# Economic Assessment of Greenhouse Gas Emissions Reduction by Vehicle Lightweighting Using Aluminum and High-Strength Steel

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**Keywords:**

automobile
cost-benefit analysis
industrial ecology
life cycle assessment (LCA)
material substitution
vehicle design

Supporting information is available on the *JIE* Web site

## Summary

The life cycle greenhouse gas (GHG) reduction benefits of vehicle lightweighting (LW) were evaluated in a companion article. This article provides an economic assessment of vehicle LW with aluminum and high-strength steel. Relevant cost information taken from the literature is synthesized, compiled, and formed into estimates of GHG reduction costs through LW. GHG emissions associated with vehicle LW scenarios between 6% and 23% are analyzed alongside vehicle life cycle costs to achieve these LW levels. We use this information to estimate the cost to remove GHG emissions per metric ton by LW, and we further calculate the difference between added manufacturing cost and fuel cost savings from LW. The results show greater GHG savings derived from greater LW and added manufacturing costs as expected. The associated production costs are, however, disproportionately higher than the fuel cost savings associated with higher LW options. A sensitivity analysis of different vehicle classes confirms that vehicle LW is more cost-effective for larger vehicles. Also, the cost of GHG emissions reductions through lightweighting is compared with alternative GHG emissions reduction technologies for passenger vehicles, such as diesel, hybrid, and plug-in hybrid electric powertrains. The results find intensive LW to be a competitive and complementary approach relative to the technological alternatives within the automotive industry but more costly than GHG mitigation strategies available to other industries.

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DOI: 10.1111/j.1530-9290.2010.00288.x

Volume 15, Number 1

## Introduction

There is growing consensus among scientists, policy makers, and business leaders that they must take actions to mitigate greenhouse gas (GHG) emissions (IPCC 2007). Achieving carbon stabilization and deep cuts in GHG emissions will have a cost. The Stern (2006) report estimates the annual costs of stabilization at 500 to 550 parts per million (ppm) carbon dioxide ($CO_2$) equivalent to be clustered in the range of −2% to 5% of gross domestic product (GDP), with an average of about 1% of GDP by 2050. The fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC) estimates that in 2050, the global average macroeconomic costs for mitigation toward stabilization between 445 and 710 ppm $CO_2$ equivalent are between 1% gain and 5.5% decrease of global GDP (IPCC 2007). Current discussion focuses on where and how GHG emissions can be reduced, and with how much cost investment (Cooper et al. 2004; IPCC 2007). In the United States, the transportation sector alone emits 28% of total GHG emissions (7,074 MMT[1] $CO_2$-eq[2]). A full 16.8% of the total emissions are produced from passenger cars and light trucks (US EPA 2006).

Recently, automotive producers have been accelerating efforts to significantly improve vehicle fuel economy, with the goal of cutting both petroleum consumption and GHG emissions. Vehicle lightweighting (LW) is an option to achieve this aim. Among the potential LW materials, high-strength steel (HSS) and aluminum have been proven to achieve weight reduction while meeting vehicle safety and performance requirements. Despite potential LW advantages of these metals, their displacement of traditional mild steels (which are inexpensive and typically contain 0.16% to 0.29% carbon; Babylon 2009) has been slow because of institutional and technical barriers as well as their higher costs.

Several concept and production vehicles use light metals for LW. Some of the first popular aluminum-intensive vehicles (AIV) were produced by Audi (models A8 and A2) and Jaguar (model XJ; Scamans 2005; Henn and Leyers 2006). Taken together, these production models demonstrate the technical possibility of reducing the curb weight (vehicle weight with standard equipment, liquids, and no driver) of vehicles by 11% to 25% through material substitutions alone. This does not account for secondary mass reductions, which are defined here as mass reductions in the rest of the vehicle made possible by redesign of the vehicle after the primary weight reduction is achieved. HSS provides another approach to vehicle LW. A detailed analysis of HSS has been performed by the Ultralight Steel Auto Body (ULSAB) project (Obenchain 2002; Henn and Leyers 2006) and the Ultralight Steel Auto Body-Advanced Vehicle Concepts (ULSAB-AVC) Project. The ULSAB-AVC was a research project designed to understand steel's capability to contribute to vehicle LW. Specifically, this project considered a compact-class vehicle[3] and found that it was possible to reduce its curbweight by 18.8% through a combination of primary and secondary mass reductions (Obenchain 2002; Henn and Leyers 2006).

A number of studies have reported on the relationship between life cycle GHG emissions and the costs of alternative automotive technologies (IAMPEI 1999; IAI 2000; Austin et al. 1999; Cooper et al. 2004). Previous research has considered the potential for aluminum and HSS lightweighted vehicles to reduce life cycle emissions (Das 2000; IAI 2000; ULSAB-AVC 2002; US EPA 2004; Henn and Leyers 2006). The economic feasibility of lightweighted vehicles has not been assessed with a detailed model of a specific vehicle, however. To achieve this assessment, we build on research described in a companion article (Kim et al. 2010). In that article, we analyzed the GHG reduction benefits and emissions payback times for lightweighted vehicles that used aluminum and HSS. Five vehicle LW options for a compact-sized vehicle were developed and evaluated for life cycle GHG emissions, carbon intensity of production, and the impact of different end-of-life (EoL) management scenarios on life cycle GHG emissions.

This article presents a comprehensive analysis of LW economics to help answer the following questions:

- What are the life cycle costs to reduce GHG emissions relative to a baseline vehicle for different levels of LW using aluminum and HSS?

- What is the impact of vehicle size on the potential of LW to economically reduce GHG emissions?
- How does LW compare with other automotive GHG emission reduction strategies on the basis of cost per mass reduction of GHG emissions?

Overall, the purpose of this study is to evaluate financial costs and benefits associated with introducing vehicle LW by aluminum and HSS. We constructed a detailed design and model of a compact vehicle to evaluate the economics of LW and to provide a framework to explore model sensitivity to key cost parameters and vehicle size effects. For the study, relevant cost information from the literature was synthesized, compiled, and reviewed for accuracy by automotive industry experts at the original equipment manufacturer (OEM) level and material supplier level. In addition, we present costs to reduce GHG through LW versus implementing alternative powertrain technologies, such as diesel, hybrid, and plug-in hybrid electric vehicles. This will aid future understanding regarding the role that vehicle LW might play as a GHG reduction strategy in comparison or in addition to other vehicle design options.

## Methods and Models

Working from a model of a specific compact-sized vehicle (Ford Focus ZX3, model 2000–2004, curb weight 1,159 kilogram [kg][4]), we develop five vehicle LW scenarios in the companion article (Kim et al. 2010). In addition to that work, we constructed the following models described in this section:

- vehicle fuel economy model
- life cycle GHG emissions model
- life cycle cost model.

Further detailed description of these models is provided in the Supporting Information on the Web.

