass reduction with the expanded use of plastics and polymer composites. These plastic materials are considerably less dense than all the automotive metals discussed above, and, up to now, these materials have tended to fill many of the non-structural functions of vehicles for example in many interior components. To illustrate their low density compared to the rest of the vehicles' materials, modern vehicles are about 8% plastic by mass, but 50% plastic by volume (Bandivadekar et al, 2008). Automobiles utilize a wide range of plastic types, including polypropylenes, polyesters, and vinyl esters. These materials are utilized in hatches, roofs, interior panels, instrument panels, and hundreds of other parts. Although primarily replacing non-structural vehicle components, plastics have continued to make in-roads in bumper systems and in composite beam applications, and a number of studies have found potential to supplant structural beams and frame components (Stodolsky et al, 1995b; Lovins and Cramer, 2004). Also included in this general category are the more costly composites, like glass fiber and carbon fiber reinforced polymers. These materials, to date, are used primarily in limited applications in low-production-volume vehicles.

Particular substitution possibilities for all of these materials are described and elaborated upon further below in Section 3.4. The general applications of these automotive materials follow directly from their material properties. Figure 7 shows the material properties of the main material options for the construction of the various vehicle components. All the numbers shown in the chart are approximate and should only be viewed as illustrative, as there are many different grades and types of the general materials that are listed (data are based on Caceres, 2007: U.S. DOE, 2006; Powers, 2000; Lovins and Cramer, 2004; Stodolsky et al, 1995b). Yield strength and cost are shown in logarithmic scale in order to accommodate their large variation across materials. As introduced above, steel has historically taken on almost all of the primary structural functions of vehicles' body and chassis components. Increasingly, lower density and higher cost alternative materials (aluminum, magnesium, plastics) and stronger steels that require less of their use are supplanting the lower carbon steels. Many plastics, despite their relative high cost per mass and low strength, are still critical components due to how light and shapeable they are, which enables lower fabrication costs (e.g., sheet molded composite [SMC]). The highest strength glass and carbon reinforced composites and titanium alloy materials have remained expensive and rare in automotive applications. In a more comprehensive material comparison, other factors would further differentiate these materials' relative advantages and disadvantages in terms of their stiffness, elongation properties, creep deformation, corrosiveness, ductibility, reparability, etc.

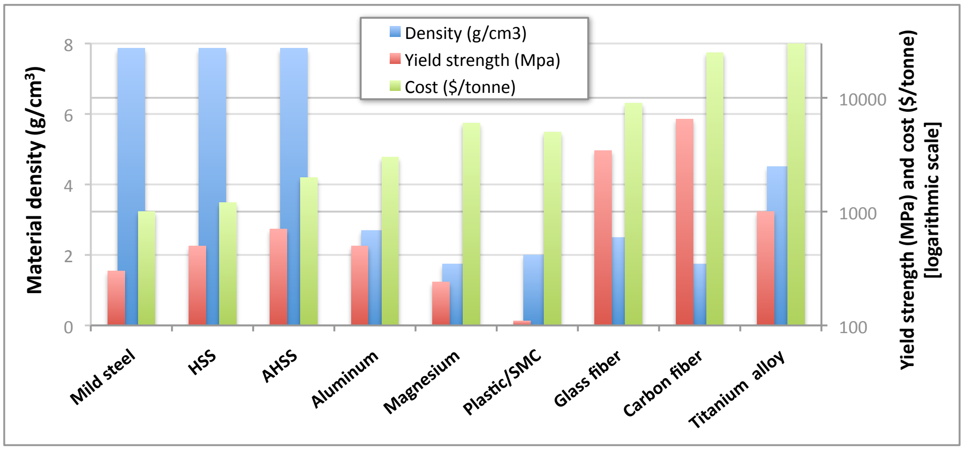


Figure 7. Automotive material properties and approximate costs (based on data from Caceres, 2007: U.S. DOE, 2006; Powers, 2000; Lovins and Cramer, 2004; Stodolsky et al, 1995b)

Despite the increased material cost of moving toward stronger and more mass-optimized metals (HSS, aluminum, magnesium) and non-metals (e.g., plastics, carbon fiber), their potential for *net component cost* improvements keeps each one of them advancing and penetrating further within various automotive applications. To demonstrate how this net cost decrease occurs, Figure 8 shows how the use of higher strength steel alloys can affect material cost, material use, and overall cost. The figure shows how, despite shifting toward more expensive materials (up to 10% higher cost per mass), the reductions in the use of that material reduce more substantially to actually reduce the part cost by more than 10%. The example is for four particular grades of high-strength steel as potential substitutes for the B-pillar between vehicle front and rear doors, using data from ThyssenKrupp (Adam, 2009). However, the principle is widely applicable – as similar trade-offs in material choice, material thickness, and the overall amount of required material exist in many vehicle components and with different materials. This demonstrates how stronger and more expensive materials that are utilzed in mass-optimized ways can be utilized with net manufacturing cost savings.

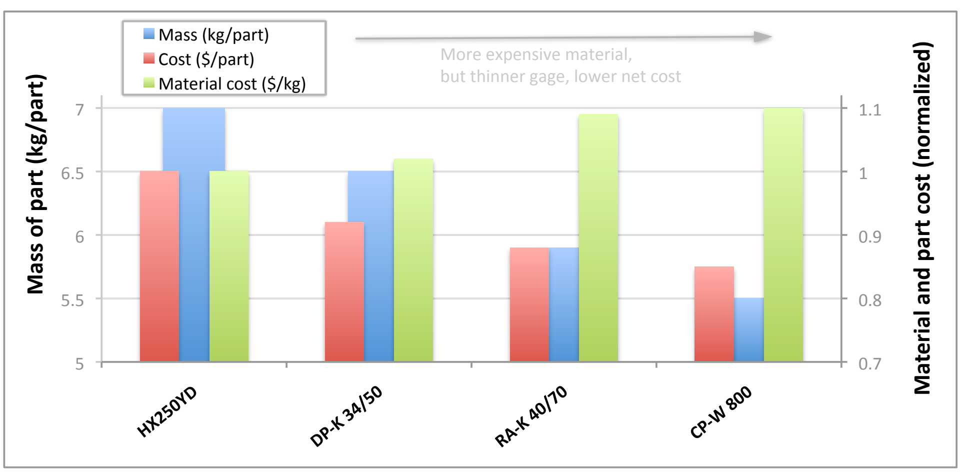
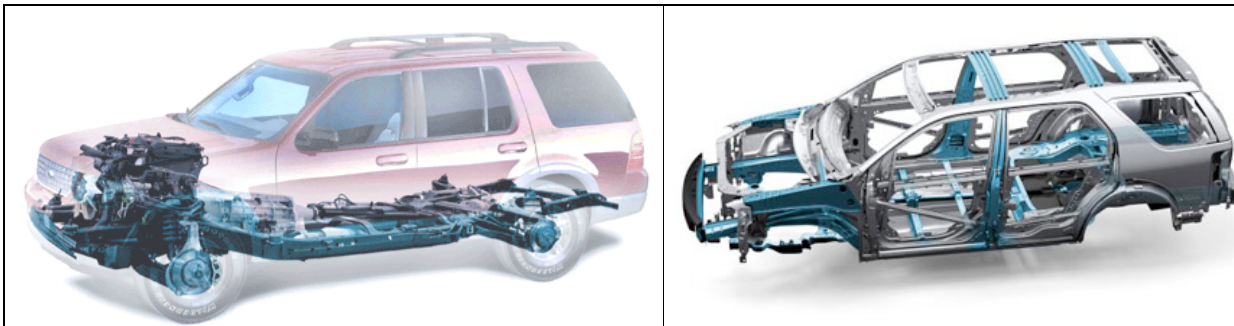


Figure 8. Example of higher-strength, higher-cost materials achieving a net decrease in component cost (based on steel alloy options for B-pillar from Adam, 2009)

Another critical transformation in automobiles over the past couple decades is in the way that vehicles have been constructed. Originally, vehicles were most commonly manufactured with a body-on-frame construction, whereby a vehicle body structure and frame are independently built and they are later combined (e.g., bolted together) during the vehicle production process. Instead, unitized body, or "unibody" construction, all of the vehicle's body components (including body, side beams, panels, floor pan, roof) and the traditional chassis frame structure are constructed together as one integrated load-bearing structure. Figure 9 depicts body-on-frame and unibody designs for two sport utility vehicles. The innovation required more design planning, as many different body types (e.g., sedan, station wagon, limousine) could easily be placed on one existing frame. However, ultimately this led to a reduction in components and weight of the overall body structure and related cost reductions.



http://blogs.cars.com/photos/uncategorized/2008/06/09/explorer_chassis_final.gif	*http://static.howstuffworks.com/gif/cg-suv-safety-3.jpg*
Body-on-frame	*Unibody*

Figure 9. Illustration of body-on-frame and unibody vehicle construction

The use of unibody construction began to be deployed widely for smaller cars in the 1960s and slowly took over as the dominant vehicle construction for larger cars through the 1980s. Currently unibody construction represents nearly all of passenger car production and most of the smaller sport utility vehicles (i.e., crossover or car-based sport utility vehicles) production in the U.S. Unibody vehicles represented about 59% of U.S. light duty vehicles in 2000 and about three-quarters of the new vehicle fleet in 2008, and they are forecasted to continue this trend to be 80% of the 2015 new vehicle fleet (Schultz and Abraham, 2009). The remaining one-quarter of light duty vehicles that are predominantly body-on-frame construction is comprised of the larger sport utility vehicles, full-size vans, and pickups, as body-on-frame structure provides a more rigid structure that is well suited for high towing capacity.

Improved design techniques have enabled a systems level design of vehicles. This is contrary to the more common piece-meal approach, whereby an automaker or supplier changes one frame piece or substitutes a new material incrementally, piece-by-piece. Tools like computer-aided design (CAD) and finite element analysis were pioneered in the 1980s. Then computer-aided engineering (CAE) techniques developed extensively through the 1990s, allowing automotive engineers to increasingly design vehicles virtually while accounting for the interaction of vehicle parts in a much more sophisticated manner. Some automotive engineers suggest that these past CAE and CAD efforts are just the beginning of such new designing techniques for vehicle mass reduction. Advanced simulation tools, such as biomimetic topology, help strategically target advanced high-strength steel material gauges and materials to shed unnecessary vehicle weight on the order of 120 lbs from body structures (Brooke and Evans, 2009).

Mass-optimization from a whole-vehicle perspective opens up the possibility for much larger vehicle mass-reduction opportunities. For example, secondary mass-reduction effects, sometimes called mass decompounding, can be very important (see, e.g., Malen and Reddy, 2007; Bjelkengren, 2006). Secondary mass-reduction is possible as reducing the mass of one vehicle part can beget further reductions elsewhere due to reduced requirements of the powertrain, suspension, and body structure to support and propel the various vehicle systems. New more holistic approaches that include integrated vehicle systems design, secondary mass effects, multi-material concepts, and new manufacturing processes are expected to help optimize vehicles for much greater potential mass reduction (see, e.g., Friedrich and Schumann, 2001; Glennan, 2007; Goede et al, 2009; Lotus Engineering, 2010). The results of these new design techniques are examined below.

3.2. The existing fleet of vehicle models

The above section introduces details and trends related to the composition and design of vehicles. A broader way of examining vehicle mass characteristics is to look at a snapshot of the current vehicle fleet. The fundamental vehicle size-to-weight relationship for the U.S. light duty vehicle fleet is shown in Figure 10. The figure shows that, for a given vehicle size, it would be possible to approximately estimate the weight of that vehicle, based on the current spread of vehicle models across all of the different categories (e.g., compact cars, to small sport utility vehicles, to large pickup trucks). Here, vehicle size is measured as the area between the wheels (i.e., wheelbase multiplied by average track width). Based on this figure, it is also possible to pick out which vehicles are relatively heavy for a vehicle of that size (above the regression line), and which vehicles are relatively light (below the line). This important distinction shows that within this basic size-weight spread of the vehicle fleet there is a large apparent discrepancy in the weight characteristics of vehicle models: comparatively light vehicle models can be as low as 25% below the line and comparatively heavy vehicle designs can be as high as 40% above the line that defines the average model vehicle size-to-weight relationship.

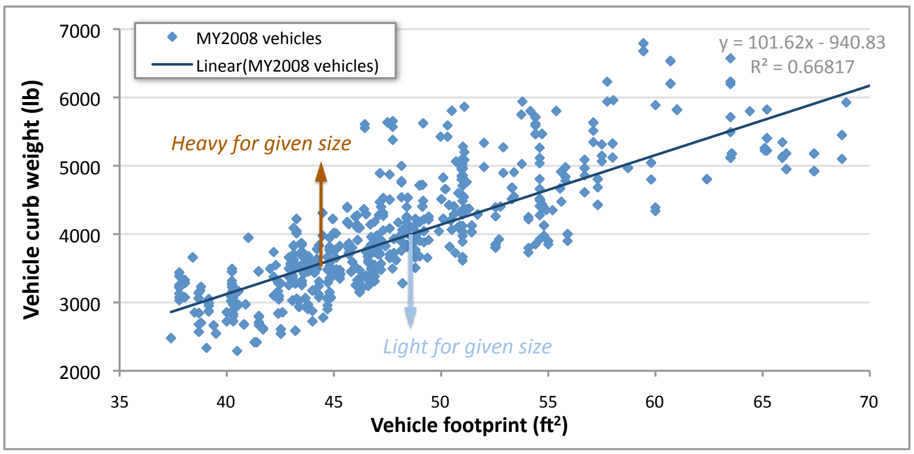


Figure 10. Model year 2008 U.S. light duty vehicle curb weight and size

Noting the historical trade-offs in vehicle attributes (as shown above in Figure 2), another way to see how vehicle efficiency technologies are allocated in vehicles is to examine a snapshot of the existing vehicle fleet – but with a look in particular at how the different automaker groups' sales fleets compare to one another. Figure 11 shows the sales-averaged size and weight of each automaker group, with the spread of individual model year 2008 vehicles in the background. Within a single model year snapshot, the sales-weighted average size and weight positions for each manufacturer gives some indication of how different automaker groups are utilizing mass-reduction technologies in their vehicle models.

As is shown in the figure, automakers have different average vehicle size and weight characteristics. Based on a linear regression of these automaker group average weights and sizes, various automakers have relatively heavy vehicles for their size, while others are comparatively light. The relatively heavy automaker averages (those above the regression line) are companies that tend to specialize in luxury and higher performance vehicles. Another factor in relative weights is the fraction of vehicles that are body-on-frame construction. The heavier manufacturers tend to manufacture vehicles that, on average, have higher power, higher-displacement engines, which result in an increase in the weight of the powertrain, which is one of the heaviest vehicle component systems. Also, to the extent to which the automakers specialize in luxury vehicle segments, their vehicles generally have increased premium content (e.g., electronics, leather and power seats, sun-roofs, etc), which can be another factor in their relatively high weight. Also shown in the figure is how some manufacturers are selling vehicles that have comparatively low mass for their size. When compared to the industry trendline, Hyundai-Kia (8% lighter than the industry trendline) and Honda (6% lighter) show relatively low average weight for the size of their vehicles. Differences in automaker designs and material choices – their deployment of mass-reduction technologies – are critical determinants in automakers' relative weight-to-size characteristics.

