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SERIES: U.S. PASSENGER VEHICLE TECHNOLOGY TRENDS

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Lightweighting Technology Developments

Reduction of weight/mass is one of the most important strategies for lowering vehicle emissions and fuel consumption. Engine, transmission, hybrid, and thermal management technologies are all designed to reduce energy losses and increase efficiency. By contrast, weight reduction lowers the amount of energy needed to move the vehicle, regardless of the efficiency of the propulsion system.

Weight directly affects the power needed to accelerate a vehicle and overcome tire-rolling resistance. It also determines the amount of energy dissipated by the brakes. Figure 1 illustrates the energy requirements for combined city/highway driving on the U.S. vehicle certification test cycles. Reducing weight has larger proportional impacts on the total vehicle load than improvements in aerodynamics or tire rolling resistance.

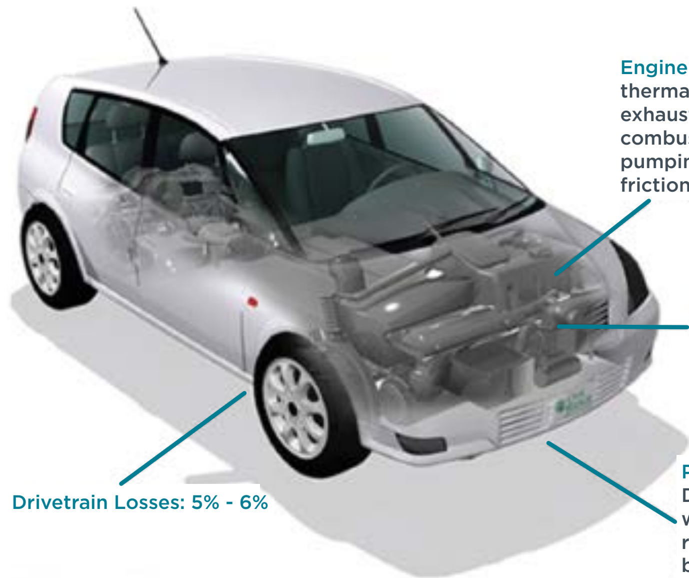

Figure 1. Energy requirements for combined city/highway driving on U.S. vehicle certification test cycles. Greater mass generates greater rolling resistance and braking losses. (Source: www.fueleconomy.gov)

ABOUT THIS SERIES Under efficiency standards adopted in 2012, the U.S. passenger vehicle fleet must achieve an average fuel economy of 49.1 mpg in 2025, or 54.5 mpg as measured in terms of carbon dioxide emissions with various credits for additional climate benefits factored in. Although the fleet-average targets may change—the regulation provides for recalculating the fuel economy targets annually based on the mix of cars, pickups, and SUVs actually sold—they will still represent an average energy-efficiency improvement of 4.1% per year.

Automakers have responded by developing fuel-saving technologies even more rapidly and at lower cost than the U.S. EPA and NHTSA projected in 2011–2012, when the supporting analyses for the 2017–2025 rule were developed. In particular, innovations in conventional (as opposed to hybrid or electric) power trains and vehicle body design are significantly outpacing initial expectations. These technical briefs highlight the most important innovations and trends in those conventional automotive technologies.

For other papers in this series, as well as the more detailed technology surveys on which these briefs are based, go to www.theicct.org/series/us-passenger-vehicle-technology-trends.

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THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