### *Vehicle Fuel Economy Model*

The baseline compact vehicle considered here was lightweighted by component substitution for aluminum (Tessieri and Ng 1995; Austin et al. 1999; Neumann and Schindler 2002) and HSS (Das et al. 1997; Das 1999), as discussed in the companion article (Kim et al. 2010). In this work, we extended the model to vehicle sizes not previously considered, including a mid-sized vehicle (1,504 kg) and a luxury class vehicle (1,869 kg). We applied the same LW scenarios for the mid-sized and luxury vehicle as for the compact vehicle and as shown in table 1.

**Table 1** Fuel economy simulation results of the lightweighting (LW) options

| *Vehicle class* | *LW option* | *Fuel economy (miles per gallon [mpg])* |
|---|---|---|
| Compact-sized | Baseline | 33.0 |
| | 6% HSS | 34.2 |
| | 6% Al | 34.2 |
| | 11% Al | 35.2 |
| | 19% HSS | 36.7 |
| | 23% Al | 37.5 |
| Mid-sized | Baseline | 30.5 |
| | 6% HSS | 31.5 |
| | 6% Al | 31.5 |
| | 11% Al | 32.5 |
| | 19% HSS | 33.9 |
| | 23% Al | 34.7 |
| Luxury | Baseline | 21.5 |
| | 6% HSS | 22.3 |
| | 6% Al | 22.3 |
| | 11% Al | 22.9 |
| | 19% HSS | 23.9 |
| | 23% Al | 24.5 |

*Note*: HSS = high-strength steel; Al = aluminum.

As seen in table 1, the compact-sized baseline vehicle has a fuel economy of 33 miles per gallon (mpg[5]) for the Federal Test Procedure (FTP)-75 drive cycle (the most common fuel economy metric in the United States and that used for regulation). In the 6% weight reduction scenario, the fuel economy is increased to 34.2 mpg. The fuel economy is increased to 35.2 mpg, 36.7 mpg, and 37.5 mpg in the 11%, 19%, and 23% mass reduction scenarios, respectively. The simulation results are in a reasonable range (3.6% to 13.8% fuel consumption reduction effect for 6% to 23% weight reduction) when compared with previous research, which suggests a 1.3% to 10.3% fuel

**Table 2** Fuel economy and net additional manufacturing costs of selected vehicle technologies for compact-sized vehicles

| *Vehicle technology* | *Fuel economy (mpg)* | *Additional manufacturing cost compared with the baseline (\$) in 2004* |
|---|---|---|
| Diesel powertrain | 40.5 (Frangi 2001b)<br>Diesel fuel price range (\$2.5/gallon to \$5.0/gallon) | 1,074 to 1,500 (Frangi 2001b) |
| Gasoline hybrid powertrain | 44 (Thomas 2003) | 2,495 to 3,000 (Thomas 2003) |
| PHEV powertrain | 44 (with engine; Kulcinski 2000), 0.177 kWh/mi (with motor; Meier and Kulcinski 2000)<br>Charge sustaining 25%, charge depleting 75% (Pesaran 2007)<br>0.668 kg $CO_2$-eq/kWh (US DOE 2002; emission factor of electricity grid) | 3,500 to 8,000 (Simpson 2006) |

*Note*: One gallon (gal) ≈ 3.79 liters. One kilowatt-hour (kWh) ≈ $3.6 \times 10^6$ joules (J, SI) ≈ $3.412 \times 10^3$ British Thermal Units (BTU). One mile (mi) ≈ 1.61 kilometers (km, SI); mpg = miles per gallon; PHEV = plug-in hybrid electric vehicle; kg $CO_2$-eq/kWh = kilogram carbon dioxide equivalent per kilowatt-hour.

consumption reduction effect for 6.3% to 14.8% weight reduction (Wohlecker et al. 2007). Another article claimed that a 10% decrease in vehicle mass results in 5% to 10% improvement in fuel economy (Montalbo et al. 2008). The results in table 1 meet this range of fuel economy improvement for associated decreases in vehicle mass.

A calculation of life cycle GHG emissions considering fuel economy also must involve a calculation of vehicle miles traveled (VMT). VMT is known to be a function of vehicle age, and therefore here we follow the description by Das (2000), which is summarized in the companion article (Kim et al. 2010).

To compare the GHG savings with the costs of LW for advanced powertrain technologies, we considered diesel, hybrid, and PHEV-20 (plug-in hybrid electric vehicle with 20-mile electricity range) powertrains. Compact-sized vehicles with diesel and hybrid powertrain were modeled in AVL Cruise[6] for prediction of the fuel economy. The performance of a PHEV vehicle is taken from several references (Kulcinski 2000; Meier and Kulcinski 2000; US DOE 2002; Pesaran 2007) that considered a compact-sized baseline vehicle similar to the one considered in this article. Net additional manufacturing costs compared with the baseline vehicle are taken from several literature sources (Frangi 2001b; Thomas 2003; Simpson 2006). Lower and upper bounds on costs are provided for characterization of cost uncertainty. Table 2 summarizes the fuel economy and net additional manufacturing cost of selected vehicle technologies.

### *Life Cycle GHG Emissions*

Life cycle GHG emissions for the mid-sized vehicle and the luxury vehicle are calculated on the basis of vehicle material and performance models. We use the same life cycle GHG emission model developed in the companion article (Kim et al. 2010). Also, we use the same VMT model and emission factors for the vehicle use phase as well as GHG emissions for the end-of-life vehicle (ELV) processes. Table 3 summarizes the vehicle total life cycle GHG emissions by vehicle class.

It is expected that hybrid electric vehicles (HEVs) and PHEVs have greater emissions from the vehicle production stage due to battery production. In this article, it is assumed that GHG emissions for these vehicles are 500 kg $CO_2$-eq more than the baseline vehicle in the production phases, on the basis of the work of Estudillo and

**Table 3** Life cycle greenhouse gas (GHG) emissions for modeled compact, mid-sized, and luxury vehicles (kg $CO_2$-eq)

| | *Compact-sized* | | *Mid-sized* | | *Luxury* | |
|---|---|---|---|---|---|---|
| *LW options* | *Low* | *High* | *Low* | *High* | *Low* | *High* |
| Baseline | 40,065 | 62,000 | 43,331 | 66,717 | 66,103 | 101,450 |
| 6% HSS LW | 37,305 | 58,516 | 40,069 | 62,238 | 61,619 | 94,639 |
| 6% Al LW | 37,325 | 58,666 | 39,619 | 61,825 | 60,604 | 94,585 |
| 11% Al LW | 34,376 | 54,497 | 36,248 | 57,524 | 56,361 | 88,645 |
| 19% HSS LW | 31,171 | 49,472 | 32,306 | 52,350 | 51,656 | 82,529 |
| 23% Al LW | 29,611 | 48,837 | 30,319 | 49,779 | 49,113 | 79,235 |

*Note*: kg $CO_2$-eq = kilograms carbon dioxide equivalent; HSS = high-strength steel; LW = lightweighting; Al = aluminum.

colleagues (2005). Additionally, we take battery manufacturing emissions numbers for the PHEV from work by Samaras and Meisterling (2008), who estimate average annual emissions of 360 to 1,080 kg $CO_2$-eq associated with lithium ion batteries for PHEVs. The GHG emission difference at the EoL phase is expected to be small compared to the total life cycle GHG emissions for the different vehicles, and therefore is not considered here. We calculated use-phase GHG emissions using fuel economy results from AVL Cruise and the VMT model of Das (2000). Table 4 summarizes the life cycle GHG emissions for the diesel vehicle, HEV, and PHEV.