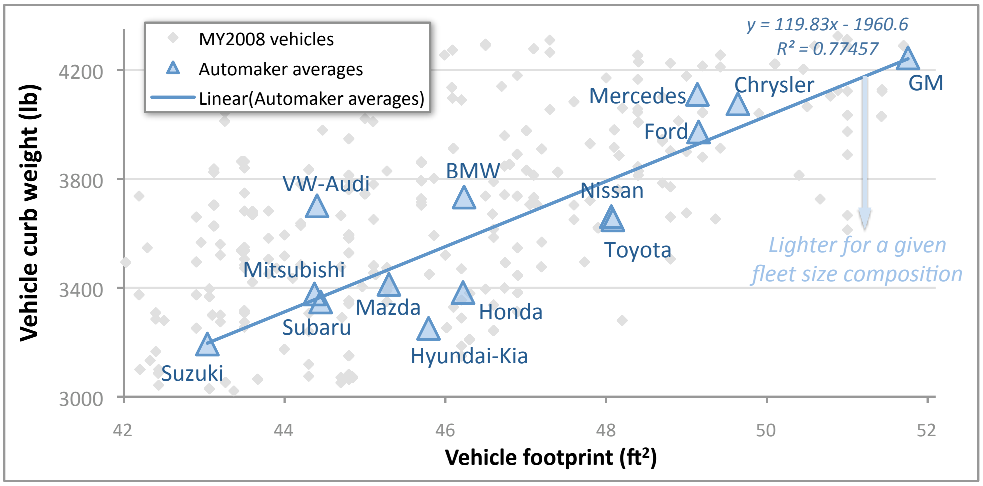


Figure 11. Sales-weighted average vehicle weight and size for each automaker group

3.3. Emerging mass-reduction technology and automaker plans

Building on the two previous sections on general vehicle mass trends and current automaker vehicle fleet mass characteristics, this section summarizes near-term future automaker plans regarding the emerging mass-reduction technologies. Recent media announcements, technical specifications, and product developments from automakers provide a clear indication of the types of mass-reduction technologies that will be utilized across new vehicles in upcoming years. Various automotive industry plans are summarized here in order to highlight the diversity of different technology approaches that industry is exploring, as well as to highlight common technology threads that cross the different company strategies. The future plans that are recounted here are essentially all foreshadowed by the emerging trends that were introduced above regarding advanced materials and mass-optimized vehicle designs.

From a general planning perspective, nearly all automakers have made some statement regarding vehicle mass reduction being a core part of the overall technology strategy that they will utilize to achieve future fuel economy and CO_2 emission standards. Ford has stated that it intends to reduce the weight of its vehicles by 250-750 lb per model from 2011 to 2020 (Ford, 2009). For context, the midpoint of that range of reductions would correspond to a 12% reduction from the current Ford new light duty vehicle sales fleet. Similarly, Nissan has a target of a 15% mass reduction per vehicle by 2015 (Keith, 2010). This reduction would represent over a 500-lb reduction from their 2008 light duty vehicle average. Mazda's statement about achieving a 220-lb reduction per vehicle (Lago, 2009; GCC, 2008) is equivalent to about a 6% reduction for the company's current fleet, and Mazda has indicated that it is targeting an additional 220-lb reduction by 2016 (U.S. EPA, 2009b). Toyota stated that it could end up reducing the mass of the Corolla and mid-size models by 30% and 10%, respectively, in the 2015 timeframe (U.S. EPA, 2009b). The low end of those targets, 10%, is equivalent to 350 lb per Toyota vehicle in 2008.

Federal U.S. regulators, in their assessment of automaker strategies to comply with upcoming fuel economy and CO_2 standards, pointed to the above announcements and mass-reduction technology trends. In their final analysis, they suggested that the overall average per-vehicle mass reductions could be about 4% for new vehicles of model year 2016. Their analysis indicated that the response would differ depending on the class of vehicles. Cars averaged a 3.8% mass reduction and light trucks averaged a 4.5% reduction. The smallest cars saw the smaller effects – a 75-lb reduction (2.8%) – while the effect increased to a 376-lb (7.0%) reduction for the larger trucks (U.S. EPA and NHTSA, 2010).

Although other automakers have been less forthcoming in providing such quantitative weight reduction targets as those cited above, essentially every automaker does nonetheless indicate that future fuel economy standards provide a major inducement for the commercialization of mass-reduction technologies. In addition to the quantitative announcements above, automaker announcements indicate that essentially every automaker continues to deploy a variety of mass-reduction technologies. For example, in releases regarding products from General Motors, Chrysler, Volkswagen, Porsche, Audi, Mercedes, and BMW, there are statements about wider commercialization of lighter front-wheel drive architectures, lighter interior components, increased use of less-dense materials, multi-material use, and mass-optimized vehicle design techniques (see, e.g., GMC, 2009; Gerard, 2008; Chrysler, 2009; Goede et al, 2009; Stahl, 2010; EAA, 2007; Tan, 2008; BMW, 2008).

Details on emerging technologies and product announcements from automakers provide some definition on the types of mass reductions that can be realized from various technologies. It must be re-emphasized here that the actual reduction in mass from any model year redesign has historically been quite rare. Automobile engineers routinely refer to a model "weight creep," whereby vehicle models incrementally increase in mass as they typically add size and more content. Analysis of particular models (see, e.g., the progression of the Volkswagen Golf [Lotus Engineering, 2010; EAA, 2007]) show the types of year-to-year changes that are well known to automotive engineers due to vehicles getting larger, adding content, and increasing in powertrain size and performance (Also see Chapter 2, above).

Noting this historical incremental upward mass creep trend of vehicles, many "mass reductions" can occur alongside increases in content and overall vehicle mass. These unseen reductions in vehicle component mass can be observed in isolation by examining changes in individual parts of new and redesigned vehicles. Therefore quantifying the impact of emerging mass reduction techniques requires the isolation of particular parts or systems (e.g., the engine, the body, smaller parts). Although most such mass reductions within current vehicles cannot always be definitively known or quantified, in some cases automakers release small amounts of information related to innovations in mass-reduced parts when they publicly release and promote new models.

Table 2 summarizes vehicle components that have seen mass-reduction innovations in material use or design in automotive applications. As shown, there is a large array of different measures, big and small, being utilized to reduce component mass within vehicles. The mass reductions are taken from many different sources, many of them being automaker press release materials for the vehicle models that are distributed for automobile shows and reviews. Note the mass-reduction technologies are shown in units of lbs, the more common U.S. unit. As enumerated in the table, there are many potential mass-reduction opportunities throughout the vehicles' various components and systems that have been utilized in production vehicles. However, there are countless other measures that are less publicized and more subtle than those that are documented here. Some of the innovations (e.g., high-strength steel in all body parts; aluminum engine and wheels) are relatively widespread, whereas others are in lower volume production, are just emerging, or are relatively rare.

Engine mass savings result from increasing the use of high-strength steels, aluminum, and magnesium components across the engine and its auxiliary components. Some Ford models found reductions of about 100 lbs when switching to aluminum or aluminum-magnesium alloy engine blocks (see, e.g., Tyll, 2010; Kulekci, 2008). Various other engine-related components can be switched to less dense components like valves, connection rods, crankshafts, manifolds, and the engine cradle for weight reductions that vary from 1 to 12 lbs for technologies that have been used by General Motors, Honda, Porsche, and Audi (Kulekci, 2007; U.S. AMP, 2009; Gerard, 2008).

The switching of many body parts to aluminum has been embraced by a number of automakers, especially Audi and Jaguar. Honda first produced the all-aluminum body Acura NS-X in 1990 (Muraoka and Miyaoka, 1993). Since, Audi has increasingly utilized aluminum in the frame of its vehicles. The 2000 Audi A2 in Europe was among the early production vehicles with a body entirely made of aluminum, resulting in about a 40% reduction in the weight (Autointell, 2000). The model's primary weight savings of 295 lb from the aluminum body begat another 165 lb in secondary reductions via the drivetrain, motor, and chassis systems (EAA, 2007). The larger Audi A8 sedan uses 1147 lb of aluminum (EAA, 2007) in its aluminum-intensive design. This amount of aluminum amounts to about 25% of the current model's overall curb mass and is almost three times the average U.S. vehicle aluminum composition. Audi has continued to expand these aluminum mass-reduction concepts into other vehicle models. For example, the TT model for model year 2008 used aluminum extensively for a 220-lb weight reduction, the model year 2011 A6 uses Audi's second generation of space frame innovations for a 50% reduction in body weight, and Audi could apply the technology to the A3 and Q7 (Brooke and Evans, 2009). Also, the latest A5 prototype uses the aluminum frame for a 242-lb reduction (Lavirnc, 2009).

Table 2. Component weight-reduction potential from technologies on production vehicles

Vehicle system	Subcomponent	New material or technique [a]	Weight reduction (lb) [b]	Example automaker (models) [c]	Source(s)
Power-train	Block	Aluminum block	100	Ford (Mustang); most vehicles	Tyell, 2010; Ford, 2010
	Engine, housing, etc	Alum-Mg-composite	112	BMW (R6)	Kulekci, 2008
	Engine	Smaller optimized molds (Al)	55	Toyota (Camry)	Simpson, 2007
	Valvetrain	Titanium intake valves	0.74	GM (Z06)	Gerard, 2008
	Connecting rod (8)	Titanium	3.5	GM (Z06); Honda (NSX)	Gerard, 2008
	Driveshaft	Composite	7	Nissan; Mazda: Mitsubishi	ACC, 2006
	Cradle system	Aluminum	22	GM (Impala)	Taub et al, 2007
	Engine cradle	Magnesium	11-12	GM (Z06)	Gerard, 2008; US AMP, 200x
	Intake manifold	Magnesium	10	GM (V8); Chrysler	Kulekci, 2008: US AMP
	Camshaft case	Magnesium	2	Porsche (911)	Kukekci, 2008: US AMP
	Auxiliaries	Magnesium	11	Audi (A8)	Kulekci, 2008
	Oil pan	Modular composite	2	Mercedes (C class)	Stewart, 2009
	Trans. housing	Aluminum	8	BMW (730d); GM (Z06)	Gerard, 2008
	Trans. housing	Magnesium	9-10	Volvo; Porsche (911); Mercedes; VW (Passat); Audi (A4, A8)	Kulekci, 2008; US AMP
Body and closures	Unibody design	Vs. truck body-on-frame	150-300	Honda (Ridgeline); Ford; Kia; most SUV models	Honda, 2010; Motor Trend, 2009
	Frame	Aluminum-intensive body	200-350	Audi (TT, A2, A8); Jaguar (XJ); Lotus; Honda (NSX, Insight)	Brooke and Evans, 2009; Autointel, 1999: EAA, 2007; Audi, 2010
	Frame	Aluminum spaceframe	122	GM (Z06)	Taub et al, 2007
	Panel	Thinner, aluminum alloy	14	Audi (A8)	Audi, 2010
	Panel	Composite	42	BMW	Diem et al, 2002
	Doors (4)	Aluminum-intensive	5-50	Nissan (370z); BMW (7); Jaguar (XJ)	Keith, 2010; BMW, 2008; Birch, 2010
	Doors (4)	New production process	86	Porsche (Cayenne)	Stahl, 2010
	Door inner (4)	Magnesium	24-47		Kulekci, 2008; US AMP
	Hood	Aluminum	15	Honda (MDX); Nissan (370z)	Monaghan, 2007; Keith, 2010
	Roof	Aluminum	15	BWW (7 series)	BMW, 2008
	Lift gate	Magnesium	5-10		Kulekci, 2008; US AMP
Suspen. and chassis	Chassis	Aluminum	145	Porsche (Cayenne)	Carney, 2010
	Chassis	Hydroformed steel structure, tubular design	100	Ford (F150)	FordF150.net, 2010
	Steering wheel	Magnesium	1.1	Ford (Thunderbird, Taurus); Chrysler (Plymouth); Toyota (LS430); BMW (Mini); GM (Z06)	Kulekci, 2008; Gerard, 2008
	Steering column	Magnesium	1-2	GM (Z06)	Kulekci, 2008; Gerard, 2008; US AMP
	Wheels (4)	Magnesium	26	Toyota (Supra); Porsche (911); Alfa Romeo	Kulekci, 2008; US AMP
	Wheels (4)	Lighterweight alloy, design	13	Mercedes (C-class)	Tan, 2008
	Brake system	Heat dissipation, stainless steel pins, aluminum caps	30	Audi (A8)	Audi, 2010
	Tires	Design (low RR)	4	Mercedes (C-class)	Tan, 2008
	Suspension	Control arms (2)	6	Dodge (Ram)	SSAB, 2009
Interior	Seat frame (4)	Magnesium	28	Toyota (LS430); Mercedes (Roadster)	Kulekci, 2008; US AMP
	Instrument panel	Magnesium	7-13	Chrysler (Jeep); GM; Ford (Explorer, F150); Audi (A8); Toyota (Century); GM	Kulekci, 2008; US AMP; Taub et al, 2007
	Dashboard	Fiber-reinforced thermoplastic	18	VW (Golf)	Stewart, 2009
	Console and shifter	Injection molded glass reinforced polypropylene	5	Ford (Flex)	Stewart, 2009
Misc.	Windows	Design, material thickness	3	Mercedes (C-class)	Tan, 2008
	Running board	Glass-reinforced polypropylene	9	Ford (Escape)	Stewart, 2009

[a] *These technologies can include a change in design, a reduction in parts, a reduction in material amount, and use of various metallic alloys; note that weight (lb) and mass (kg) variables are used in this report. 1 kg = 2.205 lb.*
[b] *Weight reduction estimates are approximate, based on media sources and technical reports*
[c] *A number of these models are not available in the U.S.; some model names have changed in recent product changes*

Along with the mass-reduction technology concepts being commercialized by Audi, other automakers also claim "first" status in developing aluminum vehicle bodies, although generally in lower production volume performance and luxury vehicles with more limited production. Lotus has also employed aluminum body technology in its mass-efficient sports cars through the 1990s. Honda and Jaguar have both employed aluminum sheet body structures. Honda, with its Acura NS-X in 1990, offered the first all-aluminum body, chassis, and suspension. The NS-X's aluminum design reduced body-in-white weight by 309 lb (40%) and overall vehicle weight by 441 lb (Komatsu et al, 1991; Muraoka and Miyaoka, 1993). Meanwhile, Honda, as mentioned above, currently is one of the bigger users of high-strength steel in its vehicle bodies to result in one of the more mass-efficient fleets. The Jaguar XJ design pioneered its own full aluminum body and also extensively utilizes high-strength steels and composites, reduces adhesive use by 10%, reduces the required parts by 15%, and uses glass-reinforced plastics for a 700-lb reduction in vehicle weight (Birch, 2010).

Also highlighted in Table 2 for mass-efficient body innovations being deployed is the use of unibody construction for trucks. As introduced above, over three quarters of light duty vehicles in the U.S. are unibody construction, with the remaining body-on-frame vehicles being mostly mid-size and larger pickup trucks and sport utility vehicles. The only unibody pickup truck that has been commercialized is the Honda Ridgeline, which is roughly estimated to offer an equivalent weight reduction of 300 lb versus similarly equipped and powered competitor pickup trucks. Several reports suggest that unibody design could eventually penetrate all larger light trucks for which there are not high towing requirements. For example, the Ford Explorer would convert from body-on-frame to unibody for a 150-lb weight reduction in upcoming years (Motor Trend, 2009). Another automaker, Kia is transitioning its Sorrento sport utility vehicle to a front-wheel-drive unibody layout and is considering a unibody pickup that could be comparable to the Ridgeline (Johnson, 2008).

Outside of the core body frame structure, mass-reduction technology features in other areas can add up to substantial mass reductions. Lighter roof panels, beams, side panels are being deployed by many different automakers. Thinner gage high strength steels and aluminum are the main substitutes, but some limited magnesium is also being utilized. Within the suspension and chassis system, major mass reductions are being found from aluminum wheels and redesigned braking systems. Also, more simply (and without material substitution), many suspension and chassis parts can see secondary mass reductions from reduction in their size that result from mass reductions elsewhere on the vehicle. In the interior, magnesium substitution shows considerable mass reductions in the instrument panel and seat frames.