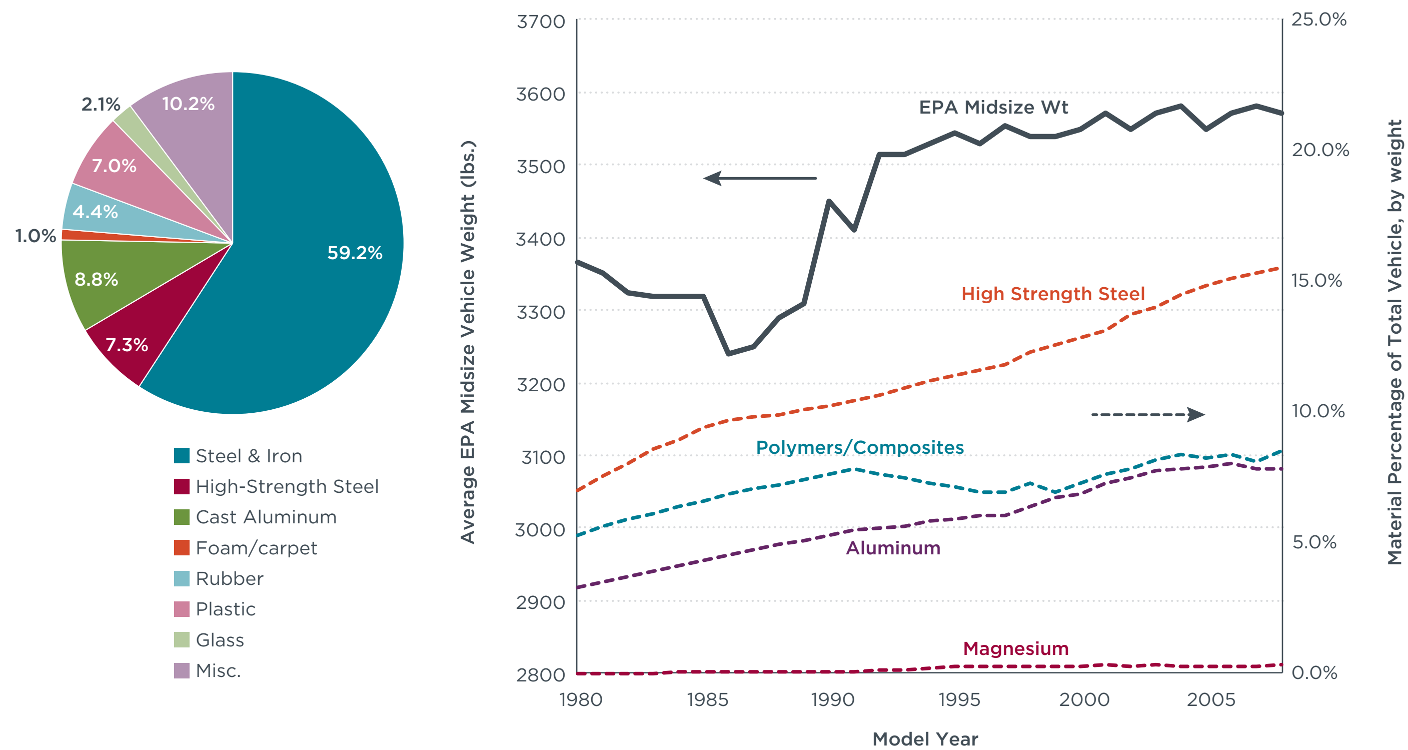

Figure 2. Left: approximate makeup of a 2011 Silverado 1500 used by FEV to assess the cost-effectiveness of lightweighting a pickup truck. (Source: Caffrey, C., Bolon, K., Kolwich, G., Johnston, R., & Shaw, T. [2015]. Cost-effectiveness of a lightweight design for 2020–2025: An assessment of a light-duty pickup truck. SAE Technical Paper 2015-01-0559, doi:10.4271/2015-01-0559). Right: Historical trends in lightweight material makeup for an average vehicle. (Source: Goguen, S., Schutte, C., & Joost, W. [2015]. Lightweight materials. Presented at the 2015 Department of Energy Vehicle Technologies Program Annual Merit Review, June 8–12, 2015, Washington, D.C., Slide 4.)

Lighter vehicle weight also improves handling, braking, ride, cargo capacity, and acceleration—all features highly desired by customers. A secondary way to improve efficiency gains is to downsize the engine to maintain constant performance, as smaller engines are more efficient. Numerous studies have indicated that a 10% weight reduction can reduce fuel consumption by 6%–7% if the engine is downsized to maintain constant performance, and by 4%–5% if the engine is not downsized. This technical brief focuses on mass reduction while keeping approximately constant vehicle size, safety, and performance.

Since U.S. regulators adopted vehicle efficiency standards in 2012, automakers and parts suppliers have made substantially greater strides in lightweighting than projected. Material costs are falling, better materials are being developed, and computer-aided design tools are improving rapidly. Heavier materials, especially iron and conventional steel, can be replaced with lighter ones. The potential gains yet to be made from lightweighting are at least double the regulators' estimates for the 2017–2025 final rule, at only about one third of the projected cost.[1]

TECHNOLOGY HISTORY

Steel has been the primary material used in vehicles for decades. As shown in Figure 2, the proportions of plastics and aluminum have gradually increased over time, but until recently they were used primarily for independent components, such as plastic bumpers and aluminum engines. These components had little impact on safety and noise, vibration, and harshness (NVH).