### *Life Cycle Cost*

Material composition data for components were taken from the literature (Tessieri and Ng 1995). Industry experts also provided updated information and improved estimates for the specific vehicle considered here. Data from the work of Powers (2000), EEA (1998), TAA (various years), and LME (2008) were compiled into a cost model for the acquisition and manufacturing of lightweight materials. The cost model also includes estimated producer costs for LW vehicles, costs to establish a collection and recycling infrastructure, sorting costs per unit, production costs of using secondary versus primary materials, and scenarios for material value at EoL.

**Table 4** Life cycle greenhouse gas (GHG) emissions for the compact-sized diesel vehicles, hybrid electric vehicle (HEVs), and plug-in hybrid electric vehicles (PHEVs)

| | *Life cycle GHG emissions (kg $CO_2$-eq)* | |
|---|---|---|
| *Powertrain* | *Low* | *High* |
| Diesel | 32,630 | 50,261 |
| HEV | 30,179 | 46,560 |
| PHEV-20 | 25,859 | 40,573 |

*Note*: kg $CO_2$-eq = kilograms carbon dioxide equivalent; PHEV-20 = PHEV with 20-mile electricity range.

Materials costs were estimated with the assistance of an aluminum producer and WorldAutoSteel (Middletown, Ohio, United States). The following costs[7] were assumed: mild steel ($0.80/kg), HSS ($0.95/kg), cast aluminum ($4.5/kg), and wrought aluminum alloy ($4.3/kg for automotive alloy 5XXX, and $4.8/kg for automotive alloy 6XXX), according to Long (2007) and Opbroek (2007). We estimated material costs for each LW option with cost information from 2007. Noting that the baseline vehicle (1,159 kg) is composed of conventional stamped steel, we estimated costs associated with the added material costs and manufacturing as new materials were applied. Costs for secondary LW are also considered. The estimated cost for the aluminum-intensive body-in-white (BIW) manufacturing follows EEA (1998), and for the HSS BIW, costs follow results from the work of ULSAB-AVC (2002). At the BIW stage, the car body sheet metal (including doors, hoods, and deck lids) has been assembled, but the components (chassis, motor) and trim (windshields, seats, upholstery, electronics, etc.) have not yet

**Table 5** Main assumptions of manufacturing facility conditions

| *Facility condition* | *Assumption* |
|---|---|
| Length of production | 5 years |
| Equipment life | 20 years |
| Cost of building | $2,000/m^2$ |
| Cost of electricity | $0.1/kWh ($2.7/MJ) |
| Production volume | 200,000/year |
| Inflation rate | 3% |

*Note*: $m^2$ = square meter; kWh = kilowatt-hour; MJ = megajoule.

been added (Babylon 2009). The main manufacturing assumptions are provided in table 5. The assumptions for production capital investment cost and manufacturing cost for steel and aluminum BIW are derived from the work of EEA (1998).

We report a range of values due to the significant uncertainty in material production and vehicle manufacturing costs. From the work of EEA (1998), ULSAB-AVC (2002), and Frangi (2001), it is found that the BIW manufacturing cost for a typical compact-sized vehicle is in the range of $1,181 to $1,680. The capital investment cost is assumed at $871 million, for a production volume of 200,000 vehicles per year (EEA 1998). We assumed a production volume of 200,000 vehicles per year because cost data used in this study were based on literature values estimated at this production level. Naturally, this would be hard to achieve in the early phase of LW introduction, and LW production costs would be expected to be higher for smaller production volumes. One reference (EEA 1998) does provide information on manufacturing cost estimates of steel and aluminum BIW for production volumes of 20,000 and 200,000 vehicles. The sensitivity analysis, available as Supporting Information on the Web, shows that as the production volume is increased, the manufacturing cost difference between steel and aluminum BIW is reduced. AIVs are competitive at larger production volumes, whereas steel-intensive vehicles have cost advantages at smaller production volumes.

According to the ULSAB-AVC project, the BIW manufacturing cost for the C-class vehicle at 6% LW with HSS is $2,711 (ULSAB-AVC 2002). The BIW manufacturing cost for 11% LW with HSS is $2,921, and the capital investment cost is $954 million (200,000 vehicles per year; EEA 1998). Nineteen percent LW with HSS is possible when secondary weight reductions due to component downsizing are considered (Obenchain 2002; Henn and Leyers 2006). The total cost for LW of the BIW, closure, engine and transmission, and chassis and suspension is assumed at $5,040, which is derived from the work of ULSAB-AVC (2002). From the work of Scamans (2005) and Henn and Leyers (2006), we determined that 23% LW for the compact-sized vehicle is possible when conventional steel is substituted with aluminum for the BIW, closure, and engine and transmission subassemblies. The cost for the 23% aluminum LW is estimated at $5,196, which is based on the aluminum-intensive BIW manufacturing cost (EEA 1998). Costs for aluminum-intensive closure, engine and transmission, and chassis and suspension components are estimated according to the same ratio of the relative costs and weights of the BIW for the conventional and LW vehicles. A detailed description of the model is presented in the Supporting Information on the Web.

These costs are somewhat higher than some professionals in the automotive industry currently expect on the basis of the work of Estudillo and colleagues (2005). Therefore, we also apply a lower bound for manufacturing costs, which was estimated by discussion with experts from the auto industry. The above values from the literature are taken as upper bound costs, for the following range of costs: 6% aluminum LW ($1,182 to $2,301), 6% HSS LW ($1,176 to $2,711; ULSAB-AVC 2002), 11% LW ($1,821 to $2,921; EEA 1998), 19% LW ($3,528 to $5,040), and 23% aluminum LW ($3,620 to $5,196). The costs include not only material but also manufacturing costs. Therefore, the cost difference between HSS vehicles and AIVs deviates from their material cost differences taken alone. Table 6 summarizes estimated material and manufacturing costs compared with the baseline for each LW option for three classes of vehicle.