As mentioned above, Ford has committed to a 250 to 750 lb reduction in vehicle models' weight by 2020. In recent model year redesigns, Ford appears to be getting an early start on this commitment. The 2009 Ford F-150 saw an overall 100-lb reduction from its predecessor (Brooke and Evans, 2009). Shifts from larger cast-iron engine at Ford to all-aluminum ones result in a 100-lb weight reduction and improved power-to-weight ratio, improved fuel economy, acceleration, handling, and steering precision (Tyll, 2010; Ford, 2010). Ford's use of plastics in new running boards, center console/shifter assembly netted additional reductions (Stewart, 2009), and a new tubular steel chassis for the F150 pickup was found to reduce that model's weight by 100 lb (FordF150.net, 2010).

Mazda's redesign of its compact Mazda2 in 2008 resulted in a 100-kg mass reduction from the previous year (Brooke and Evans, 2009). As noted above, Mazda has installed a near-term target of a 100 kg (220 lb) mass reduction per vehicle for all its vehicles during model redesigns from 2011 to 2015; Mazda's logic is that improving current technologies (engine, transmission, stop-start, mass reduction), they can achieve a 30% fuel consumption improvement without hybrid technology (Lago, 2009, GCC, 2008). For the Mazda2 model, a 100-kg weight reduction is equivalent a 10% mass reduction.

Although Porsche has not made such an across-the-board commitment regarding mass-reduction technology as Ford and Mazda, its latest Cayenne model is among the largest of all year-on-year mass reductions. The announced 400-lb reduction for the V-8 Cayenne from model year 2010 to 2011 comes from a combination of many mass-reduction technologies. The lower mass model uses high-strength steel throughout; increased aluminum content in the chassis, suspension, hood, fenders, doors, and hatch; a new production process for the doors; and a lower mass all-wheel-drive system. Despite adding 154 lbs in additional equipment, the mass-reduction technology measures resulted in a net 400-lb overall reduction for the 2011 Cayenne (Carney, 2010; Stahl, 2010).

In some rare cases, vehicle models have had overall reductions in mass as a result of mass-reduction technologies that more than offset the additional mass that the model may have taken (due to increased engine size, increased content, etc) at the same time. Several examples of whole-vehicle mass reductions are shown in Table 3. A number of the examples include models that were listed above for having mass-optimized parts or components, but these models generally applied mass-reduction technologies in a more concerted way to actually achieve an overall reduction from the previous models' curb mass. As shown, several models showed over 400 lb of weight reductions with a given design. Note that, of these vehicle models, the ones with the largest weight reductions or 400 lbs or greater have been relatively limited production of niche market models (e.g., Honda NS-X, Audi A2, Jaguar XJ). However, some vehicle models that achieved reductions of 100-400 lb per vehicle have larger sales (e.g., Mazda2, Cayenne, TT, 370z, F150).

Table 3. Examples of overall vehicle weight reduction from production vehicles

Vehicle make and model (year)	Features	Weight reduction, lbs (percent)	Source (s)
Honda NSX (1990)	• Nearly all aluminum body, chassis, suspension • Increased aluminum content from 7% to 31% • Body-in-white weight reduction from 350 to 210 kg (40%) • Overall vehicle weight reduction from 1565 to 1365 kg	441 (13%)	Muraoka and Miyaoka, 1993
Audi A2 (2000)	• Aluminum-intensive space frame • Direct body weight savings of 134 kg (vs steel) • Secondary savings of 75 kg from drivetrain, motor, chassis	461 (18%)	EAA, 2007; Autointel, 1999
Jaguar XJ (2010)	• Aluminum body frame, shell • 10% reduction in adhesive use • Glass-filled polymide/ultra-high strength steel B-pillar • Hydroformed A-pillar/cantrail extrusion assembly • Composites, glass-reinforced plastic molding • Overall 15% few parts for the whole vehicle	717 (15%)	Birch, 2010
Porsche Cayenne (2011)	• Increased use of high-strength steel throughout • Aluminum and high-strength steel chassis parts • Aluminum fenders, hood, doors, rear hatch • New production process for doors • If subtract 154 lb of added features, 10% reduction (554 lb)	400 (8%)	Carney, 2010; Stahl, 2010
Mazda Mazda2 (2008)	• Wide application of high-strength steels • Aluminum engine head, block, wheels	220 (9%)	Brown, 2007
Audi TT (2008)	• Aluminum-steel hybrid frame (58% Al, 42% HSS)	220 (7%)	Brooke and Evans, 2009
Ford F150 (2009)	• Hydroformed steel body structure • Use of tubular ultra high strength steel	100 (2%)	FordF150.net, 2008
Nissan 370Z (2011)	• Wide application of high strength steels • Aluminum door panels, hatch, hood	95 (3%)	Keith, 2010

Although they do not achieve particularly high efficiency or low CO_2 emissions, and they do not even achieve overall mass reductions in many cases, low-volume sport cars can exhibit inordinate amounts of mass-reduction technology features due to the resulting improvement in performance. Like the pioneering mass-efficient Honda NS-X model, the mass-reduction features on the recent Chevrolet Corvette Z06, for example, are very advanced and too numerous to list here. A partial list includes aluminum spaceframe, a carbon fiber-skinned balsawood core floor pan, magnesium roof frame, hydroformed aluminum roof bow, aluminum allow transmission housing, high-strength steel crankshaft, titanium intake valves, titanium connecting rods, magnesium steering column, carbon fiber wheel houses (Gerard, 2008). Some of these types of mass-reduction innovations also occur on various models by Audi, BMW and other automakers that specialize in performance models (as shown above in Table 2).

Literally, it is safe to assume that these mass-reduction technology innovations at the scale of that niche market Corvette Z06 are equivalent to over a hundred kilogram of mass reduction. However, as utilized in such a performance-oriented model, the mass reductions are not realized. A clear reason for the unseen nature of these models' mass-reduction is that their powertrains are sized 2-3 times the typical vehicle size and power output for that vehicle size. For example the Corvette engine is a 6.0-liter 505-horsepower engine, whereas an average U.S. vehicle of that weight has a 3-liter 200-horsepower engine. As a result, these high-powered sports cars' suspension systems and other vehicle components are also beefed up to support the powertrain. Nonetheless, these types of innovative mass-reduction techniques typically see their introductions in niche sports cars and can work their way into premium sports cars and luxury vehicles before penetrating high-volume production vehicle models.

Another indication of automakers' intent to deploy mass-reduction vehicle designs and increased use of advanced materials is in the direct statements by automobile engineers and designers. Table 4 provides direct quotes from industry representatives from various media sources and technical reports. These statements confirm that stronger advanced materials and mass-optimized designs are critical components of automakers' future vehicle plans. The quotes are from representatives of General Motors, Ford, Nissan, Volkswagen, Fiat, and BMW and show a general importance of mass-reduction technologies now and for future vehicle designs. Of course, the exact plans of automakers for the different automobile manufacturing companies role out of new materials and designs is proprietary and a part of their strategic product planning for the future. These direct statements, as well as the above information related to mass-reduction plans of individual automakers and the increasing rollout of emerging mass-optimized components, all suggest that mass-reduction technology is a major vehicle efficiency technology lever for near- and mid-term commercialization.

Table 4. Automaker industry statements regarding plans for vehicle mass-reduction technology

Affiliation	Quote	Source
General Motors	"We use a lot of aluminum today-about 300 pounds per vehicle-and are likely to use more lightweight materials in the future."	Keith, 2010
Ford	"The use of advanced materials such as magnesium, aluminum and ultra high-strength boron steel offers automakers structural strength at a reduced weight to help improve fuel economy and meet safety and durability requirements"	Keith, 2010
Nissan	"We are working to reduce the thickness of steel sheet by enhancing the strength, expanding the use of aluminum and other lightweight materials, and reducing vehicle weight by rationalizing vehicle body structure"	Keith, 2010
BMW	"Lightweight construction is a core aspect for sustainable mobility improving both fuel consumption and CO_2 emissions, two key elements of our EfficientDynamics strategy….we will be able to produce carbon fiber enhanced components in large volumes at competitive costs for the first time. This is particularly relevant for electric-powered vehicles."	BMW and SGL, 2010
Volkswagen	"Material design and manufacturing technologies remain key technologies in vehicle development. Only integrated approaches that work on these three key technologies will be successful in the future. In addition to the development of metals and light metals, the research on fibre-reinforced plastics will play a major role."	Goede et al, 2009
Fiat	"A reduction of fuel consumption attains big importance because of the possible economical savings. In order to achieve that, different ways are followed: alternative engine concepts (for example electric engines instead of combustion ones) or weight reduction of the vehicle structure. Using lightweight materials and different joining techniques helps to reach this aim"	Nuñez, 2009
Volkswagen	"Lightweight design is a key measure for reducing vehicle fuel consumption, along with power train efficiency, aerodynamics and electrical power management"	Krinke, 2009
BMW	"A dynamic vehicle with a low fuel consumption finally demands a stiff body with a low weight. To achieve the initially mentioned targets, it is therefore necessary to design a body which offers good stiffness values and a high level of passive safety at a low weight.	Prestorf, 2009
BMW	"Light weight design can be achieved by engineering light weight, manufacturing light weight and material light weight design"	Prestorf, 2009
Volkswagen	"Automotive light weight solutions are necessary more than ever to reduce CO_2 emissions."	Stehlin, 2008
Volkswagen	"All the car manufacturers are working on advanced multi-material concepts that better exploit materials lightening potential combining steel, aluminum, magnesium, plastics and composites."	Stehlin, 2008
Volkswagen	"Multi-Material Concepts promise cost effective light weight solutions"	Stehlin, 2008
General Motors	"Undoubtedly many of the component and system innovations in the Z06 will provide a foundation for technologies that will be incorporated in the electronically propelled vehicles of the future."	Gerard, 2008
General Motors	"One trend is clear – vehicles will consist of a more balanced use of many materials in the future, incorporating more lightweight materials such as nanocomposites and aluminum and magnesium sheet."	Glennan, 2007
Renault	"To meet commitments on CO_2 emission levels, it is important that we stabilize vehicle weight as from now, and then start bringing it down. This requirement goes a long way to explaining the many current exploratory programmes (with names like 90g CO_2 and 3 l/100 km), which will drive work on all factors having a bearing on fuel consumption, including vehicle weight."	Maeder, 2001
Honda	"The desire for weight reduction for automobiles is increasing more and more … an increase of aluminum material will surely be required. The company will be delighted if any technology to apply aluminum to the car body developed by Honda to reduce car weight is useful for other automobile companies."	Muraoka and Miyaoka, 1993
Ford	"Excess weight kills any self-propelled vehicle... Weight may be desirable in a steam roller but nowhere else"	Ford, 1924

3.4. Advanced mass-optimized vehicle designs

The above section and tables show the types of mass-reduction opportunities that occur with piece-by-piece or component-level changes from vehicles that have been produced commercially. Although those demonstrate significant mass reduction in vehicles, there is the potential for more substantial mass reduction when the systematic and comprehensive redesign of vehicles is done with the expressed goal of a mass-efficient vehicle. Whereas the above section on emerging mass-reduction technology illustrates what is being done in the automobile fleet to reduce the weight of components, this section chronicles more advanced vehicle redesign concepts that illustrate where future vehicle designs could be headed.

This section provides a summary of findings from a number of major research projects that have sought to determine the mass-reduction technology potential for future vehicles. Although some of the technology efforts described here are somewhat older, each of the projects demonstrates advanced mass-reduction technologies that are currently not embraced widely by automakers and therefore are still highly relevant. The vehicle concepts summarized here each involved a substantial research undertaking in terms of analytical, engineering, and demonstration effort, and they each help to provide a better understanding of the potential for future mass-efficient vehicle design. Before comparing various technology aspects of the conceptual mass-optimized designs, brief summary tables are provided for the following vehicle concepts:

- 1990-2005: Honda NS-X (Table 5)
- 2000: Ford's P2000 (Table 6)
- 2000: DaimlerChrysler's ESX (Table 7)
- 2000: General Motors Precept (Table 8)
- 2000-2004: Rocky Mountain Institute Revolution Hypercar (Table 9)
- 2000-present: Audi A2 and A8 aluminum space frame (Table 10)
- 2004-present: Jaguar all-aluminum XJ body (Table 11)
- 2001: Porsche Engineering ULSAB Advanced Vehicle Concept (Table 12)
- 2001-2003: Ford/US Army IMPACT Ford F150 (Table 13)
- 2003-2007: Auto/Steel Partnership Future Generation Vehicle (Table 14)
- 2004: ThyssenKrupp New Steel Body (Table 15)
- 2005-2006: DaimlerChrysler Dodge Durango Next Generation Frame (Table 16)
- 2007-2008: U.S. Advanced Materials Partnership magnesium-intensive vehicle (Table 17)
- 2007-2008: IBIS and Aluminum Association aluminum-intensive vehicle (Table 18)
- 2005-2009: Volkswagen-led European Super Light Car (Table 19)
- 2010: WorldAutoSteel Future Steel Vehicle (Table 20)
- 2010: Lotus Engineering Low and High Development Vehicles (Table 21)

Table 5. Summary of Honda NS-X

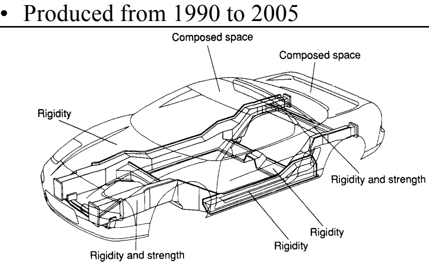
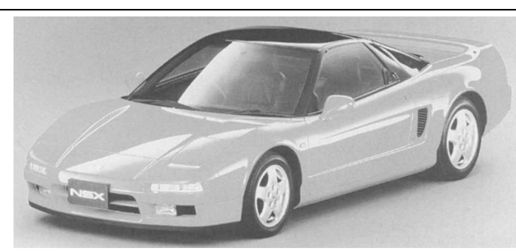
Mass-reduction features, findings	• Nearly all aluminum body, chassis, suspension; stamped aluminum frame • Increased aluminum content from 7% to 31%
Mass-reduction impact	• Body-in-white reduction: 309 lb (40%) • Overall vehicle reduction: 441 lb (13%)
Sources	• Komatsu, Y., K. Ban, T. Ito, Y. Muraoka, T. Yahaba, K. Yasunaga, and M. Shiokawa, 1991. Application of Aluminum Automotive Body for Honda NSX. *Society of Automotive Engineers*. 910548. • Muraoka, Y. and H. Miyaoka, 1993. Development of an all-aluminum automotive body. *Journal of Materials Processing Technology*. **38**: 655-674.
Status	• Produced from 1990 to 2005
Illustrations	 

Table 6. Summary of Ford P2000

Mass-reduction features, findings	• Aluminum-stamped body, substitution of less dense metals and composites • Aluminum (733 lb, or 37%) magnesium (4.3 lb, 3%), titanium (11 lb, 0.5%), and carbon fiber (8 lb, 0.4%) • Secondary effects: smaller powertrain and other components
Mass-reduction impact	• Body-in-white reduction: 476 lb (54%) • Overall vehicle reduction: 1238 lb (38%)
Sources	• Automotive Engineering International, 2010. Battle of the metals: the aluminum angle. *http://www.sae.org/automag/metals/10.htm* Accessed April 9, 2010. • Carpenter, J.A., E. Daniels, P. Sklad, C.D. Warren, M. Smith, 2007. FreedomCAR Automotive Lightweighting Materials. Orlando, Florida. February 28.
Status	• Prototype built and tested in late 1990s, similar Ford Prodigy unveiled at auto shows in 1999-2000
Illustration	 *http://us1.webpublications.com.au/static/images/articles/i6/0647_8lo.jpg*  *http://www.electrifyingtimes.com/fordprodigy.jpg*