The key technology breakthrough for improved lightweight design has been computers. While computer-aided design, computer simulations, and on-board computer controls have transformed all aspects of technology development, they are especially important for increasing the use of lightweight materials. There are hundreds of parts that interact in a motor vehicle. Changing the materials used in any of them can have unexpected effects on crash results

1 This technical brief is based on *Lightweighting technology development and trends in U.S. passenger vehicles* (Isenstadt et al., 2016); http://www.theicct.org/lightweighting-technology-development-and-trends-us-passenger-vehicles

or NVH. In the past, manufacturers had to rely on theory and testing to determine those effects. That required building prototypes for each part iteration, slowing the process and adding costs.

With today's advanced computer simulations, designers can eliminate much of that work, simultaneously optimizing the material, shape, and thickness of every part for weight reduction, NVH, and crash protection. These tools also enable secondary weight reduction. If the body is lighter, then brakes and suspension can also be lighter.

Ford Motor Company's development of the aluminum-body F-150 pickup truck illustrates the point. Advances in computer-assisted engineering enabled Ford to take the big gamble in switching from steel to aluminum. In 2014, F-150 engineers reported that because of computer assistance, they could generate designs 50 times faster than 15 years earlier.[2] The digital tools enabled engineers to experiment with more materials and test components against an array of strength and stiffness requirements.

Since 1975, advanced materials have played an expanding role in lightweighting and now offer more weight reduction than front-wheel drive schemes and frame construction type, as shown in Figure 3.

Average vehicle weight remained roughly constant from 2004 to 2015. Clearly, whatever lightweighting occurred in the past decade primarily offset the increased weight of upscale features, safety enhancements, and increased vehicle size. During this period, average horsepower relative to weight increased by 11%, according to the U.S. Environmental Protection Agency (EPA) 2015 Fuel Economy Trends report.[3] Passenger vehicles have reduced fuel consumption by 21% since 2004. Overall, vehicles have become safer and more powerful, all without reducing weight.

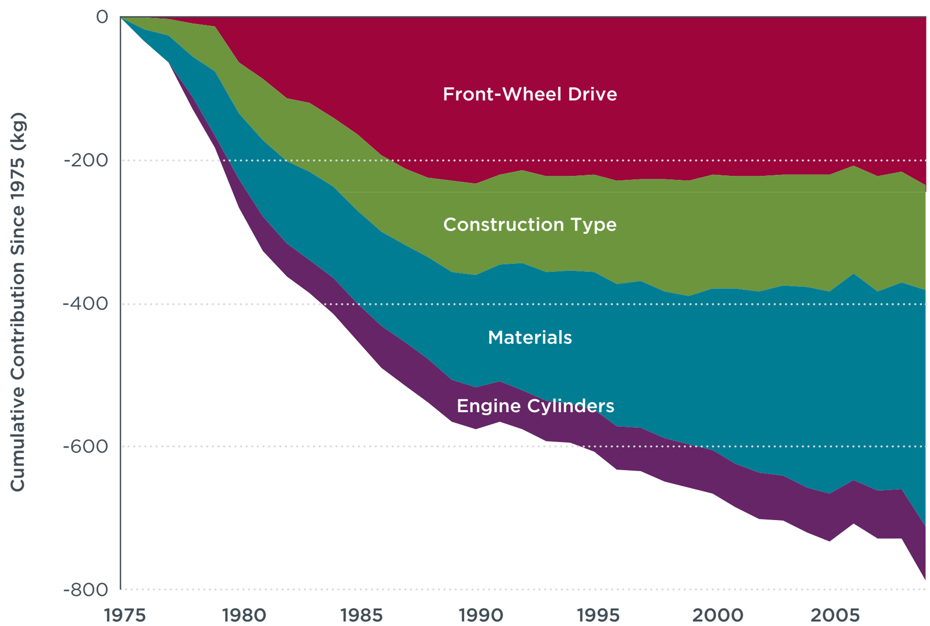

Figure 3. Cumulative contribution of weight reduction in vehicles since 1975 showing increased role of materials usage responsible for lightweighting strategy. (Source: MacKenzie, D., Zoepf, S., & Heywood, J. [2014]. Determinants of US passenger car weight. *International Journal of Vehicle Design, 65*(1), 73–93 doi:10.1504/IJVD.2014.060066).

HISTORICAL ESTIMATES OF COSTS AND BENEFITS

In 2002, the National Academy of Sciences (NAS) estimated that a 5% weight reduction would result in a 3%–4% decline in fuel consumption with the same performance. The cost would be $210 to $350 for passenger cars and $350 to $710 for light-duty trucks, the NAS found. That works out to $1.20 to $2.00 a pound, assuming a 3,500-lb base car. This NAS report[4] served as the starting point for the National Highway Traffic Safety Administration's (NHTSA's) light-truck CAFE standards for 2008–2011. NHTSA further considered substituting high-strength steel or aluminum or plastic for cold-rolled steel at a cost of $0.75–$1.75 for each pound of reduction.