We compared a mid-sized vehicle (similar to a Ford Taurus) and a luxury class vehicle (similar to a Ford Crown Victoria) with the compact-sized vehicle to evaluate vehicle size effects on LW

**Table 6** Estimation of net additional manufacturing cost for the mid-sized and luxury class vehicle over vehicle lifetimes

| | *Net additional manufacturing cost ($)* | | | |
|---|---|---|---|---|
| *Lightweighting options* | *Compact-sized* | *Mid-sized* | *Luxury class* | *Cost increase in percentage (%)* |
| 6% HSS LW | 400 to 1,031 | 460 to 1,186 | 520 to 1,340 | 34 to 61 |
| 6% Al LW | 406 to 621 | 467 to 714 | 528 to 807 | 34 to 37 |
| 11% Al LW | 640 to 1,241 | 740 to 1,427 | 832 to 1,613 | 54 to 74 |
| 19% HSS LW | 2,752 to 3,360 | 3,165 to 3,864 | 3,578 to 4,368 | 200 to 233 |
| 23% Al LW | 2,844 to 3,516 | 3,271 to 4,043 | 3,697 to 4,571 | 209 to 240 |

*Note*: HSS = high-strength steel; LW = lightweighting; Al = aluminum.

costs and benefits. We applied the same percentages of LW from the compact-sized to the mid-sized and the luxury vehicle and used AVL Cruise to predict the fuel economy associated with the five LW options. We applied materials costs as above and assumed the net additional manufacturing costs for the mid-sized and luxury vehicles by multiplying with scale factors (due to a lack of better information in the public domain). The scale factors for the net additional manufacturing costs of the mid-sized and luxury vehicles were assumed to be 1.15 and 1.3, respectively, relative to the calculated LW costs for the baseline vehicle. These estimated values were reviewed by a materials expert from the automotive industry, who confirmed that they were reasonable values (Sanders 2008). Additional costs for alternative powertrains were taken from the literature, as listed in table 7.

For the use-phase cost, we consider only fuel cost, which is directly influenced by the vehicle LW, assuming that maintenance costs are equal across all vehicles. A gasoline fuel price range between $2.0/gallon and $4.5/gallon was considered. ELV recycling costs (including shredder and sorting costs) and the expected recovery revenue (USGS, various years) for the LW options are compared with the baseline vehicle. The cost model considers both cost and revenue for increased recycling of light metals. By way of trends, we have observed that as LW with aluminum is intensified, there is less ferrous material value at EoL to recover, whereas the aluminum material value increases substantially. Due to the higher total EoL value of aluminum relative to steel, the overall EoL value of the vehicle increases significantly with aluminum LW, despite (slightly) lower recovery efficiencies for aluminum versus steel. Figure 1 summarizes the life cycle costs for the lightweighted vehicles, where we use the ELV recovery rate and vehicle scrappage rate model from the work of Schmoyer (2001). Vehicle scrappage rate is lower than ELV recovery rate due to ELV leakage outside the recycling infrastructure. *EoL cost Low* in figure 1 means that EoL costs are based on vehicle scrappage rates, whereas *Eol cost High* means that the EoL cost is based on ELV recovery rates.

**Table 7** Estimation of net additional manufacturing cost for selected powertrains over vehicle lifetimes

| *Powertrain* | *Net additional manufacturing cost (with source of data)* |
|---|---|
| Diesel engine | $1,074 to $1,500 (Frangi 2001b) |
| HEV powertrain | $2,495 to $3,000 (Thomas 2003) |
| PHEV powertrain | $3,500 to $8,000 (Simpson 2006) |

*Note*: HEV = hybrid electric vehicle; PHEV = plug-in hybrid electric vehicle.

## Results

### *Cost-Benefit Analysis for Lightweighting of Compact-Sized Vehicle*

This section first considers the costs to producers and consumers to remove a metric ton of $CO_2$-eq relative to the baseline vehicle for each

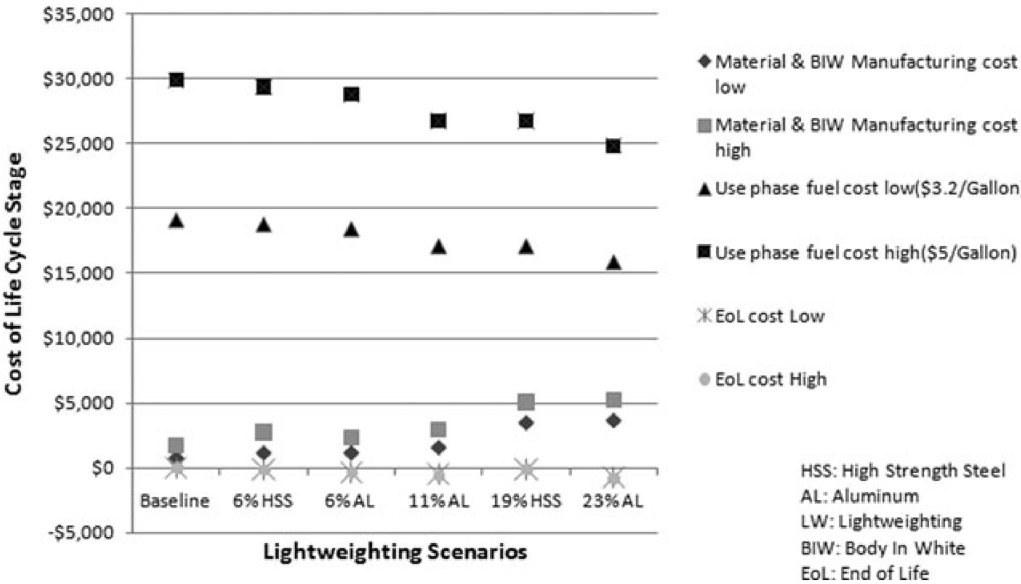


**Figure 1** Costs by life cycle stage for lightweighted vehicles considered in this study. BIW = body in white; EoL = end of life; HSS = high-strength steel; AL = aluminum.

LW scenario of the compact vehicle. Under the above assumptions, we calculate that for the 11% LW option, producers must spend an additional \$817 to \$1,241 to save 4,310 to 5,003 kg $CO_2$-eq (for the baseline emission factor case). When we calculate the GHG emissions saving per unit LW investment (in dollars), the result is \$163 to \$287 per metric ton $CO_2$-eq for the 11% LW option, which turns out to be the least expensive from the standpoint of unit cost to reduce GHG emissions. In calculating this number, we acknowledge that this value is not a driver for decision making on the part of producers and that LW need not be used entirely for improving fuel economy (e.g., it can be used instead to increase vehicle acceleration). We leave it to future research to understand market penetration of LW vehicles and the use of LW to improve fuel economy versus acceleration (e.g., see the Methods section in the work of Michalek et al. 2005). Table 8 summarizes the results for all LW options.