Table 7. Summary of DaimlerChrysler ESX

Mass-reduction features, findings	• Extensive use of plastics throughout the vehicle, including in body • Structural injection-molded body panels and aluminum with aluminum frame • Similar to Dodge Intrepid vehicle, but ESX3 body design resulted in 90% reduction in part count from steel • Diesel-fueled mild hybrid (15-kW motor) with 72 mpg; projected cost premium of $7,500
Mass-reduction impact	• Body-in-white reduction: 46% • Overall vehicle reduction: 1238 lb (38%)
Sources	• Winter, D., 1998. "Chrysler's plastic car push." *http://wardsautoworld.com/ar/auto_chryslers_plastic_car_2/*. September 1. • Jost, K., 2000. "Dodge's mild hybrid." *https://www.sae.org/automag/globalview_05-00/02.htm*. May. • Visnic, B., 2000. "Injection molding for low-cost high mileage." *http://wardsautoworld.com/ar/auto_injection_molding_lowcost/*. March 1.
Status	• Prototype built and tested in late 1990s
Illustration	 *http://www.autointell.net/nao_companies/daimlerchrysler/dodge/dodge-esx3-01.htm*

Table 8. Summary of General Motors Precept

Mass-reduction features, findings	• Aluminum intensive body, chassis, exterior panels, seat frames; carbon fiber bumper beams • Novel chassis design with matrix composite brackets
Mass-reduction impact	• Body reduction: 397 lb (45%) • Overall vehicle reduction: 656 lb (20%)
Sources	• Automotive Engineering International, 2010a. Battle of the metals: the aluminum angle. *http://www.sae.org/automag/metals/10.htm* Accessed April 10, 2010. • Autospeed, 2000. The 2000 PNGV Concept Cars. Autospeed Issue 97. *http://autospeed.com/cms/title_The-2000-PNGV-Concept-Cars/A_0647/article.html*. September 12. Accessed April 10, 2010.
Status	• Prototype developed in late 1990s; built in 2000
Illustration	 *http://us1.webpublications.com.au/static/images/articles/i6/0647_11lo.jpg*

Table 9. Summary of Rocky Mountain Institute Revolution

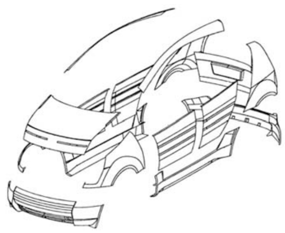
Mass-reduction features, findings	• Vehicle optimization including integration, parts consolidation, advanced material substitution • Carbon fiber-intensive body frame, plastic body panels, carbon-fiber drive shafts • In-wheel motors, shared motor/brake housing; advanced composite and aluminum front-end structure • At $30,000 to $35,000 per vehicle, roughly cost-competitive with luxury sport-utility vehicles
Mass-reduction impact	• Body-in-white reduction: 537 lb (57%) • Overall vehicle reduction: 2080 lb (52%)
Source	• Lovins, A.B., and D.R.Cramer, 2004. Hypercars®, hydrogen, and the automotive transition. *Int. J. Vehicle Design* 35: 50-85.
Status	• Prototype developed 2000-2004
Illustration	  

Table 10. Summary of aluminum-intensive Audi space frame technology

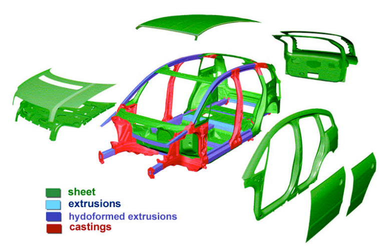
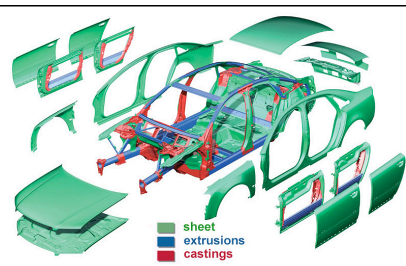
Mass-reduction features, findings	• Aluminum-intensive spaceframe body (and powertrain, chassis, and suspension) • Overall aluminum composition of 700 lb (34% of overall weight) for Audi A2 • Overall aluminum composition of 1150 lb (25% of overall weight) for Audi A8 • A2: body savings versus steel of 134 kg, secondary savings of 75 kg from drivetrain, motor, chassis
Mass-reduction impact	• Body-in-white reduction: 300-500 lb (30-40%) • Overall A2 vehicle reduction: 461 lb (18%)
Sources	• Autointell, 1999. World's first volume-production aluminum car Audi A2 – fascinating technology and a new form of agility. http://www.autointell.com/european_companies/volkswagen/audi-ag/audi-cars/audi-a2/audiag1112.htm. • European Aluminum Association (EAA), 2007. *Aluminum in Cars*. September. • European Aluminum Association (EAA), 2010. Automotive Aluminum Manual (AAM). http://www.eaa.net/en/applications/automotive/aluminium-automotive-manual/
Status	• Introduced in 1999 in compact A2, currently used in Audi A8 • New version of spaceframe being used in TT coupe, under consideration for A5, A6 and other models
Illustration (A2, 1999)	 *http://www.xwomm.com/datagrip/datagrip/pictures/gross/acab_1h _2.jpg*  *http://www.xwomm.com/datagrip/datagrip/pictures/gross/acab_1e_4.jpg*
Illustration (A8, 2002)	 *http://www.xwomm.com/datagrip/datagrip/pictures/gross/acab_3d_2.jpg*  *http://www.xwomm.com/datagrip/datagrip/pictures/gross/acab_3b_2.jpg*

Table 11. Summary of aluminum-intensive Jaguar XJ

Mass-reduction features, findings	• Aluminum-intensive body frame and shell; hydroformed A-pillar/cantrail extrusion assembly • Glass-filled polymide/ultra-high strength steel B-pillar; composites, glass-reinforced plastic molding • Overall 15% few parts for the whole vehicle, 10% reduction in adhesive use
Mass-reduction impact	• Body-in-white reduction: 250-350 lb (25-30%) • Overall vehicle reduction: 717 lb (15%)
Sources	• Birch, S., 2010. "Jaguar remakes XJ." http://www.sae.org/mags/sve/7547. March 4. Accessed April 8. • European Aluminum Association (EAA), 2007. *Aluminum in Cars*. September.
Status	• Introduced in XJ in 2002; currently available
Illustration	

Table 12. Summary of Porsche Engineering Advanced Concept Vehicle

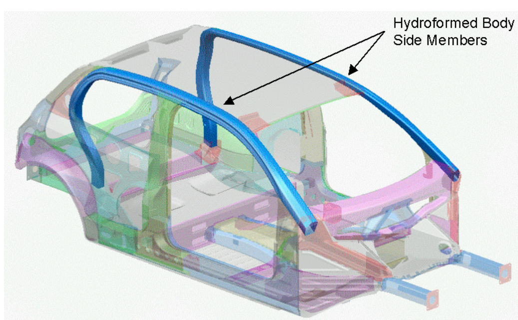
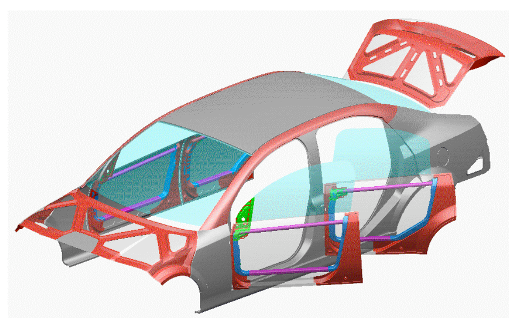
Mass-reduction features, findings	• Mass-optimized steel-intensive design; meet 2004 safety regulations; cost minimization is final priority • Developed two vehicle designs on European C-class (small hatchback) and PNGV-class (mid-size sedan) • Holistic approach to simultaneously consider all systems of the vehicle together • Demonstrated for frontal, side, and rear impacts that are comparable with Four- and Five-Star vehicles • Manufacturing assessment for new materials and fabrication methods demonstrates affordable design
Mass-reduction impact	• Body-in-white reduction: 91-99 lb (17%) • Overall vehicle reduction: 472-1042 lb (19-32%)
Status	• Supported by American Iron & Steel Institute • Called UltraLight Steel Auto Body – Advanced Vehicle Concepts (ULSAB-AVC) program • Engineering design study in 2001
Source	• Porsche Engineering Services Inc., 2001. *ULSAB-AVC: Engineering Report: The design, materials, manufacturing, performance and economic analysis of ULSAB-AVC (Advanced Vehicle Concepts)*. October.
Illustrations C-class hatchback and Sedan	 

Table 13. Summary of Ford and U.S. Army IMPACT Ford F150

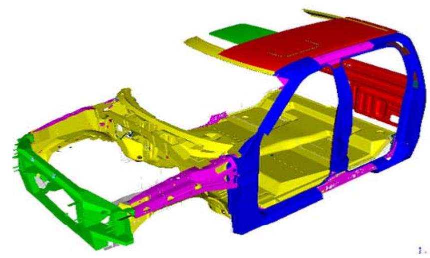
Mass-reduction features, findings	• Intensive use (and stated preference for) high-strength steels throughout the vehicle • Heavy use of dual-phase steel structures, bake hardened steels, and reduced steel gage • Body structure is almost 100% high strength steel • Found substantial reductions of 18% or greater in all major truck systems (powertrain, cab/front, chassis, pick-up box, closures, and interior) • Final design had roughly the same percent steel composition (most steel shifted to high strength alloys) • Body designed for five-star government crash test rating for passenger side impacts (computer analysis) • Found most weight reduction came with cost savings • The first 19% overall vehicle weight reduction (1000 lb) came at net zero cost • The full 25% reduction came at a $500 increase in the total variable vehicle cost
Mass-reduction impact	• Overall vehicle reduction: 1310 lb (25%) • Body-in-white (cab+front-end) reduction: 130 lb (20%)
Status	• Joint project between Ford, American Iron & Steel Institute, University of Louisville, U.S. Army TACOM • Developed and built redesigned Ford F150 over 1998-2003 • Individual weight reduction techniques (60% of them) have been utilized in Ford model platforms in the six years from IMPACT project completion in 2001 to the 2007 report.
Source	• Geck, P. J. Goff, R. Sohmshetty, K. Laurin, G. Prater, V. Furman, 2007. IMPACT Phase II – Study to Remove 25% of the Weight from a Pick-up Truck. *Society of Automotive Engineers*. 2007-01-1727.
Illustrations	 

Table 14. Summary of Auto/Steel Partnership Future Generation Vehicle

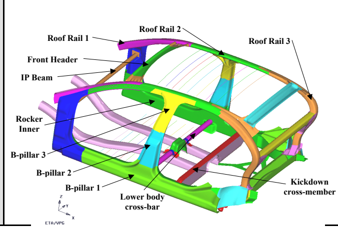
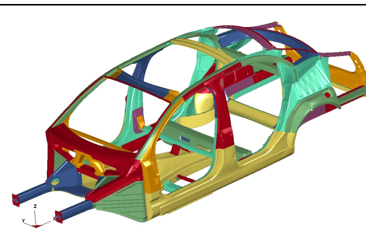
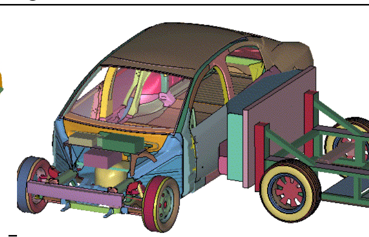
Mass-reduction features, findings	• Intensive use of high-strength steels to replace iron and milder steels throughout vehicle • Use of higher strength steel enables thinner gages and redesigned components • Passenger compartment: 30% mass reduction, improved crash performance, no additional cost • Front-end structure: 32% mass reduction, no additional cost • Rear chassis: 24% mass reduction, no additional cost • Closures: 22% mass reduction, no additional cost
Mass-reduction impacts	• Overall vehicle reduction: 20-30% • Body-in-white reduction: 204-214 lb (30%)
Status	• Supported by the Auto/Steel Partnership, conducted by Altair Engineering • Series of design, engineering, cost, and crashworthiness analyses completed between 2003 and 2007 • Many demonstrated uses of high-strength steel and design techniques are being introduced and commercialized gradually across new vehicle models today
Sources	• Altair Engineering, 2003. *Lightweight SUV Frame: Design Development.* May. • Auto Steel Partnership (ASP), 2005. *Lightweight Front End Structure Project: Phase I & II Final Report.* • Auto Steel Partnership (ASP), 2007. *Future Generation Passenger Compartment. Phase I Report*. June. Accessed December 10, 2009. • Heimbuch, R.A., 2009. "Auto/Steel Partnership: Hydroforming Materials and Lubricant, Lightweight Rear Chassis Structures, Future Generation Passenger Compartment" • Krupitzer, R., 2009. "Automotive Steels and Future Vehicles." Bloomberg Cars & Fuels Summit. Dec 1.
Illustrations	  

Table 15. Summary of ThyssenKrupp New Steel Body

Mass-reduction features, findings	• Developed mass-reduced vehicle using higher strength steels, tubular steel construction, new forming techniques (e.g., hydroforming), based on compact van Opel Zafira, which is popular in Europe • Examined stiffness, crash, and impact load path • Cost impacts: benefits from reduced materials (8%), assembly (2%), and tooling (4%), but increased component manufacturing costs (16%) • Estimated approximate net 2% increase in manufacturing cost of body structure.
Mass-reduction impacts	• Body-in-white reduction: 170 lb (24%) • Potential savings estimated be around 30% with mass-optimization
Status	• Conducted by Thyssen Krupp Stahl • Called New Steel Body ® • Engineering design study in 2004
Source	• ThyssenKrupp, 2004. *NewSteelBody: For a lighter automotive future*.
Illustrations	 

Table 16. Summary of DaimlerChrysler Dodge Durango Next Generation Frame project

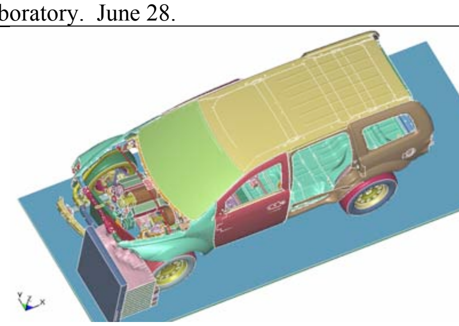
Mass-reduction features	• Develop, build aluminum-steel hybrid frame, and design all-aluminum frame for sport utility vehicle • Created a computer aided design (CAE) model • Evaluated impact on noise, vibration, and harshness (NVH) and durability • Completed CAE and design iterations for DaimlerChrysler 5-Star crashworthiness rating. • Analyses "satisfy all the DCX requirements for 5-Star crashworthiness, NVH, and durability. • Assembled prototype frame into full –size vehicle and road tested
Mass-reduction impacts	• Hybrid aluminum-steel frame reduction: 92 lb (30%) • Designed aluminum frame reduction: ~140 lb (46%)
Status	• Developed by DaimlerChrysler and Pacific Northwest National Laboratory • Also with Tower Automotive, Alcoa, Assured Design, Defiance, Mercia • Designed and built 3 prototype frames for testing ~2005-2006
Sources	• U.S. Department of Energy (US DOE), 2006. "Lightweight materials pave the road for energy-efficient vehicles." *http://www.eurekaalert.org/features/doe/2006-06/dnnl-limp062906.php*. June 26. Accessed March 20, 2010. • U.S. Department of Energy (US DOE), 2006. *Progress Report for High Strength Weight Reduction Materials.* March. • 21st Century Truck Partnership, 2006. Roadmap and Technical White Papers. 21CTP-0003. December. • 21st Century Truck Partnership, 2005. Transportation Materials Research and Development for Heavy Vehicle Applications. Pacific Northwest National Laboratory. June 28.
Illustrations	 

Table 17. Summary of Advanced Materials Partnership magnesium-intensive vehicle project