For the 2017–2025 rulemaking, EPA and NHTSA found that a 10% weight reduction corresponds to roughly a 5% decrease in fuel consumption, without maintaining constant performance. The agencies estimate that downsizing power train and other components to maintain performance on a lightweighted vehicle would result in a 6%–8% saving in fuel consumption.

2 Seetharaman, D. (2014, January 13). Ford's bet on F-150 reflects new tech, Mulally's imprint. http://finance.yahoo.com/news/fords-bet-f-150-reflects-050615777.html

3 U.S. Environmental Protection Agency. (2015). Light-duty automotive technology, carbon dioxide emissions, and fuel economy trends: 1975 through 2015. https://www3.epa.gov/fueleconomy/fetrends/1975-2015/420r15016.pdf

4 Transportation Research Board and National Research Council. (2002). *Effectiveness and impact of Corporate Average Fuel Economy (CAFE) standards.* Washington, D.C.: National Academies Press. doi:10.17226/10172.

Based on public and confidential reports and data, the agencies determined that as much as a 20% mass reduction from the MY2008 baseline was cost-effective using technology available at the time. This high percentage of reduction is possible specifically for larger vehicles, such as pickup trucks, utility vehicles, and minivans. They recommended lower maximum mass reductions for lighter and smaller vehicles, reflecting safety concerns.

After considering numerous studies, the agencies settled on a direct manufacturing cost (DMC) for MY2017, calculated as follows (2010$):

$$DMC\left[\frac{\$}{lb}\right] = 4.36\left[\frac{\$}{\%\text{-}lb}\right]*mass\_reduction\ [\%]$$

Thus, a 20% reduction would cost 4.36*0.20, or $0.87/lb, and a 10% reduction would cost about $0.44/lb. As an example, a 3,800-lb vehicle with 10% weight reduction would cost an additional $167; a 15% reduction would cost $373. These figures are significantly lower than the NAS 2002 cost estimate, whose reported cost range applied for only a 5% decrease in weight.

CURRENT FUEL CONSUMPTION REDUCTION AND COST

Lightweighting has become a key strategy for meeting future CAFE standards. The benefits are even larger for electric vehicles, as it reduces battery size and cost and/or increases range. A number of lightweight materials are now in production, including high-strength steels, aluminum alloys, magnesium, plastics, and composites. These materials must be cost-effective compared with alternative technologies, both at high volume for mainstream products and at low volume for luxury and high-performance vehicles.

Table 1. Sample of vehicle mass reductions.

Vehicle Make	Model Year	Weight reduction (kg)	Weight reduction (%)	Relative to
Ford F-150	2016	288	14%	2014
Acura MDX	2017	172	8%	2013
GM Cadillac CTS	2017	95	5%	2013
Audi Q7	2016	115	5%	2015
Chrysler Pacifica	2017	146	7%	2016
Nissan Leaf	2016	59	4%	2012
Opel Astra	2016	173	12%	2015
Chevrolet Malibu	2016	135	9%	2015
GMC Acadia	2017	318	15%	2016
Chevrolet Volt	2017	110	6%	2014
Chevrolet Cruze	2017	103	7%	2015
Mazda Miata	2016	67	6%	2015
BMW M3/M4	2017	63	4%	2013
Chevrolet Equinox	2018	182	10%	2016
Chevrolet Camaro	2016	177	10%	2015

Sources: U.S. News Car Rankings and Advice, autobytel.com, Acura, gmauthority.com, GMC, Chevrolet, Nissan, Mazda, Ford, Cadillac, Audi, Opel, Auto Week, BMW, and Auto News.

Manufacturers already produce vehicles with substantial mass reductions, as shown in Table 1. These vehicles are a sampling of many makes and models that have shed a remarkable amount of weight within a single redesign. For most of these vehicles, the weight-reduction percentage is similar to, if not greater than, the 7% mass reduction predicted by EPA/NHTSA for the 2017–2025 period. In all of these cases, the weight reductions reflect a multi-material approach and updated manufacturing processes/computer simulations. No single material or method dominates.