Table 9 provides fuel cost savings relative to additional sales cost. For example, a consumer can save 626 gallons of fuel under an 11% LW scenario while paying an additional \$817 to \$1,241 up front (if we assume that a change in production cost affects vehicle purchase price by the same amount). If we assume a fuel price of \$4.5/gallon,

**Table 8** Cost-benefit analysis: Producer perspective

| *LW option over baseline* | *Additional cost (\$)* | *GHG saving (kg $CO_2$-eq)* | *GHG saving (\$/metric ton $CO_2$-eq)* |
|---|---|---|---|
| 6% HSS | 400 to 1,031 | 1,930 to 2,712 | 148 to 534 |
| 6% Al | 406 to 621 | 2,242 to 2,745 | 148 to 277 |
| 11% Al | 640 to 1,241 | 4,310 to 5,003 | 128 to 287 |
| 19% HSS | 2,752 to 3,360 | 5,792 to 7,809 | 352 to 579 |
| 23% Al | 2,844 to 3,516 | 8,150 to 9,026 | 315 to 431 |

*Note:* LW = lightweighting; GHG = greenhouse gas; kg $CO_2$-eq = kilograms carbon dioxide equivalent; \$/metric ton $CO_2$-eq = dollars per metric ton carbon dioxide equivalent; HSS = high-strength steel; Al = aluminum.

**Table 9** Cost-benefit analysis: Consumer perspective

| *LW option over baseline* | *Fuel saving (gallon)* | *Net present value of fuel cost saving at $4.5/gallon ($)* | *Additional manufacturing cost ($)* | *Fuel cost saving − addl. manufacturing cost for LW ($)* |
|---|---|---|---|---|
| 6% HSS | 215 | 765 | 400 to 1,031 | −266 to 365 |
| 6% Al | 215 | 605 | 406 to 621 | −16 to 199 |
| 11% Al | 626 | 2,240 | 640 to 1,241 | 724 to 1,600 |
| 19% HSS | 1,009 | 3,657 | 2,752 to 3,360 | 297 to 905 |
| 23% Al | 1,198 | 4,344 | 2,844 to 3,516 | 828 to 1,500 |

*Note:* LW = lightweighting; HSS = high-strength steel; Al = aluminum.

the LW vehicle can save consumers $2,240 over the total vehicle lifetime (net present value with 3% discount rate [NPV]). If we consider the additional purchase cost and assume no mark-up on this cost, the consumer would then save $724 to $1,823 NPV. It is notable that the 6% LW options (for both aluminum and HSS) could yield a financial loss to the consumer. The 23% LW case is the most favorable strategy from a consumer perspective. Nevertheless, the gains are relatively small (less than $3,000) given the timeframe over which the investment pays back (11 to 16 years) and the low discount rate applied. Figure 2 provides a scatter diagram indicating the additional manufacturing costs associated with the various LW scenarios.

### *Lightweighting Impact by Vehicle Size*

Figure 3 provides the producer costs that were estimated for LW by vehicle size, in terms of additional manufacturing costs[8] divided by life cycle GHG emission reduction (dollars per metric ton $CO_2$-eq). It is observed that a larger GHG savings occurs with a higher intensity of LW, but manufacturing costs are disproportionately

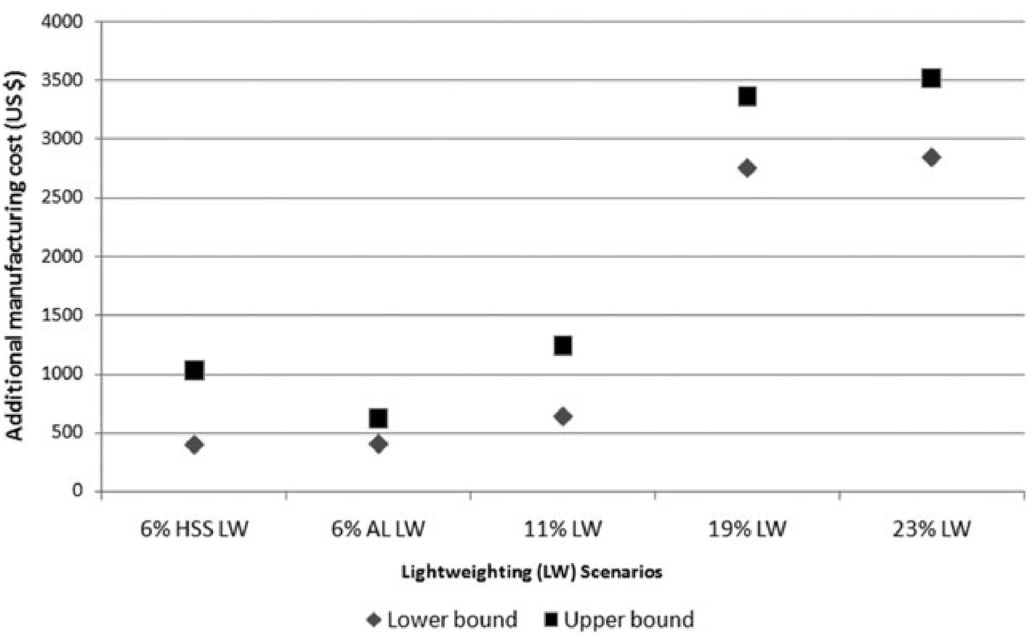


**Figure 2** Additional manufacturing costs for lightweighting (LW) scenarios. HSS = high-strength steel; AL = aluminum.

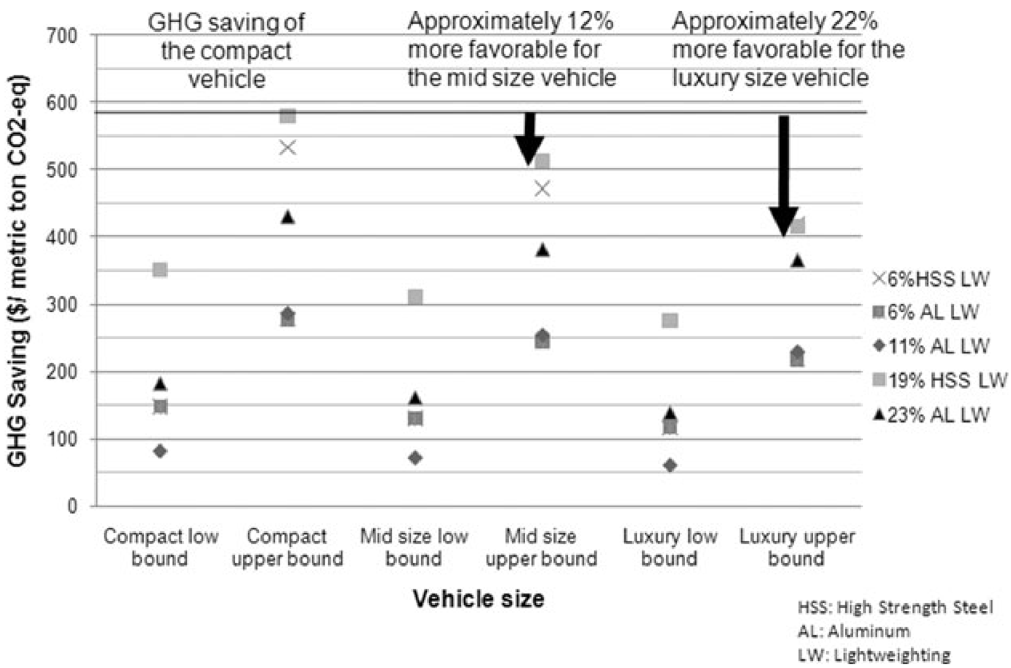


**Figure 3** Incremental greenhouse gas (GHG) saving (dollars per metric ton carbon dioxide equivalent [$CO_2$-eq]) by vehicle size. HSS = high-strength steel; AL = aluminum.