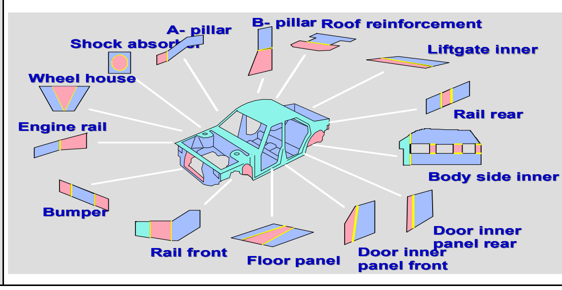
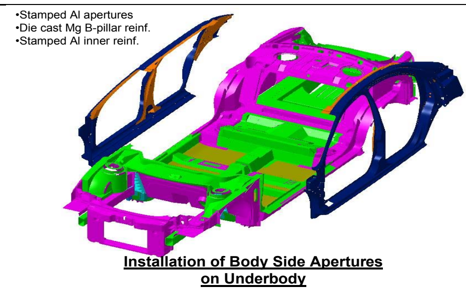
Mass-reduction features, findings	• Magnesium substitutions of many conventional steel and aluminum parts • Replace 680 lb of steel and aluminum parts with 380 lb • Viable magnesium component substitutions include body structure (panels, front end, roof frame, lift gate); powertrain (engine, transmission, intake manifold, transfer case, clutch housing, oil pan); chassis (wheels, frame, engine cradle); interior (seats, stanchions, instrument panel)
Mass-reduction impact	• Overall vehicle reduction from magnesium substitution: 300 lb (~8%) • Vehicle body-in-white concept: 356 lb (49%)
Concept body-in-white	• Hybrid magnesium/aluminum/foam body-in-white (from DaimlerChrysler) • Reduced total part count: 78% • Improved bending frequency 9%, torsion frequency 25% • Meets/exceeds all NVH and energy management goals • Better than current vehicle on current standards; meets new 50-mph offset rear impact safety standard • Increased marginal cost (+3%), decreased investment cost (-46%)
Status	• Design study by U.S. CAR, a consortium of U.S. automakers: General Motors, Ford, DaimlerChrysler
Source	• U.S. Automobile Materials Partnership (U.S. AMP), 2006. *Magnesium Vision 2020: A North American Automotive Strategic Vision for Magnesium.* U.S. Council for Automotive Research.
Illustrations	 

Table 18. Summary of IBIS and Aluminum Association aluminum-intensive vehicle

Mass-reduction features, findings	• Near full aluminum substitution for major steel components (body, panels, front/rear bumpers, wheels) • Accounted for primary weight savings from light metal substitution and also resultant secondary weight savings in engine, transmission, suspension, chassis re-sizing • Found aluminum body substitution had additional manufacturing cost of less than $200 per vehicle • Additional mass-reduction costs had synergistic effects, by reducing costs of simultaneous deployment of advanced powertrains like hybrids and diesels (i.e., additional aluminum cost were offset by reduced diesel or hybrid costs).
Mass-reduction impact	• Overall vehicle reduction: 573 lb (17%) • Body-in-white reduction: 280 lb (47%)
Status	• Project by IBIS Associates, Ricardo Inc, and Novelis Inc, supported by Aluminum Association • Engineering design analyses from 2007-2008
Sources	• Bull, M. R. Chavali, A. Mascarin, 2008. Benefit Analysis: Use of Aluminum Structures in Conjunction with Alternative Powertrain Technologies in Automobiles. Prepared for Aluminum Association. • IBIS Associates, Inc., 2008. Aluminum Vehicle Structure: Manufacturing and Lifecycle Cost Analysis Hybrid Drive and Diesel Vehicles. Report 2008-05. Prepared for Aluminum Association • Casadei, A. and R. Broda, 2007. Impact of Vehicle Weight Reduction on Fuel Economy for Various Vehicle Architectures. Prepared for Aluminum Association.

Table 19. Summary of Volkswagen-led European Super Light Car project

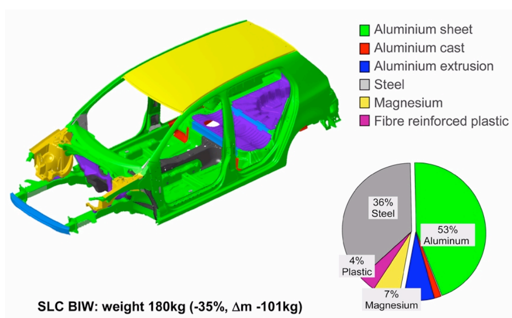
Mass-reduction features, findings	• Develop and demonstrate a multi-material concept approach, including design, materials, and processes • Provide balance between mass reduction and affordability without compromise in safety, stiffness • Based on C-class compact car, similar to a Volkswagen Golf • Design objectives: Affordable mass-reduced vehicle of the future; improved production and assembly; improved design modeling reliability for future resigns • Found major reductions (32-42%) in all major body-in-white components (body, front end, floor) • Utilized diverse material mix: 53% aluminum, 36% steel, 7% magnesium, 4% fiber-reinforced plastic • Utilized continuous, cold, high-speed forming techniques and laser and magnetic welding • Examined structural, crash, fatigue impacts of design and found “The static and crash simulations have proved that the SuperLIGHT-Car body concept has equivalent performances as the C-class reference car”
Mass-reduction impact	• Body-in-white design reduction: 221 lb (35%) • Body-in-white prototype reduction: 240 lb (39%)
Status	• Project conducted from 2005 to 2009 • Utilize 10.5€ million European Commission funding for total 19.2€ million • Companies involved: Volkswagen, Fiat, Daimler, Porsche, Renault, Volvo, Opel • Also involved: 10 R&D companies, 10 suppliers, 7 universities
Sources	• Stehlin, M, 2008. “Super Light Car: Sustainable Production Technologies for CO_2 Emission Reduced Lightweight Car Concepts.” Volkswagen Group. Transport Research Arena Europe. April. • Goede, M., M. Stehlin, L. Rafflenbeul, G. Kopp, E. Beeh, 2009. Super Light Car – lightweight construction thanks to a multi-material design and function integration. *European Transport Research Review. 1: 5-10* • Goede, M., and M. Stehlin, 2009. “SuperLIGHT-Car project – An integrated research approach for lightweight car body innovations.” Innovative Developments for Lightweight Vehicle Structures. Conference proceedings. Wolfsburg. May 26-27.
Illustrations	 *http://www.eaa.net/upl/4/default/img/Final%20SLC%20prototype%20car-1.jpg*  *http://motorshow.files.wordpress.com/2007/04/golf2008_1.jpg*

Table 20. Summary of EDAG and WorldAutoSteel Future Steel Vehicle project

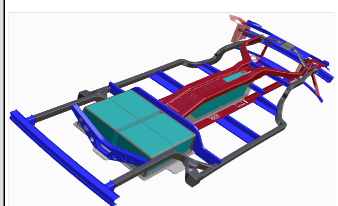
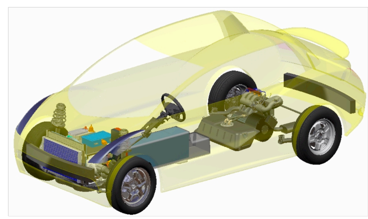
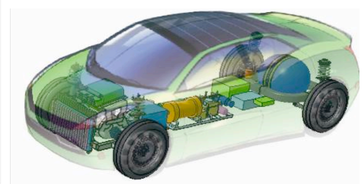
Mass-reduction features, findings	• Redesign conventional vehicle for mass reduction and advanced drivetrain simultaneously • Extensive use of high- and ultra-high- strength steel throughout vehicles • Portfolio of advanced material production (e.g., laser and induction welding, tailored tubes, variable wall) processing (e.g., hot stamping and hydroforming) techniques • Explore mass-reduced plug-in hybrid (PHEV20, PHEV40), electric (BEV), and hydrogen fuel cell (FCEV) • Two primary vehicle classes: 4-door compact hatchback (FSV1) and 4-door sedan (FSV2) • Vehicle body structures redesigned to accommodate advanced drivetrain and energy storage
Mass-reduction impact	• Body structure reduction for FSV1 hatchback: 302 lb (30%) to 340 lb (36%) • Body structure reduction for FSV2 sedan: 509 lb (41%) to 560 lb (48%)
Status	• Conducted by EDAG, supported by WorldAutoSteel • Phase 1 engineering design completed in 2009 • Phase 2 vehicle concept design and simulation is planned for 2010 • Phase 3 construction and demonstration of vehicle concept is planned for 2011
Source	• EDAG, 2009. *Future Steel Vehicle: Phase I.* Executive Summary. Prepared for WorldAutoSteel.
Illustrations	  

Table 21. Summary of Lotus Engineering Low and High Development vehicle project

Mass-reduction features, findings	• Redesign conventional mid-size vehicle for mass optimization, with two redesign architectures • Low Development vehicle technology with industry-leading manufacturing techniques that were deemed feasible for 2014 (for model year 2017 production) for assembly at existing facilities • High Development vehicle technology, with modifications to conventional joining and assembly processes that were deemed feasible for 2017 (for model year 2020 production) • Extensive use of material substitution with high-strength steel, advanced high-strength steel, aluminum, magnesium, plastics and composites throughout vehicles • Conservative use of emerging design and parts integration concepts to minimize technical risk • Using synergistic total-vehicle substantial mass reduction opportunities found at minimized piece costs • The Low Development vehicle was found to have likely piece cost reductions, whereas the High Development vehicle had nominal estimated cost increase of 3% (with potential for cost reduction)
Mass-reduction impact	• Body structure reduction for Low Development Vehicle: 127 lb (15%) • Body structure reduction for High Development Vehicle: 356 lb (42%) • Overall vehicle reduction for Low Development Vehicle: 739 lb (20%) • Overall vehicle reduction for High Development Vehicle: 1230 lb (33%)
Status	• Engineering design study conducted by Lotus Engineering • First phase of project, development of two mass-reduced vehicle designs completed in April 2010 • Next phase to test structural integrity, impact load paths, crashworthiness to validate the vehicle designs
Source	• Lotus Engineering, Inc, 2010. *An Assessment of Mass Reduction Opportunities for a 2017-2020 Model Year Vehicle Program.* April.
Illustrations	  

The various mass-reduction vehicle concepts that are summarized in the above tables allow for a number of observations related to development of mass-efficient vehicle design. Each of the above vehicle mass-reduction projects represents a major undertaking that required substantial technical expertise, engineering resources, and research and development expenditures. The projects in many instances show a packaging of some of the highlights of the most innovative mass-reduction ideas that automotive engineers have developed for mainstream vehicles (as were shown in the previous section on emerging trends) – but have not yet been put together in high-production mass-efficient vehicles. In other cases, the designs are the cutting edge of new mass-reduction techniques that are just emerging (e.g., a beam design, a hydroforming process, a new alloy, an integrated-part design) and could gradually be implemented in new models over the next decade as mainstream vehicles move toward some combination of reduced CO_2 emissions and performance.

Together, these projects present a body of evidence regarding the scale of mass-reduction technology that is achievable in automobiles. Several of the mass-optimized vehicle designs from above are niche production vehicles with annual production in the hundreds or thousands, some are physical prototypes with very limited production of one or several vehicles, while some are engineering design concepts that develop and model the recent state-of-the-art in mass-efficiency. A number of the projects that are summarized in the above tables had very different objectives, designs, and material preferences. As a result, their differences can be quite instructive in some cases. Some of the studies provide detailed data where others do not, and therefore quantitative comparisons are somewhat limited in some cases.

A number of observations are made here regarding comparisons of the mass-reduced structural body and the overall vehicle designs. The structural body, often termed the body-in-white, along with the front-end structure is core of any physical vehicle design, to which all the other major components (suspension, interior, powertrain, etc) are integrated. The structural body is critical to the mass, size, utility, and safety characteristics of the vehicle, and is therefore the paramount feature of new mass-optimized vehicle designs. As a result, mass-reduction design studies typically devote far more attention, engineering detail, and research findings to the body.

As shown in Figure 12, the technical findings from mass-optimized vehicle design projects indicates a range of vehicle designs that reduce the vehicle body mass by 16% to 57%, with the average of these vehicle designs achieving a 30% body mass reduction. All of the low-volume vehicle production designs have body mass reductions of about 30% to 40% (e.g., Honda NS-X, Audi A2, Audi A8, Jaguar XJ). The prototype vehicle designs had mass-reduced vehicle bodies that resulted in reductions from 20% (from the IMPACT weight-reduced Ford F150) to 54% (for the Ford P2000). The more recent engineering mass-optimized design studies found vehicle bodies with reductions between 16% (for the Lotus Low Development vehicle) to 49% (for the U.S. AMP aluminum-magnesium design) from their reference vehicle designs. The much more forward-looking carbon-fiber body of the RMI Revolution resulted in a 57% reduction in body mass, the greatest reduction of all the designs presented here. A general result from these design projects is that many automotive engineering projects have found a variety of different mass-reduction vehicle designs across different light-duty vehicle classes (sportscars, sedans, pickups, sport utility vehicles), that have achieved 25% to 40% reductions in vehicle body mass.

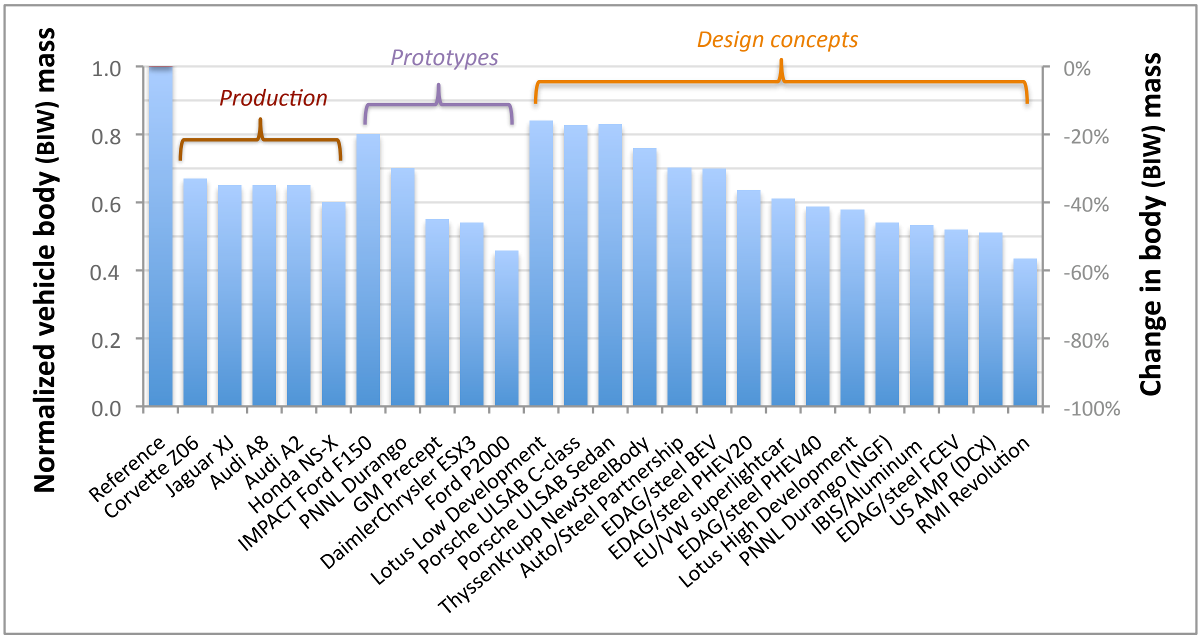


Figure 12. Mass reduction from the body structure of mass-optimized vehicle designs

Figure 13 shows the vehicle material composition by basic material categories of the two Lotus vehicles (Low and High Development) and the Volkswagen-led Super Light Car design (see Table 19 and Table 21, respectively, for details and references). The table shows only very basic material categories for steel, aluminum, plastics, etc.; however there are many different gages, alloys, grades, and types of these materials, but these distinctions are not reflected in the figure. The reference vehicle body shown is that of the Lotus study, which is a 2009 Toyota Venza, which is all steel, 5% of which is HSS. Compared to this reference, the three mass-efficient designs that are shown present new vehicle body designs that range from incremental to more advanced mixed-material bodies. The most incremental mass-reduction approach in the figure is the Lotus Low Development vehicle, which shows a 17% body mass reduction and applies nearly all high-strength steel. This approach essentially follows the industry trend toward higher strength steel types. The two other designs integrate a mix of stronger and less dense metals and composites along with high-strength steels to achieve greater body mass reductions. The Super Light Car design integrates far more aluminum and small amounts of magnesium and carbon fiber to achieve a 39% body structure mass reduction. The Lotus High Development vehicle applies more magnesium and composites to result in a 42% body mass reduction.