ALUMINUM

The 2015 Ford F-150 is the poster child for aluminum lightweighting. Ford reduced the truck's weight by as much as 14%, or 700 lbs (318 kg) from MY2014 on the 8-ft Styleside Supercab 3.5L EcoBoost V6. Fuel consumption, including downsized engines, decreased by 11.7%, exceeding the 9.8% estimated in the rulemaking. Aluminum makes up more than 95% of the truck's body (the frame is 77% high-strength steel) and accounts for nearly two thirds of the overall mass reduction.

Aluminum producers are continuously developing stronger aluminum alloys. Novelis, for example, is now offering aluminum sheets that are two to three times stronger than previous sheets. As a result, aluminum can be used in safety-critical parts without as much additional material. Aluminum does still cost more than steel, even though prices have dropped 33% since 2011.

By 2020, Scott Unlick, president of market research and consulting group Ducker Worldwide, projects automakers will increase aluminum consumption 41%.[5] By 2025, most hoods, half of all doors, and between one quarter and one third of trunks, roofs, and fenders are projected to

5 Scott Unlick, president, Ducker Worldwide, AMM North American Automotive Metals Conference, September 2–3, 2015, Dearborn, Michigan. http://www.amm.com/events/details/7981/north-american-automotivemetals-conference/details.html

be aluminum. The consulting group Scenaria estimated in 2012 that a 700-lb reduction is achievable with a net savings to consumers over a 5-year period. Scenaria also found that the more weight is reduced, the more the savings to consumers, despite the increasing costs of lightweighting.

STEEL

The most common focus for lightweighting is the vehicle body structure. This is because it represents as much as 25% of mass and is essential to meeting multiple safety, strength, stiffness, and noise transmission targets. It is also subject to multiple integration constraints, is a major driver of capital investment, and has the greatest impact on manufacturer body shop infrastructure. Steel has been the best solution for almost all body structures.

The steel industry has responded to the lightweighting challenge by producing a steady evolution of steel grades over the past 15 years. Legacy vehicle architectures continue to be replaced with more mass-efficient, advanced high-strength steel (AHSS) architectures.

Some recent examples of lightweighting with steel include:

» The 2015 Nissan Murano saved 146 lbs using AHSS.

» The 2015 Chrysler 200 body structure is 60% AHSS.

» Although the 2016 Chevy Malibu is larger, it is also lighter and more efficient through increased use of AHSS in the body structure and closures.

» The 2016 Hyundai Tucson body shell has been made stiffer, lighter, and safer because more than 50% of the new structure and chassis is AHSS.

» The 2017 GMC Acadia, which leverages a variety of AHSS grades in the body structure and closures, is 700 lbs lighter than its predecessor.

PLASTICS AND COMPOSITES

Plastics and composites present major opportunities for weight reduction. Today, these materials make up about 50% of a car's volume yet account for less than 10% of its weight. Thermoplastic-based materials provide an array of attractive properties, such as low density, high strength and rigidity, tailored thermal expansion properties, and recyclability.

Body and chassis components make up 60%–65% of vehicle mass. Although steel has been the traditional material, for some applications thermoplastic and composite materials offer lower density, higher stiffness and strength, and greater corrosion resistance and design flexibility. Recent examples of new plastics and composites applications include:

» Ford's 2014 Fusion Mondeo was launched with a single-piece front bumper energy absorber with tuning flexibility to meet the differing requirements in the global market. Made from a polycarbonate/polybutylene terephthalate blend, the part is 40% lighter and 10% less costly than a comparable part made out of steel.

» Long glass fiber-reinforced polypropylene, a composite resin, is replacing metal and saving as much as 50% in weight in several structural applications including front-end modules, door modules, inner tailgate components, and instrument panels.

» Because of the design freedom offered by thermoplastics, a typical fender made of thermoplastic has a total weight of 1.9 kg—a 2.9-kg weight reduction over a steel fender.

MANUFACTURING AND COMPUTATION

Traditional car manufacturing is extremely capital intensive. This acts as a barrier for designing and deploying new lightweight materials. A Ricardo study investigated the BMW i3 composite floor design, the use of plastic and aluminum in the i3 door, and the steel B-pillar in the Audi A8.

The i3 achieved a 35% weight reduction in the floor assembly compared with the traditional steel floor of a Toyota Corolla, through the use of lightweight aluminum and resin-injected carbon fiber fabric. Instead of 18 stamped steel parts joined by spot welds in the Corolla, the i3 floor assembly uses two carbon fiber fabric panels that are adhesively bonded to a welded framework of aluminum parts. A detailed cost analysis shows that the i3 floor assembly is more expensive to manufacture than the Corolla's. At $30/kg for carbon fiber fabric, the calculated cost of lightweighting is $5.70/lb. This declines to $3.84/lb at the anticipated future carbon fiber price of $15/kg. At the same time, the design strategy adopted in the i3 floor allows for a 56% reduction in capital tooling cost.