higher. Mid-sized and luxury vehicles are approximately 12% and 22% more efficient, respectively, in terms of dollars per metric ton $CO_2$-eq avoided. In figure 4, consumer benefits are estimated for LW by vehicle size as the difference between the fuel cost saving and the net additional manufacturing cost for LW. With respect to cost savings as a function of vehicle size at 23% LW, it is found that the owner of the mid-sized vehicle can save $834 to $1,606, versus $828 to $1,500 for the compact-sized vehicle and $1,550 to $2,424 for the luxury vehicle. Additional fuel cost savings for the mid-sized vehicle relative to the compact-sized vehicle (at the same percentage of LW for both vehicles) range from 0.7% to 61%, whereas the range of fuel cost savings for the luxury vehicle ranges from 45% to 91%.

According to the model, larger vehicles have additional LW benefits, although it should be noted that these benefits follow directly from the assumed ratio of net additional manufacturing costs relative to assumed additional mass. Here it was assumed that the mass of the mid-sized and luxury vehicles is 1.3 and 1.65 times that of the compact vehicle, respectively, whereas the scale factors for the net additional manufacturing costs are 1.15 and 1.3, respectively. This leads to greater cost-efficiency for GHG reduction by LW for larger vehicles. Naturally, greater manufacturing cost reductions for larger vehicles are possible, because many of the components for larger vehicle can be also produced by the same manufacturing facilities and processes as for compact vehicle. Therefore, vehicle producers can expect more cost-effective GHG reduction when they apply LW strategies to larger vehicles, as opposed to smaller vehicles. This trend of higher LW in larger vehicles is consequently observed in the market, as with vehicles such as the Jaguar XJ or Audi A8 (Scamans 2005; Henn and Leyers 2006). The strategy to use more LW with larger vehicles is also driven by regulatory factors.

### *Comparison of Lightweighting Effects With Other Vehicle Technologies and Industries*

Figure 5 compares the GHG saving and financial costs of LW with three selected vehicle powertrain technologies. It is observed that the

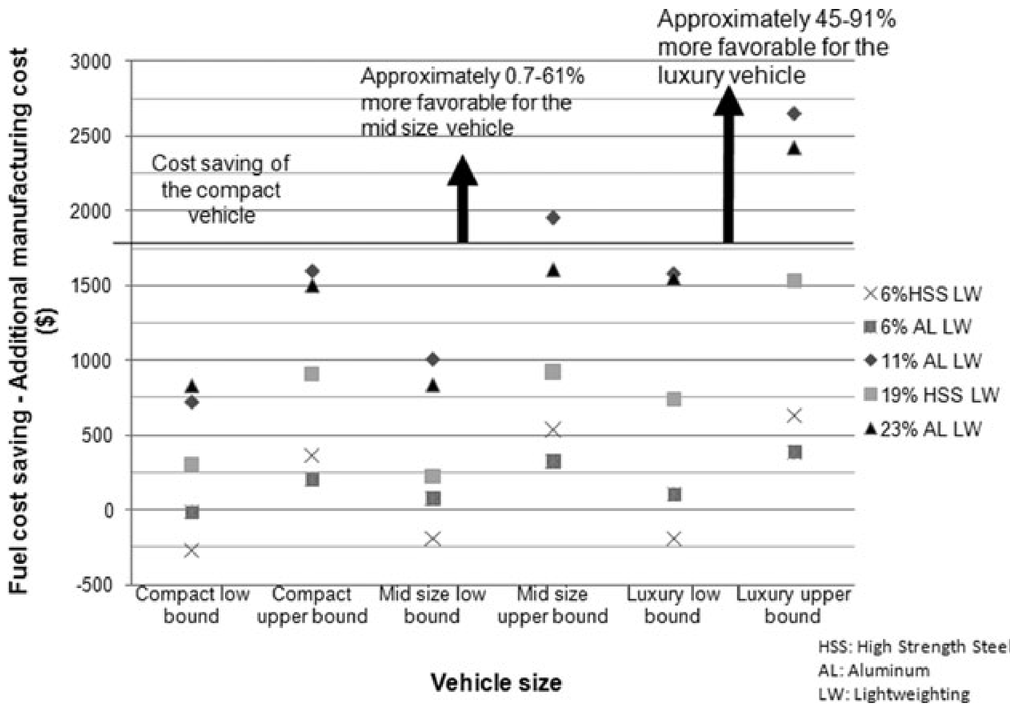


**Figure 4** Estimated consumer benefits for lightweighting (LW) by vehicle size. HSS = high-strength steel; AL = aluminum.

cost-benefit ratio in terms of technology cost per metric ton $CO_2$-eq (dollars per metric ton $CO_2$-eq) is not constant. The wide gap between the lower and upper bounds of the technology costs for reducing a metric ton of GHG is driven by the range of manufacturing cost uncertainty, which will likely be reduced in the coming years. Generally, greater GHG savings result from greater LW, but manufacturing costs are disproportionately higher. It is also found that 6% and 11% aluminum LW both have cost-effectiveness performance similar to that of the hybrid vehicle, and

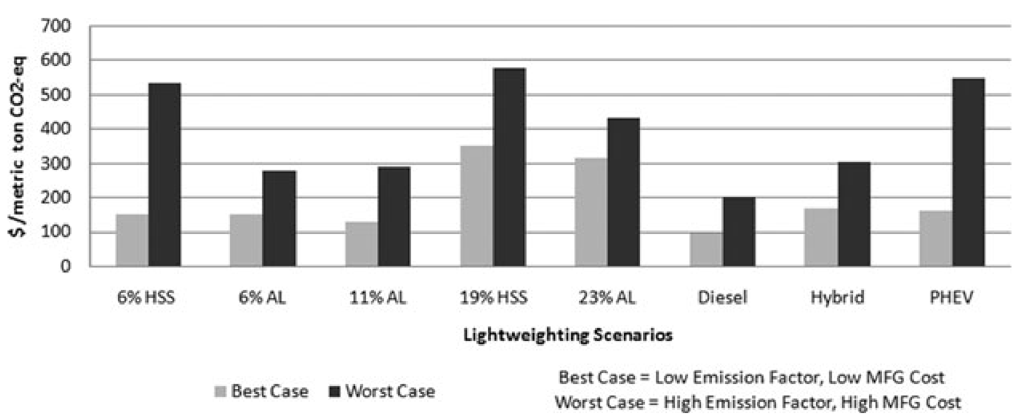


**Figure 5** Cost-benefit analysis: technology costs for reducing 1 metric ton of greenhouse gas (GHG). \$/metric ton $CO_2$-eq = dollars per metric ton of carbon dioxide equivalent; HSS = high-strength steel; AL = aluminum; PHEV = plug-in hybrid electric vehicle; MFG = manufacturing.