Both the Super Light Car and the Lotus High Development designs attest to the potential to substantially reduce vehicle body mass through integrated multi-material approaches that exploit the mass and functional properties of steel, aluminum, magnesium, and plastics. Several of the mass-optimized vehicle design studies, prototypes, and production vehicles from above focus almost exclusively on particular materials. Counter to the multi-material approach, some of the projects are steel-, aluminum-, magnesium-, or composite-intensive. Of the studies that held explicit strict preferences for materials, the aluminum and steel-based approaches indicated that single-metal approaches could result in mass reductions of comparable magnitude to the multi-material approach. The EDAG steel industry project finds potential body mass reductions from 30% to 46% from essentially all high-strength steel bodies (See Table 20). Likewise, the IBIS aluminum industry project finds that body mass reductions up to 47% could result from an essentially all-aluminum vehicle body design (See Table 18).

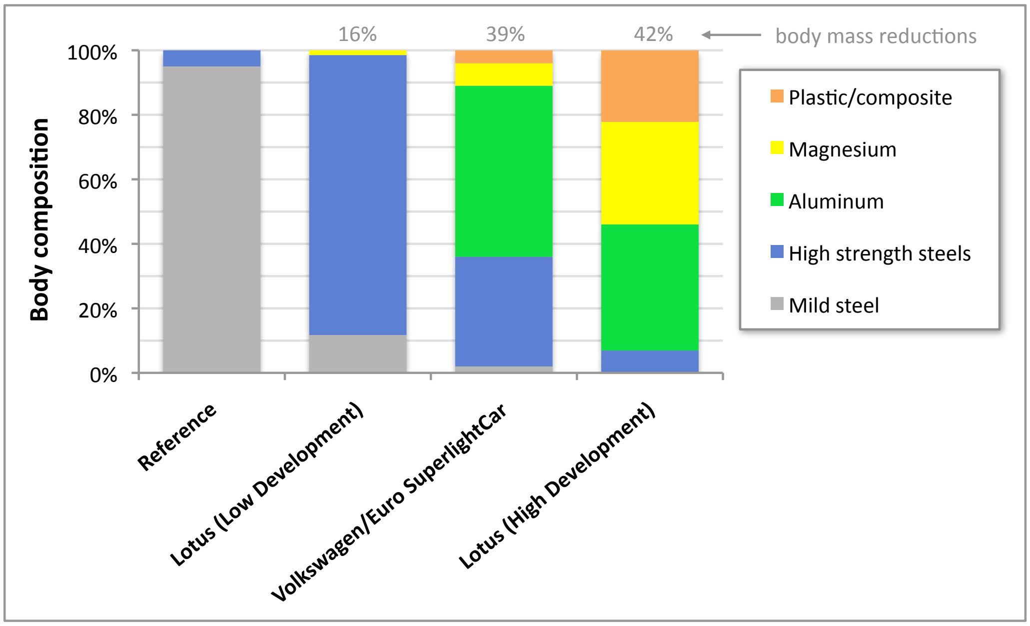


Figure 13. Material composition of mass-optimized vehicle body designs

Another point of comparison of the mass-reduced designs is how the vehicles' body mass reductions and the overall vehicle mass are related for the various designs. Figure 14 shows the percentage body reduction (x-axis) and the overall vehicle mass reduction (y-axis) for mass-optimized vehicle designs from above. Shown in this figure, there are a few critical differences between the studies. Several of the studies (e.g., the EDAG and IBIS studies) show high relative body mass reduction compared to their overall vehicle mass reduction. This could be attributed to these studies particular interests in documenting the strengths of particular metals (steel for EDAG and aluminum for IBIS), and therefore being more specifically targeted at replacing structural metal components than on addressing the various other potential mass-reduction areas (e.g., interior components) that are less based on steel and aluminum. As a result, these studies would appear to overlook more diverse multi-material, plastic, fiber-reinforced materials, and magnesium technologies that are exploited in several of the holistic projects (e.g., Ford P2000, RMI Revolution, Lotus), which found that greater overall vehicle mass reductions were achievable.

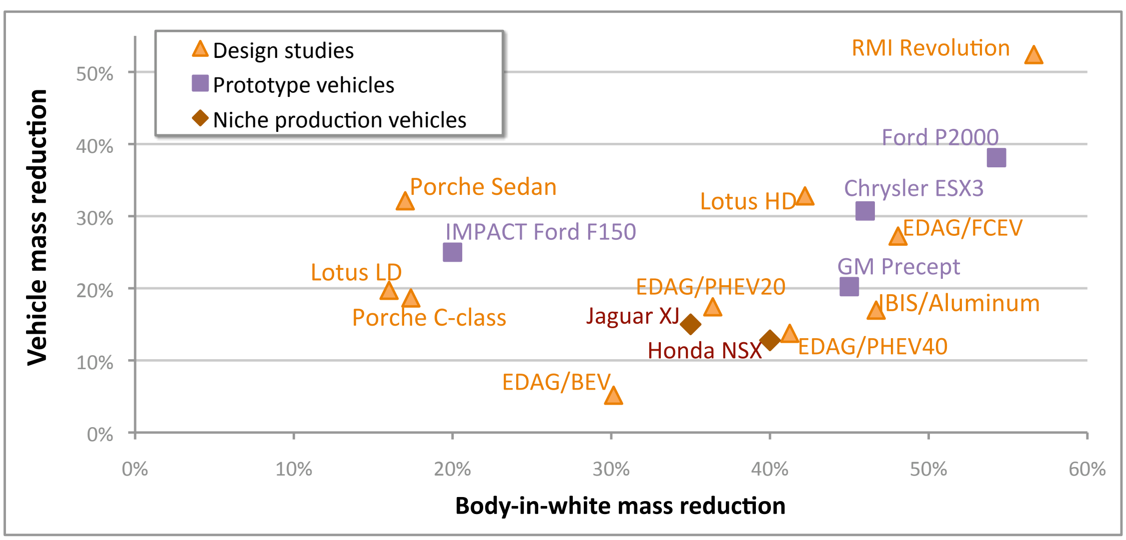


Figure 14. Vehicle body and overall vehicle mass impacts from mass-optimized designs

The three vehicle prototypes from the U.S. Partnership for a New Generation of Vehicles (PNGV) program provide examples of the types of materials that can be used to achieve mass-optimized vehicle designs. Figure 15 shows the PNGV vehicles' material composition and overall vehicle mass-reductions (data are from Schexnaydor et al, 2001). The PNGV program had targeted an 80 mile-per-gallon mid-size sedan, and the three prototype vehicles each ultimately achieved greater than 70 miles per gallon with hybrid vehicle systems and mass-reduced designs. The achieved mass reductions were approximately 20% (for the General Motors Precept), 31% (for the Daimler-Chrysler ESX3), and 38% (for the Ford P2000), and each one accomplished the reductions with different material and design approaches. Each PNGV vehicle made much greater use of aluminum (mostly in the vehicle body structure), with two to five times more aluminum than the reference vehicle. The Daimler-Chrysler ESX3 made extensive use of plastics, including injection-molded thermoplastics and also carbon and glass fiber. The Daimler-Chrysler and Ford prototypes also used magnesium more heavily, at 55 and 39 kg, respectively. All three models met the Federal Motor Vehicle Safety Standards (FMVSS) along with many of the other PNGV program goals (NRC, 2000).

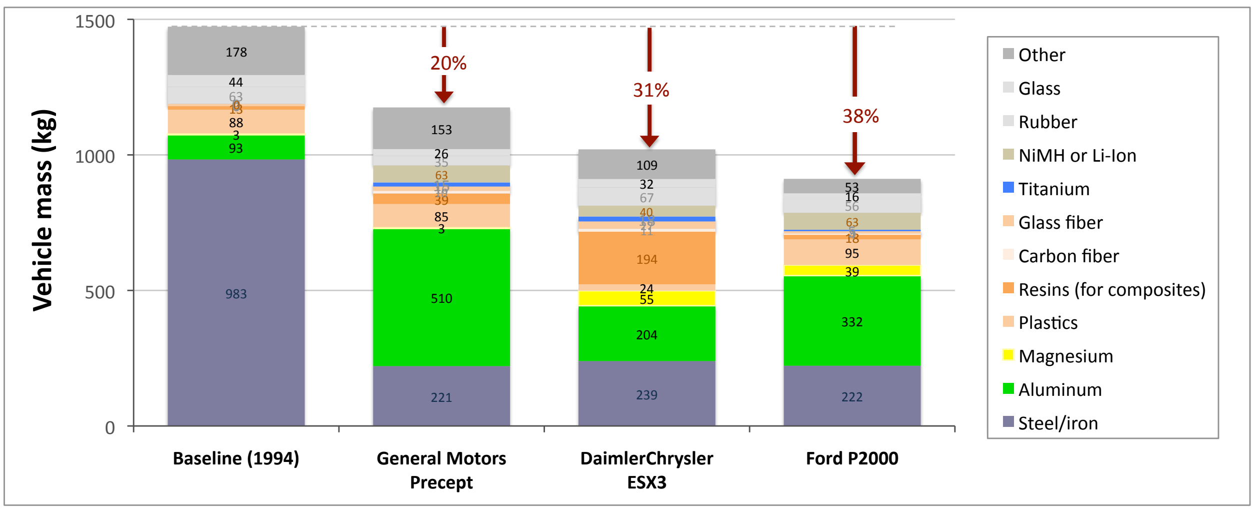
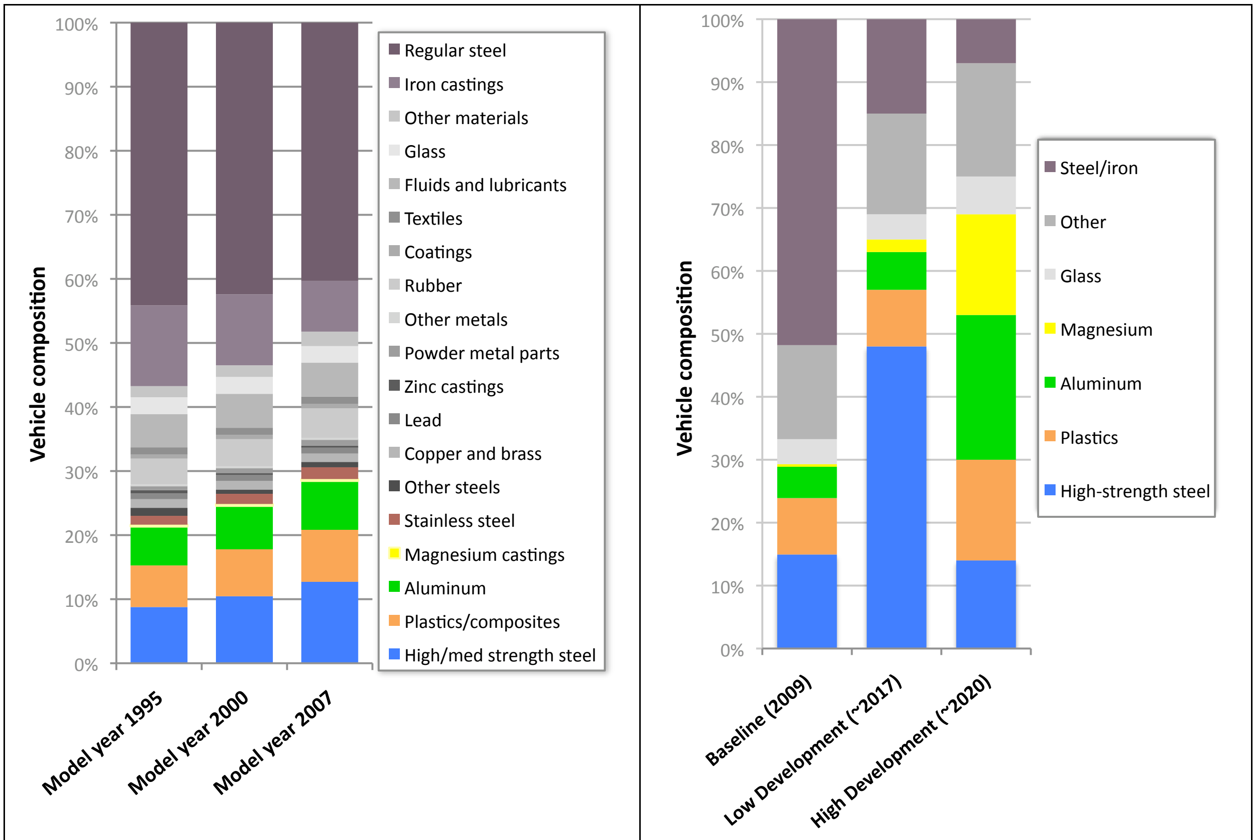


Figure 15. Vehicle mass reduction and material composition of PNGV prototypes

Figure 16 shows how the Lotus mass-optimized vehicle designs compare with automotive material composition trends from the past fifteen years (from Ward's Automotive, 2009). Looking only at the historical data on the left-hand-side of the figure, a couple historical trends are clear. Iron, regular steel, and other steel content in vehicles is decreasing (by 37%, 9%, and 33%, respectively from 1995 to 2007), while advanced materials and mass-optimized designs have entered the vehicle fleet. These broad trends were discussed above, as well as the individual component trends (e.g., in engine heads and blocks, panels) that are linked to the material trends. The primary substitutes in the historical mass-reduction trend are high-strength steel (45% increase from 1995-2007), plastics and composites (25% increase), aluminum (23% increase), and magnesium (127% increase).

The Lotus design concepts show an apparent continuation of the recent historical trend in shifting vehicle material composition. The Lotus report indicates that the Low Development vehicle mass-reduction technology concepts are available in 2014 for model year 2017 commercial deployment. The primary material change for the Low Development vehicle is to greatly increase the amount of high-strength steel usage in the structural body components. The High Development Lotus vehicle design utilizes techniques that are to be implementable in a model year 2020 commercial deployment. This more advanced mass-optimized vehicle design employs a more diverse array of materials and integration techniques in the vehicle's structural body and throughout all of the other vehicle systems. In percentage terms, this vehicle utilizes substantially more magnesium, aluminum, plastics and uses about the same amount of high-strength steels as the reference vehicle design. These increases in the usage of lower density materials occur at the expense of iron and mild steel, which see decreases in their composition percentage.



Historical trend, 1995-2007 *(Ward's Automotive, 2009)*	*Mass-reduced vehicle design* *(Lotus Engineering, 2010)*

Figure 16. Comparison of Lotus mass-reduced designs to historical vehicle composition trend

To give further perspective on the vehicle weight breakdown from the mass-optimized vehicle designs from the Lotus study, Figure 17 shows the Lotus reference, Low Development, and High Development vehicles' mass and material composition. The above figure, by normalizing mass to 100% of the reference Toyota Venza that was the benchmark, does not reflect the actual gross amount of the materials that are being utilized in the two mass-reduced Lotus designs. As shown in Figure 17, the two Lotus designs reduce the overall vehicle mass by 20% and 33%, respectively, when including that study's constant-performance re-sized hybrid powertrain. From this figure, it becomes clear that even though the percentage composition of higher cost materials like magnesium, aluminum, and composites each increase, their actual material amounts by-mass do not change much for the Low Development Vehicle. For example, the Low Development vehicle results in an increase in magnesium by 20 kg, a decrease in plastic/composite content by 30 kg, and a decrease in aluminum by 3 kg; meanwhile, the use of high-strength steel sees a 400-kg increase from the reference vehicle. The High Development vehicle, however, shows greater increases in non-steel materials; for example the magnesium and aluminum content both increase by over 170 kg from the baseline vehicle.