Despite savings of 35% in weight and 56% in capital investment, the i3 floor would not appear to meet the currently acceptable $1–$3 benchmark for cost per pound of weight savings. However, for an all-electric vehicle, such as the i3, the value of weight reduction is higher than for conventional autos because it allows a direct reduction in the amount of battery cells or the size of the fuel cell stack, with major secondary cost reductions.

For the i3's front door, BMW uses aluminum and polypropylene to produce a component that is 36% lighter than the traditional all-steel door of the Corolla. While the i3 door is more expensive than the Corolla's, the total cost of lightweighting the door was just under $1 per pound, making it a cost-effective strategy.

The B-pillar in the Audi A8 is made of steel, much like the Corolla B-pillar. But the A8 part is 30% lighter because of the use of fewer, stronger parts. As a result, material cost is 23% lower, process cost 15% lower, and tooling cost 36% lower. The lightweighting cost reduction of $0.34 per pound shows the potential for simultaneously reducing weight and cost with better materials and design.

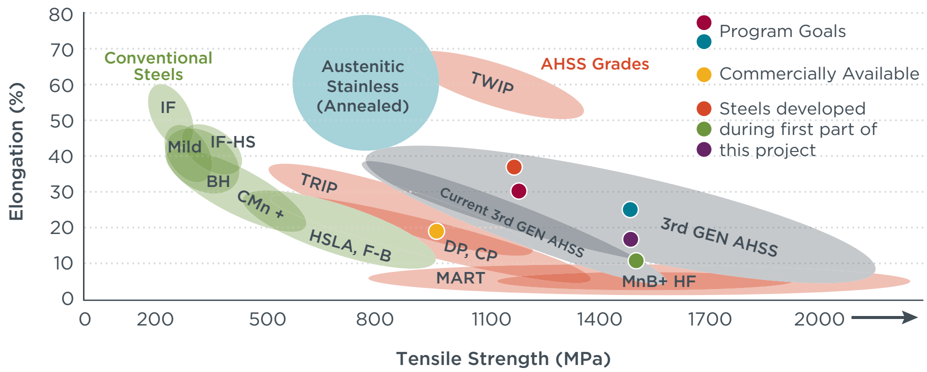

Figure 4. Demonstrated new advanced high-strength steels. (Source: Goguen, S., Schutte, C., & Joost, W. [2015]. Lightweight materials. Presented at the 2015 DOE Vehicle Technologies Program Annual Merit Review, June 8–12, 2015, Washington, D.C.).

IMPROVEMENTS UNDER DEVELOPMENT

A significant method for reducing material cost and mass is functional integration. New designs can reduce mass, size, and cost simultaneously while improving performance.

STEEL

Ferrous alloys, especially steel, still offer potential advantages for cost and weight reduction. Recent developments in micro-alloyed steels featuring carefully engineered quantities of manganese, molybdenum, and silicon have resulted in an ultra-high-strength steel with extremely high specific strength after heat treatment. These materials also offer the ability to cast uniquely thin-walled shapes and complex geometries. These "third-generation" steels (see Figure 4) provide not only high strength but also enhanced ductility, which will expand the possibility for an additional 5%–10% reduction in body structure mass over what the federal regulatory agencies projected for 2025.

In a project for the Department of Energy, IBIS Associates demonstrated that optimizing a midsize steel vehicle through part redesign, body panel weight reduction, and other measures could reduce mass by 3.2%–16.5% at a cost reduction of $0.79 to $1.90 per pound. Weight optimization *reduces* the cost of the vehicle.

ALUMINUM, PLASTICS, AND COMPOSITES

Recognizing a trend toward lighter castings, the Department of Energy in 2013 introduced material performance goals[6] associated with lightweighting calling for the displacement of conventional ferrous castings with low-density magnesium, aluminum, and AHSS castings. Lightweight ferrous castings have not been a major focus of the automotive industry because of the benefits of lower-density casting materials.

Broader adoption of thermoplastic materials is expected in applications where they are proven, and greater penetration is expected in new applications. Integrating components and materials can optimize and simplify designs. The industry is expected to validate a greater number of applications based on hybrid solutions or use of multiple materials, such as thermoplastics and metal.

Another significant change is continuing improvement in higher-temperature-resistant polymers, which allow lower density materials to be used for further replacement of metals.