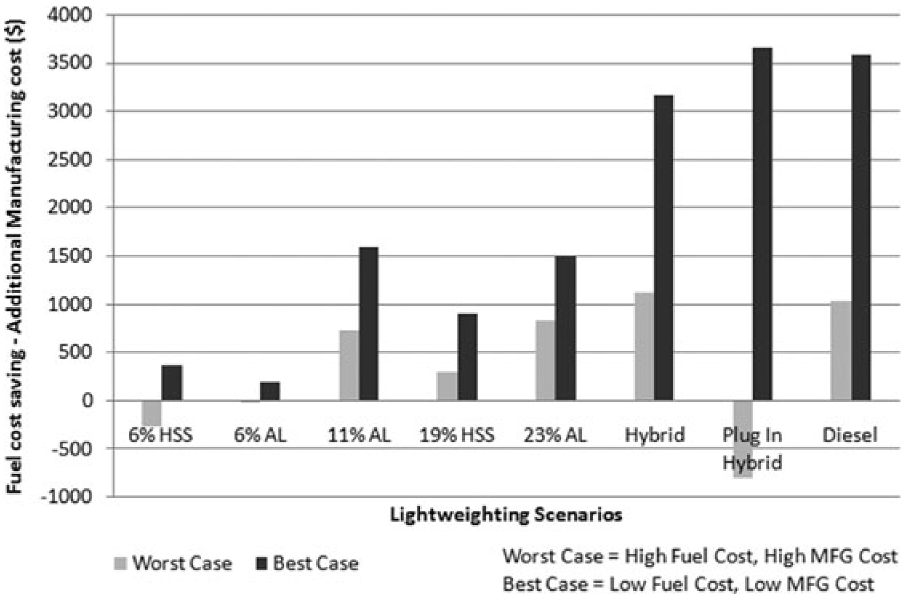


**Figure 6** Cost-benefit analysis: fuel cost savings minus the additional manufacturing (MFG) cost. HSS = high-strength steel; AL = aluminum.

they have the best cost-effectiveness among the LW options considered in this analysis. Both hybrid and PHEV strategies are more cost-effective than the more intensive LW scenarios considered here, however. Meanwhile, the diesel powertrain technology is observed to have better performance than the 6% and 11% LW scenarios. The emission factor for the electricity grid that powers the PHEV is assumed to be 0.668 kilograms carbon dioxide equivalent per kilowatt-hour (kg $CO_2$-eq/kWh), which is the average of U.S. GHG emission coefficient for electricity generation in 1998–2000 (US DOE 2002). We excluded upstream emissions from electricity because their inclusion did not change the results significantly.

Figure 6 provides the estimation of cost-saving effects for different powertrain technologies as compared with LW options. The 23% LW option is the best solution from the perspective of cost-effectiveness to the consumer, where cost-effectiveness is defined as the fuel cost savings to the consumer over the vehicle lifetime (relative to the baseline vehicle at a discount rate of 3%) minus the up-front added cost to purchase the vehicle. The diesel powertrain performs better in this regard than 11% LW, whereas the hybrid powertrain presents better performance than 6% or 19% LW. We observe that the PHEV is not an attractive means for reducing GHG emissions for the upper bound additional manufacturing cost ($8,000). From the analysis, we can conclude that 11% of LW has relatively good performance from both producer and consumer points of view, followed by the diesel powertrain.

From the analysis, we can conclude that a relatively low level of LW (6% to 11%) is competitive with advanced powertrain technologies, such as hybrid and PHEV. Diesel technology provides the best performance for technology cost per metric ton $CO_2$-eq due to its relatively low manufacturing cost. This suggests that the combination of low LW levels with diesel powertrain could be promising as a near-term producer strategy to significantly and cost-effectively reduce GHG emissions where such vehicles are not prevalent. In fact, it is already the basic strategy observed in the European Union (EU) automotive market (Henn and Leyers 2006). Finally, it is worth noting that in all cases the total fuel cost savings over the life of the vehicle is still relatively small (at most $1,700) relative to the up-front cost of the vehicle.

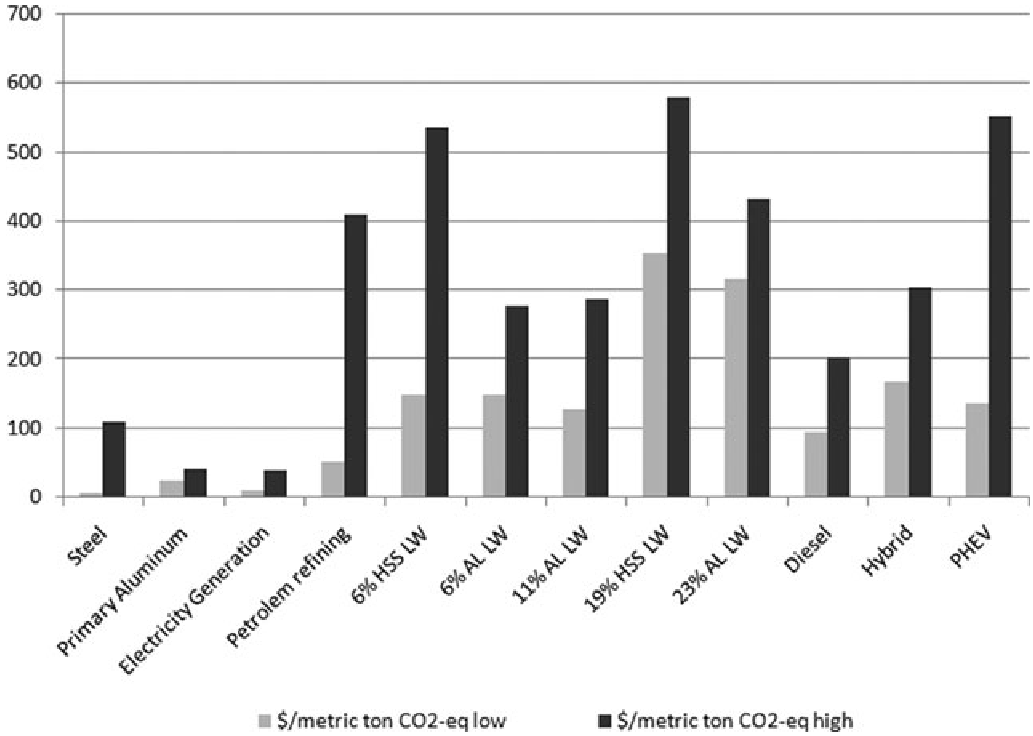


**Figure 7** Comparison of greenhouse gas (GHG) reduction potential of lightweighting for the automotive industry with possible actions in other industries (EPRI 2006; IPCC 2007). HSS = high-strength steel; LW = lightweighting; Al = aluminum; PHEV = plug-in hybrid electric vehicle.