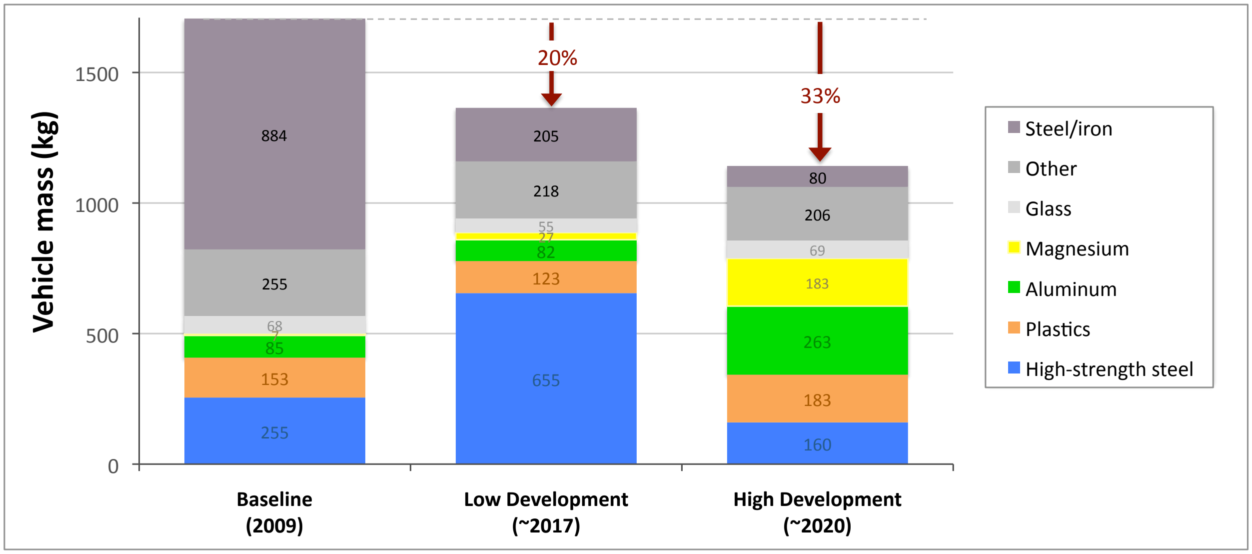


Figure 17. The mass by material of the Lotus baseline and mass-reduced vehicle designs

Despite the greater use of the higher-cost stronger steels, aluminum, magnesium and composites, some of the studies suggest that the mass-optimized vehicle designs could have minimal or modest cost impacts on new vehicle manufacturing costs. Table 22 highlights major findings from the above studies related to the cost impacts of utilizing mass-reduction technologies in new vehicle designs. The findings indicate that by using higher-cost advanced materials, the net result can actually be an overall reduction in the vehicle cost for a number of the mass-optimized designs. In many cases, material cost increases are offset entirely by the reduction of the use of that material due to the material being stronger and therefore less of the material being required. Furthermore, cost reductions occur in some of the studies because optimized techniques for using purpose-built tubular designs, forming techniques with less structural material, and variable gage materials allowed for further reductions in material use in stronger structures. Another mechanism that allowed for cost reductions in some components within the studies' mass-optimized designs was parts consolidation, whereby the integration of parts allows for major reductions in the overall part count in many of the body structures and other systems throughout the vehicle.

Table 22 suggests that manufacturing cost reductions seem likely for many of the more near-term incremental options for vehicle mass reduction up to about 20%. The near-term incremental options generally involve greater use of emerging material substitution alternatives that are currently employed by only a fraction of the light-duty vehicles in the 2009 fleet and still utilize forming and assembly techniques that are common but not widespread in current manufacturing practices. Such near-term mass-*and*-cost reduction findings often include prodigious use of high-strength steels, indicating that some of the emerging steel-intensive designs, in particular, appear to present the low-hanging fruit of vehicle mass-optimization. For example, the IMPACT Ford F150 project found that vehicle designs that reduce the pickup's mass by 19% come at net-zero manufacturing cost, whereas the full 25% mass-reduction package came with a $500 per vehicle cost increase. The ThyssenKrupp steel design resulted in a 24% body mass reduction, with potential for secondary mass reductions from design optimization elsewhere on the vehicle, at a 2% cost increase. The Low Development Lotus design, which relied on the use of advanced steel alloys, similarly demonstrates that a 20% mass-reduced vehicle could actually decrease the overall vehicle piece costs by 2%. Aluminum-intensive designs also showed the potential for minimal net-vehicle costs with substantial mass reductions. In particular, the IBIS aluminum-intensive design, even though its aluminum unibody structure had a cost premium of over $500, offers an overall vehicle cost increase of less than $200, due to its inclusion of powertrain re-sizing and secondary mass-reduciton effects, for a vehicle that had its mass reduced by 17% from its baseline steel-intensive vehicle.

More advanced mass-optimized concepts that went beyond the above incremental steel and aluminum techniques were found to deliver greater mass reductions but come at increased vehicle costs. More innovative mass-optimized designs that exploit stronger materials and reach further into cutting-edge assembly and manufacturing techniques offered mass reductions of 35% and greater. The multi-material design of the Volkswagen-led mass-reduction project shows the feasibility of a unibody structure of aluminum, magnesium, and composites that delivers up to a 39% body mass reduction that has costs that are less than 10€ per kilogram of reduction. However, the ability to fully compare that study is limited here, because that study neither clearly spells out the derivation of its costs nor examines the potential for whole vehicle mass reductions that many of the other studies detailed here demonstrate for holistic vehicle designs that exploit the full capability of parts integration and mass decompounding elsewhere on the vehicle. On the other hand, the Lotus High Development case does present such comprehensive cost and whole-vehicle analysis. That study finds that a 33% vehicle mass reduction is achievable at a 3% cost increase, which would roughly correspond to a $400-600 per vehicle increase in manufacturing cost (with an uncertainty ranging from a 3% cost decrease to a 9% cost increase).

Table 22. Findings related to the costs of mass-reduced vehicle designs

Project	Mass reduction [a]	Cost impact findings [a]
IMPACT Ford F150	• Body: 20% • Vehicle: 25%	• Most mass reduction actions came with cost savings from baseline • A 19% overall vehicle mass reduction comes at net zero cost • A 25% mass reduction comes at a $500 increase in the total variable vehicle manufacturing cost of the vehicle • Mass-reduction features are currently entering Ford's new vehicle fleet
Porsche Engineering ULSAB-AVC	• Body: 17% • Vehicle: 19-32%	• The total estimated manufactured cost of the mass-optimized vehicles is found to be about $9,200 to $10,200 per vehicle. • Mass-optimized vehicle designs using high-strength steels are affordable with minimal additional manufacturing costs
ThyssenKrupp New Steel Body	• Body: 24%	• Material, assembly, tool/die costs decrease; production costs increase • Overall: 24% body mass reduction has a 2% manufacturing cost increase
IBIS aluminum-intensive design	• Body: 48% • Vehicle: 17%	• Aluminum body has a $500-600 cost increase from steel (22% increase) • Aluminum vehicle overall has an approximate $100 additional cost (1% increase) over conventional baseline vehicle retail price
EDAG steel-intensive Future Steel Vehicle	• Body: 16-30% • Vehicle: 17%	• Found mass-optimization allows hybrids and plug-ins can have improved total ownership cost from conventional 2020 vehicles (i.e., reductions in fuel consumption and other benefits offset mass-reduction and powertrain costs).
US AMP concept magnesium-intensive body	• Body: 49%	• Reduced part count (-78%) along with reduced mass (-161 kg) • Increased variable cost (3%), decreased investment cost (-46%)
Volkswagen-led Super Light Car	• Body: 14-39%	• Steel-intensive (-14%, 40 kg): less than 2.5 €/kg • Multi-material, economic (-22%, 62 kg): less than 5.0 €/kg • Multi-material, advanced (-39%, 114 kg): less than 10 €/kg • "Multi-material concepts promise cost effective light weight solutions"
Lotus Engineering Low Development	• Body: 16% • Vehicle: 20%	• Body-in-white cost decreases by 18%, or about $60/vehicle • The vehicle cost is decreased by 2%, or about $300/vehicle
Lotus Engineering High Development	• Body: 42% • Vehicle: 33%	• Body-in-white cost increases by 35%, or about $1000/vehicle • The vehicle cost is increases by 3%, or about $500/vehicle
RMI Revolution	• Body: 57% • Vehicle: 52%	• Sticker price of $35,000, designed for cost comparability with luxury sport utility vehicles (e.g., Lexus RX, Mercedes ML). • Cost-competitiveness due to parts consolidation and reduction and the reduction in use of materials offsetting price of high-cost composites

[a] *This table's findings are based on a variety of sources from the various projects (See Tables 5-21 above for further details and sources)*

4. Implications

The above review of technology developments in vehicle designs and advanced materials suggests that mass-reduction technology has been, is, and will continue being, a core component of automobile manufacturers' efforts to improve the efficiency of light-duty vehicles. Directly following from these developments are a number of broader implications for optimal policy frameworks to best promote mass-optimization technology in the near- and long-term timeframes. This section discusses policy-related implications that follow from the above technology assessment.

4.1. Vehicle mass-reduction and policies for CO_2 emissions and fuel economy

Standards for CO_2 emissions and fuel economy exist for most major automobile markets. The standards are designed to be technology neutral so as to promote the full range of potential efficiency technologies – from improved engine combustion, to increased transmission efficiency, to mass-reduction, to electric drivetrains. However, there are considerable differences in the standard designs that, as a result, provide different incentives for different types of efficiency technology.

As shown in Table 23, a number of the major global automotive markets have various forms of CO_2, fuel consumption, and fuel economy standards. Together about 70% of the world automobile market has some form of standards that will promote efficiency. Of those standards, nearly every one has some accommodation for the varying utility, size, or mass of the vehicle. In particular, three of the four largest markets – Europe, China, and Japan – index their standards to the mass of the vehicle. The U.S. and Canada index their standards to the size of the vehicles. Other smaller markets have regulatory standards that use engine size (e.g., in South Korea, Taiwan). Nearly every regulatory program uses some form of attribute-basis to take into consideration the diverse fleet of vehicle sizes and the different automakers' particular vehicle sales characteristics. With attribute-based standards, more lax targets are applied to larger or heavier vehicles and the results are to somewhat levelize the automaker-specific impacts from standards and to more directly regulate the technical efficiency of all vehicles of all sizes.

Table 23. Worldwide automobile efficiency and GHG standards

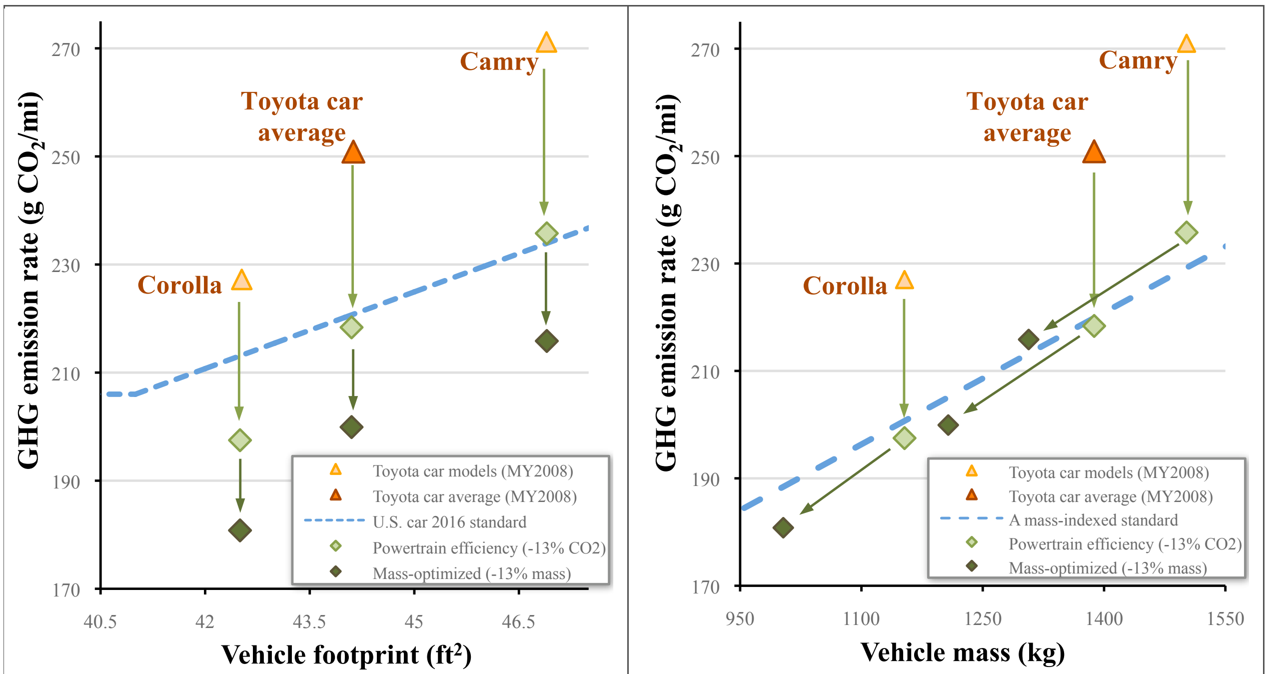
Country/region	Annual automobile sales in millions in 2009 (and world market share)[a]	Regulatory metric [b]	Standard design elements
European Union	14 (24%)	CO_2 (CO_2/kilometer)	Mass-indexed, continuous
United States	10 (18%)	FE (mile/gallon); GHG (CO_2e/mile)	Size-indexed, continuous, two classes
China	8 (14%)	FC (liter/100kilometer)	Mass-indexed, discrete
Japan	5 (8%)	FE (kilometer/liter)	Mass-indexed, discrete
Canada	1.5 (3%)	GHG (CO_2e/mile)	Size-indexed, continuous, two classes
South Korea	1.1 (2%)	FE (kilometer/liter)	Engine size-indexed
Australia	0.9 (2%)	FC (liter/100kilometer)	Flat
Taiwan	0.3 (1%)	FE (kilometer/liter)	Engine size-indexed

[a] *Based on data from JD Power, AutomotiveNews; data are approximate, some countries use different vehicle category definitions.*
[b] *Abbreviations: CO_2 =carbon dioxide; GHG=greenhouse gas; FE=fuel economy; FC=fuel consumption*

Because of the different regulatory designs with different attribute-based structures, the standards will offer different levels of compliance incentive for different approaches to improve the fuel economy or CO_2 emissions of vehicles. All of the standard structures provide a direct incentive for automakers to deploy new technologies that increase powertrain efficiency; however, attribute-based standards can introduce different levels of incentive for other automaker strategies. Generally, engine-size-indexed standards take away the incentive for deploying a greater percentage of smaller engines, size-based standards take away the incentive to shift the fleet composition smaller, and mass-based designs take away the incentive to sell vehicles with more mass-reduction technology. Standard designs that are "flat," or have no accommodation for different vehicle attributes, maintain the incentive for automakers to use any of the potential CO_2-reduction strategies – including all efficiency technology and sales fleet composition strategies.

Among the basic regulatory structures employed worldwide, of particular importance for this review of mass-reduction technology is the popularity of the mass-based vehicle standards – which are in effect in China, Europe and Japan (almost half of the world automobile market). On the surface, because vehicle mass is a fundamental determinant of vehicle efficiency, it seems that mass could be a logical choice for the regulatory structure of the vehicle standards. However, as illustrated above, vehicle mass-reduction technology (advanced materials, mass-optimized designs) is a major technology strategy for increasing vehicle efficiency. As a result, by using a mass-based standard structure, the core efficiency technology of mass-reduction is essentially neutralized.