NEW ARCHITECTURES/ COMPUTATION

A potential hindrance to vehicle design optimization for lightweighting is that global manufacturers offer a wide variety of models across numerous markets with different fuel economy/greenhouse gas standards and customer expectations. One solution is a unified global platform, in which bodies are shared and the number of overall models is reduced. For example, under its New Global Architecture, Toyota expects to reduce vehicle weight by 20% in transforming its entire lineup by 2020. With a strategy of developing fewer models, an automaker can achieve greater optimization and greater efficiency. Some manufacturers are even collaborating to produce specific parts and designs to reduce costs.

6 U.S. Department of Energy, Vehicle Technologies Office. (2013). *Workshop report: Light-duty vehicles technical requirements and gaps for lightweight and propulsion materials.* Retrieved from https://www1.eere.energy.gov/vehiclesandfuels/pdfs/wr_ldvehicles.pdf

CONSUMER ACCEPTANCE

Lightweighting can have substantial value to customers beyond fuel savings. Benefits include better performance, ride, handling, and braking, as well as higher towing and payload capacity. For the 2025 rule, the EPA and NHTSA did not weigh the value of these benefits, instead assigning the entire cost of lightweighting to fuel consumption/carbon dioxide (CO_2) reductions. This dramatically understates the benefits of lightweighting while overstating the costs of reducing fuel consumption and CO_2.

For example, Ford's website for the F-150 pickup does not even mention improved fuel economy when discussing benefits of the aluminum body:

> **THE MATERIAL THAT MADE EVERY OTHER TRUCK HISTORY**
> The use of high-strength, military-grade, aluminum alloy not only makes F-150 lighter and more agile than ever before, it is also one of the reasons it can haul and tow more than any other half-ton pickup.

Manufacturers themselves are expressing a high level of confidence in lightweighting. A 2014 DuPont-sponsored WardsAuto survey determined that lightweighting goals are at the top of manufacturers' design efforts. Of the companies surveyed, 49% said lightweighting was their main strategy for meeting 2025 standards. Other responses in the top three were engine efficiency (39%) and electrification (26%).

Two thirds of respondents said they thought emissions standards would become more stringent, but less than one fifth said they were confident that today's materials portfolio is sufficient to meet 2025 CAFE standards.

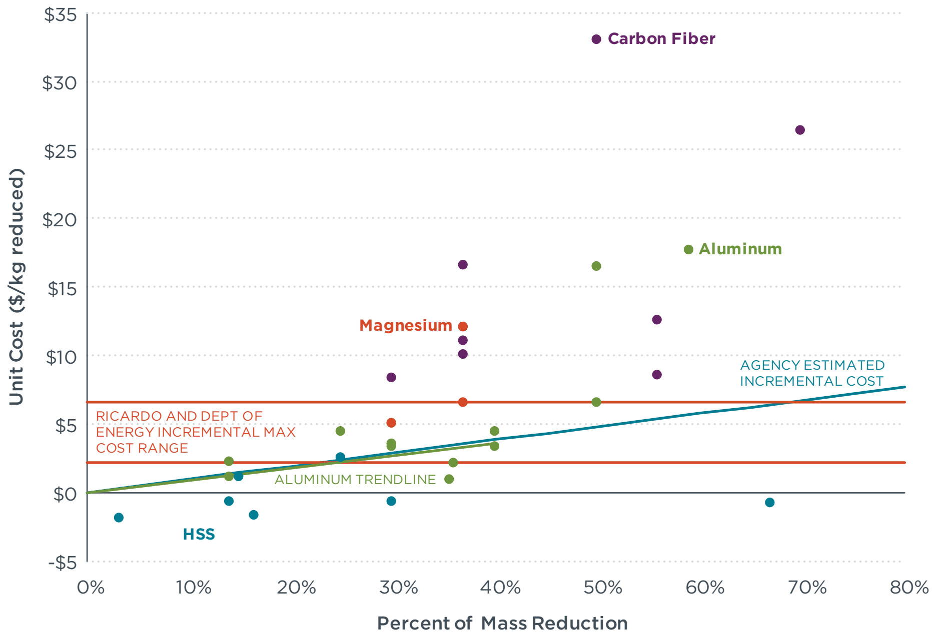

Figure 5. Potential mass reduction (%) vs. cost per kg reduced.

IMPLICATIONS FOR MIDTERM EVALUATION

Many advances in lightweighting have surpassed the 2012 agency predictions in support of the 2017–2025 standards. Stronger and lighter materials are available at lower costs than assumed. Advances in modeling/simulation tools and joining techniques have opened the floodgates to unprecedented levels of material/design optimization. Even more improvements in materials and design are coming.

Teardown studies of lightweighting costs were not finished in time for consideration in the 2017–2025 rule. Material improvements that were not taken into account include higher strength aluminum, third-generation steels with higher strength and enhanced ductility, a new generation of ultra-high-strength steel cast components, and metal/plastic hybrid components.

Suppliers are rapidly developing the advanced materials and methods for major lightweighting gains, as well as the computational tools for simulating full vehicles all the way down to nanoscopic material behavior. As shown in Table 1, the most recent redesign of more than a dozen vehicles matched or exceeded the 7% mass reduction predicted by federal regulators for the entire 2017–2025 period.

These ongoing improvements will lower vehicle production costs below the levels projected by the agencies. For example, Figure 5 shows the cost per kilogram reduced of various materials as a function of the percentage change in mass. Each point represents a single reported value of a specific part or material. Sources include both current/in-production and estimated/developing costs and benefits. For mass reduction of up to 25%, almost all of the studies show significantly lower costs than estimated in the rulemaking.

Material advances are leading to increased competition among aluminum, steel, and composites. This is a boon to manufacturers, especially as improved computational tools and adhesives facilitate mixed materials. This competition is especially important for battery electric and fuel cell vehicles. Batteries and fuel cell stacks are expensive, and weight savings enable a direct reduction in their size and cost. Thus, even expensive materials may prove economical when the powertrain costs are included.

When the multiple other benefits of lightweighting are considered—ride, handling, braking, performance, load capacity—it is clear that implementation of lightweight materials and better design will be limited only by the speed at which computational tools improve and better materials can be brought to the market.

Figure 6 shows how the costs of lightweighting material-by-material are running below the government projections. Aluminum costs are similar to the total lightweighting costs assumed in the rule; the higher cost per pound for higher strength steels is largely offset by the reduced amount of material needed; composites can be both lighter and cheaper; and design improvements reduce the amount of material needed and so are also a cost reduction. Assuming aluminum contributes no more than a third to future lightweighting efforts, the net cost of future weight reduction should be less than a third of the agency projections in the rulemaking.

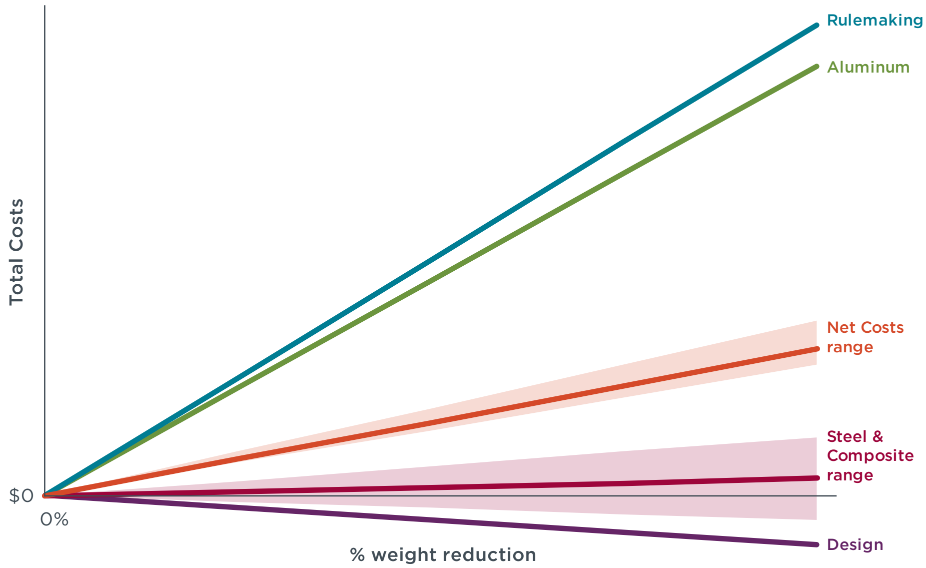

Figure 6. Total cost as a function of percent vehicle weight reduction. Note that composites include plastics, but not carbon fiber.

Thus, the primary question is: How fast can tools and materials improve and better designs be incorporated into vehicles? The current generation of vehicle redesigns is routinely achieving about 5% weight reduction on average—some are much higher. There are two redesign cycles before 2025, and, given the accelerating pace of computational tool development and improved materials, it is reasonable that each of these redesign cycles should achieve at least a 5% weight reduction. Overall, the cost of reducing weight will most likely be less than a third of the projections in the rule, and total weight reduction of 15% should be feasible by 2025—about twice as much as predicted in the rulemaking.