To demonstrate the difference in the regulatory treatment of mass-reduction technology in regulatory structures that are based on size and mass, an identical vehicle powertrain efficiency-plus-mass-reduction technology package is considered. Figure 18 illustrates the potential for efficiency improvements and vehicle mass reduction to contribute toward compliance with footprint-based and mass-based regulatory standards. In the figure, Toyota's 2008 Corolla, Camry, and average car values are shown. Then the models are modified to reflect a 13% CO_2 reduction from improved powertrain efficiency (e.g., with an improved engine and transmission) and a 13% mass reduction in both regulatory systems. In the left portion of the figure for a footprint-based standard, both the powertrain efficiency and mass-reduction technology steps result in vertical drops in the vehicle models' GHG emissions, pushing each model substantially below the diagonal regulatory standard line, thus aiding in the automaker's compliance with the standards. In the right mass-based portion of the figure, the powertrain technology is shown with a vertical improvement in CO_2 emissions; however, mass-reduction would not be a successful strategy because the mass-reduced vehicles would be subject to a more stringent standard.



Powertrain-plus-mass-reduction technology in a size-based regulatory structure	Powertrain-plus-mass-reduction technology in a mass-indexed regulatory structure

Figure 18. Impact of an identical efficiency-and-mass-reduction technology package in size- and mass-indexed CO_2 emission regulations

As shown in the above figure, the GHG benefits of vehicle mass-reduction are directly captured and incentivized in the footprint-indexed standard structure, but they are not in the mass-based regulatory design. In size-based standards, technologies like material substitution and optimized vehicle design for overall vehicle model mass reductions are fully valued toward automaker compliance. Those automakers that elect to deploy more mass-reduction technology that reduces CO_2 emissions and increases fuel economy will not be fully rewarded for this technology in mass-indexed regulatory schemes. Thus mass-indexed standards put a relative discouragement on one entire category of efficiency technology – mass-optimized design – while still promoting the use of other efficiency technologies (e.g., engine and transmission efficiency).

Mass-based standards can attempt to mitigate their relative disincentive for mass-reduction technology. A way to install some incentive for mass-optimization in a mass-based scheme is to reduce the slope of the mass-to-CO_2 emission standard-setting line. Shifting this slope to be more gradual than the actual baseline regression of existing vehicle models in the fleet would, to the extent that it is done, effectively be shifting the mass-based standard toward a flat standard. For example, the European scheme does intentionally set the standard target line at a slope that is lower than the actual fleet of vehicles to, at a minium, protect from future shifts toward a fleet with higher average mass (EP, 2009; CEC, 2007). However, as long as there is any slope in a mass-based standard target line, a mass-indexed standard will always provide less inducement for automakers to deploy mass-reduction technology than flat or size-indexed standards because vehicle models that see mass reducitons would be subject to more stringent standards in the mass-indexed structure.

As illustrated in Section 3 above, mass-reduction of components, system optimization, and comprehensive whole-vehicle designs are fundamental to many automaker plans for achieving lower CO_2 emissions and higher fuel economy. For example, Section 3.3 shows how automakers are currently deploying a whole host of engine, transmission, body, interior, and other parts throughout the vehicle, and further more, Section 3.4 indicates that those component-level changes are but smaller incremental steps compared to the larger potential of whole-vehicle mass-reduced designs. Standards that index regulatory CO_2 or fuel economy targets to the mass of vehicles run the risk of providing little to no incentive for the introduction of these technologies. If all of the critical technology tools for automakers to improve the efficiency of vehicle are to be promoted by regulatory standards, mass-indexed standards should be avoided.

4.2. Vehicle mass-reduction and electric drivetrain technology

Another critical implication of vehicle mass reduction for future automotive technology more generally is the importance of mass-optimized designs for advanced vehicle with greater electrification of the drivetrain. A critical consideration for advanced electric-drivetrain vehicle technologies – those that go beyond incremental engine, transmission, aerodynamics, and accessory improvements – is the extra electric componentry for electric motors, energy storage, and power electronics which all significantly increase the cost and weight of vehicles.

Current hybrid vehicles give some indication of how important vehicle weight and advanced electric-drive vehicle technologies are interrelated. Figure 19 shows how hybrid vehicle models define the frontier in low-CO_2 emission technology in the U.S. automobile market. The hybrid models shown in the figure result in an average CO_2 gram-per-mile reduction of 32% (corresponding to a 48% increase in fuel economy) from their similar non-hybrid counterparts. However, also shown in the figure is how these technologies exhibit a characteristic increase in weight. The hybrid models shown have, on average, a 9% weight increase over their comparable non-hybrid models, due to the addition of electric system components like batteries, motors, and motor controllers. More advanced vehicle technologies, such as plug-in-capable hybrid electric-gasoline vehicles, electric vehicles, and fuel cell vehicles offer the potential for greater vehicle efficiency improvements than hybrids, but do so with even greater upward pressure on vehicle weight as their energy storage and electric powertrain components increase in capacity and size.

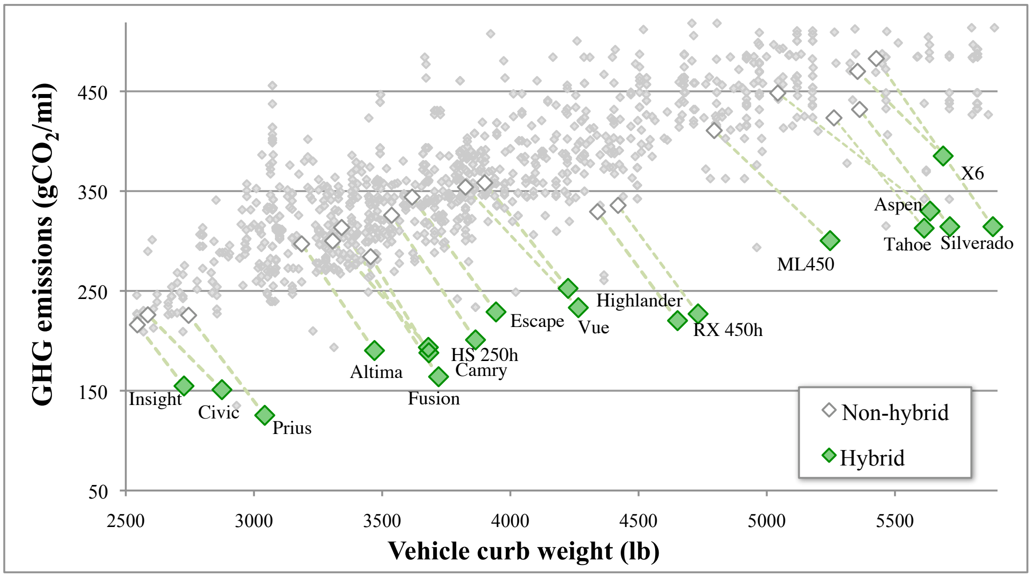


Figure 19. CO_2 emissions of model year 2008 hybrids and their non-hybrid counterparts

If mass-reduction technology countermeasures are not taken to offset mass increases from the additional vehicle electric-drive systems, the overall CO_2 or fuel economy benefits of these technologies is compromised, as is the ability to minimize the costs of these electric components. The importance of mass-optimization technology is far greater for electric-drive vehicles than for conventional vehicles, due to the requirement of designing the size of the all of the electric components (i.e., the battery pack, motor/generator, motor controller, etc) to the overall mass of the vehicle. Any amount of mass-reduction technology allows for a proportional decrease in the capacity, mass, and cost of these electric system components, which are kilogram-for-kilogram among the costliest major components on the vehicle. As a result, mass-reduction technology is not simply a core vehicle efficiency technology; it could also be an enabling technology for the affordability of the next generation of electric-drive technologies.

A number of studies indicate the importance of mass-reduction for advanced electric-drive vehicles. Most major forward-looking assessments of advanced vehicle efficiency technologies include mass-reduction as a critical component of these technology packages. For example, a number of technical studies of various levels of advanced vehicle technology include vehicle mass reductions of 14-30% (Weiss et al, 2000; Santini et al, 2001; An et al, 2001; Graham et al, 2001; Lipman and Delucchi, 2006; Cheah et al, 2007; Pagerit et al, 2006; DeLorme et al, 2009).

Several technology studies indicate that looking at mass-reduction technology and hybrid drivetrains together has synergistic effects involved. Two studies find that a 17-20% vehicle mass reduction with vehicle hybridization effectively reduces the total incremental cost required for electric powertrain components (engine, controller/inverter, batteries) while offering the increased efficiency benefits of HEVs (Graham et al, 2001; Bull et al, 2008). One of those studies found that a 17% mass-reduced hybrid would save almost $800 in per-vehicle powertrain costs over a conventional hybrid (Bull et al, 2008). A similar general relationship is found for plug-in HEVs. An aluminum-intensive design study shows that the adoption of mass-optimization technology for a 17% weight reduction could downsize battery capacity by 1 to 3 kWh; as a result, the reductions in battery costs exceed the additional costs of the mass-reduced vehicle body (IBIS, 2009). Similarly, EDAG (2009) finds that a vehicle body mass reduction of 30-48% from stronger and mass-optimized steel designs drastically reduces electric powertrain requirements for plug-in hybrid, battery electric, and fuel cell vehicles. These research findings all point to the critical importance of mass optimization to minimize the costs of electric-drive technologies for future vehicles.

5. Conclusions

The intent of this assessment is to inform discussions on the potential for automotive mass-optimization technology to contribute to reductions in the mass of vehicles (i.e., independent of "downsizing" trends toward smaller vehicles). A number of technology trends are apparent regarding the continuing emergence of mass-optimization technology in automobiles. In turn, these technology trends provoke a number of policy findings and questions. These technology and policy findings, as well as unaddressed research areas, are summarized here.

Mass-reduction technology trends for vehicles:

- *Vehicle mass-reduction has historically been a core efficiency technology for automobiles*. Automobiles have fundamentally shifted toward more mass-efficient vehicle designs with stronger and lower-density materials (e.g., front-wheel-drive, unibody construction, high-strength steels, aluminum, plastics). These mass-reduction innovations have substantially increased technical vehicle efficiency. However, these efficiency improvements are "unseen" due to several confounding trends in vehicle size, engine size, vehicle content, and vehicle performance.
- *Vehicle mass-reduction continues to be a critical emerging efficiency technology for automobiles*. Emerging trends for advanced materials, forming techniques, integrated vehicle parts, and more holistic vehicle design planning are as promising as some of the more prominently discussed near-term powertrain technologies (from valvetrain technologies, turbocharging, direct injection, dual clutch transmission) in terms of their potential for increased fuel economy and CO_2 emission reductions. For example, the application of near-term technology for a 20% reduction in vehicle mass would result in a 12% to 16% reduction in reduction in CO_2 emissions.
- *Different automakers utilize mass-reduction technology to different degrees*. Mass-reduction technology is not a discrete either-or question, as automakers all consider the mass of vehicles in the vehicle design process. Technically all vehicles use mass-optimization techniques to some extent. But the degree to which vehicle models are relatively mass optimized (i.e., have low mass for a given size or level of utility) is determined by which components or systems utilize mass-optimized designs with stronger materials.
- *Vehicle mass-reduction technologies range from incremental component substitution to major vehicle body redesigns*. Automakers, in model redesigns, can achieve up to a 20% mass reduction in vehicles at little to no additional manufacturing cost and without paradigm-shifting technologies. Looking at whole-vehicle, mass-optimized designs results in further opportunities for secondary mass-reduction effects in powertrain, chassis, and structural systems. A number of technical studies indicate that vehicle mass reductions from 20-35% could be affordable and feasible with automotive technology shifts toward advanced mass-reduction techniques; these next steps include known technology advances in materials, vehicle designs, and manufacturing processes.
- *There are multiple competing mass-optimization strategies that achieve major mass reductions*. Different automakers and suppliers specialize in different materials, processes, and components for mass reduction. Existing mass-optimization vehicle designs demonstrate how different approaches (e.g., all-steel, all-aluminum, and multi-material) can achieve 30-40% vehicle body mass reductions that also exceed structural performance objectives. More forward-looking designs that utilize carbon fiber composites for the body structure would go further yet in reducing vehicle mass.
- *Mass-reduction will only grow in importance with more advanced future vehicle technologies*. A combination of public pressure, government incentives, and technology innovation are all pushing electric-drive vehicles forward. The whole range of electric vehicles – from hybrids to plug-in-capable hybrids, full electric vehicles, and fuel cell vehicles – benefit from mass-reduction technology even far greater than conventional gasoline vehicle technologies. Mass-reduction technology delivers direct efficiency gains to all vehicles, but mass reduction could ultimately be a critical enabling technology for affordable future electric-drive technologies due to its potential to reduce the required sizes for high-cost electric powertrain components.

Policy-related findings on vehicle mass-reduction technology:

- *Vehicle efficiency policies should provide compliance incentives for all efficiency technologies – including mass-reduced materials and designs.* Mass-reduction technologies are available, and the plans of automakers indicate their clear intent to commercialize these technologies. The particular mass-indexed automobile efficiency policies in Europe, Japan, and China fail to provide a full compliance inducement to encourage the deployment of mass-optimization technology. These policies therefore run the risk of not capturing or incentivizing the potential associated energy and environmental benefits of mass-reduction technology. Whereas mass-indexed standards neutralize mass-reduction technologies, flat and size-indexed efficiency standards do not.
- *Under relatively lax fuel economy or CO_2 emission standards, mass-reduction technology has been "lost" to larger and faster vehicles*. This is in evidence from the 1987-2008 period of relatively unchanging fuel economy standards in the U.S., when mass-optimized designs and advanced materials penetrated the automobile fleet, vehicles got larger, their powertrains got larger and heavier, their acceleration performance increased, and average fuel economy was relatively stable.
- *Regulatory standards for fuel economy or CO_2 emissions can capture mass-reduction technology trends for vehicle efficiency (or not)*. Competing automobile companies naturally deploy automobile efficiency innovations, such as new mass-reduction technology. These efficiency technologies can interchangeably be used for increasing vehicle acceleration performance (under modestly increasing or stable standards) or used for public environmental goals (with increasingly stringent standards). Increased stringency of standards more fully captures and induces mass reduction in vehicles.
- *Mass-reduction technology is a potential green technology growth area*. Automobile markets that do promote mass-reduction through stringent fuel efficiency standards (i.e., those standards that are stringently set and are not mass-indexed standards) have the additional benefit of promoting innovation and growth in high-value advanced materials (e.g., advanced steels, aluminum, magnesium, composites) that could see continued growth in the automotive industry. In addition, mass-reduced vehicle fleets are in a better technical position to enable the growth in advanced electric-drive vehicle technologies over the long term.

Areas for further study:

- *To varying degrees, automotive mass-reduction technologies assessed in this report have addressed potential safety concerns*. The deployment of mass-reduced automobiles sometimes gives rise to safety questions. Potential effects of vehicle mass reduction on safety have been researched extensively. Most recently, U.S. automobile regulators found that, under the new size-indexed efficiency standards, there could be minimal to perhaps positive safety effects with a new vehicle fleet with lower average mass. However, this issue is beyond the scope of this report. Mass-reduction technologies for production vehicles examined above (e.g., increased aluminum use across the fleet, high-strength steel thoughout Honda models, and aluminum frames in Audi models) have not exhibited any known safety compromises from their incremental mass reductions. Some of the studies that resulted in larger mass reductions (e.g., the Volkswagen, Lotus, and steel projects) seek to further investigate the crashworthiness and safety implications of their mass-optimized designs.
- *Life-cycle analysis of mass-reduced materials and designs could be an important consideration.* This report discusses the implications of mass-reduction technology for reducing the energy consumption and CO_2 emissions of vehicle use. At present, the vast majority of vehicles' overall energy and CO_2 emissions are from vehicle use, and much lesser impacts are associated with upstream manufacturing processes. However, some of the materials discussed herein (e.g., aluminum and magnesium) have greater upstream material energy requirements and greenhouse gas emissions that would impact an overall assessment of their potential energy and environmental benefits.

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