In figure 7, GHG reduction potentials for the automotive industry through LW and alternative powertrains are compared with GHG reduction strategies available to material production industries as compiled by the IPCC (2007). We adjusted the IPCC data to present values with a 3% annual discount rate, because the IPCC report estimates GHG mitigation potential cost in 2030. They are also compared with the potential for GHG reduction in the electricity generation sector, which is assumed to be $10 to $40 per metric ton $CO_2$-eq today (EPRI 2006). As illustrated in figure 7, the steel industry is likely to face a cost of $20 to $50 per metric ton of GHG to reduce their GHG emissions by 15% to 40% (IPCC 2007), whereas the aluminum industry requires less than $100 per metric ton of GHG to achieve 15% to 25% of GHG reduction (IPCC 2007). The McKinsey study (Creyts et al. 2007) indicates that $50 cost per metric ton of GHG makes it possible to reduce GHG emissions in 2030 by 3.0 to 4.5 gigatons of $CO_2$-eq.[9] In short, figure 7 reveals that the automotive industry requires a greater investment per metric ton than most of the other industries listed in the work of Creyts and colleagues (2007).

Given that the above analysis indicates relatively weak market incentives for the stabilization of GHGs concentration in the automotive sector, it is expected that widespread adoption of LW and alternative powertrains will require strong policy instruments. Naturally, LW has the advantage that it can be adopted synergistically with advanced powertrain mounted vehicles to achieve the much higher amounts of GHG mitigation necessary to avoid the worst impacts of climate change in the coming decades.

## Conclusions

This article has evaluated the economics of vehicle LW and the cost-effectiveness of LW in reducing life cycle GHG emissions. Vehicle LW using aluminum and HSS is considered between the levels of 6% and 23% and evaluated for the cost to remove GHG emissions, per kilogram, and the difference between additional manufacturing cost and fuel cost savings achievable by LW.

Previous research studied the potential for aluminum and HSS lightweighted vehicles to reduce life cycle emissions (Das 2000; IAI 2000; US EPA 2004; Henn and Leyers 2006; WSO 2008). The economics of alternative automotive technologies (Fragi 2001; IAI 2000; Austin et al. 1999; Cooper et al. 2004), however, had only been studied previously at the component or subassembly level rather than at the vehicle system level. By considering the vehicle system level costs and GHG emissions savings achievable by LW, we have been able to compare the cost-effectiveness of LW in comparison to other vehicle system-level strategies, such as hybridization and alternative fuels. The article also presents a sensitivity analysis on key parameters to understand the uncertainty associated with the cost-effectiveness of LW.

Key findings from the study are as follows:

1. It was observed that the cost to remove GHG emissions by LW expressed in dollars per metric ton $CO_2$-eq was lower as the LW intensity increased. From a producer perspective, we observed that 11% of aluminum LW is the most cost-effective LW option to remove GHG emissions per kilogram. From a consumer perspective, 23% of aluminum lightweight vehicle is the most economical option. The gain to the consumer between the additional producer cost from LW and fuel cost savings, however, is still relatively small compared to the base cost of the vehicle (at most $2,700). Analysis of the LW costs and benefits by vehicle size shows that there is likely to be a greater fuel saving effect for larger vehicles.
2. Vehicle LW was compared with alternative powertrain technologies that can also reduce life cycle GHG emissions with additional production costs invested up front. Diesel vehicles, HEVs, and PHEVs were considered, and it was found that intensive LW with aluminum and HSS is cost-competitive with these alternatives. Furthermore, LW can be used with all these approaches for further GHG reductions over the vehicle life cycle.
3. Finally, the GHG saving effects of LW were compared with savings in several other industries. The results showed that automotive GHG reduction technologies are generally more costly per kilogram to reduce GHG emissions than opportunities for reduction by other industries identified by the IPCC. An in-depth policy analysis would be necessary to accurately determine how specific policy instruments, such as more stringent Corporate Average Fuel Economy (CAFE) standards; carbon taxes on fuels; or a broader cap-and-trade program, such as exists in the European Union Emission Trading Scheme (EU ETS), would affect vehicle LW relative to other GHG reduction technologies.

## Acknowledgments

This research was supported by the Alcoa Foundation's Conservation and Sustainability Fellowship Program and the National Science Foundation Materials Use: Science, Engineering and Society (NSF MUSES) grant (CMMI 0628162). One of the authors was partially funded through the Alcoa Foundation Conservation and Sustainability postdoctoral fellowship program, which is a separate entity from Alcoa. The project was initiated independently of Alcoa and the steel industry. They were consulted as industry experts in the context of the NSF MUSES grant. Any opinions, findings, and conclusions or recommendations expressed in this material are ours and do not necessarily reflect the views of the National Science Foundation or other funding and information sources. We thank Ford Motor Company, the International Iron and Steel Institute, and Alcoa Inc. for their helpful input to this research.

## Notes

1. *MMT* stands for *million metric ton* (1 teragram [tg]). One metric ton (t) = $10^3$ kilograms (kg, SI) ≈ 1.102 short tons.

2. Carbon dioxide equivalent ($CO_2$-eq) is a measure for describing the climate-forcing strength of a quantity of GHGs using the functionally equivalent amount of carbon dioxide ($CO_2$) as the reference.
3. *Compact-sized vehicle* is a classification of cars that are larger than subcompacts but smaller than mid-sized cars. Common engine sizes are 1.5 to 2.4 liters. Ford Focus and Honda Civic vehicles are in this class.
4. One kilogram (kg, SI) ≈ 2.204 pounds (lb).
5. *Mpg* is a unit of measurement that measures the distance a vehicle can travel in miles on 1 gallon of fuel. One mile (mi) ≈1.61 kilometers (km); one gallon (gal) ≈ 3.79 liters (l). Thus, 1 mpg ≈ 0.42 km/1.
6. AVL Cruise is a software package developed for vehicle simulation by AVL LIST GmbH.
7. July 2008 prices were used in this analysis.
8. All monetary values used in this article are in U.S. dollars.
9. One gigaton = $10^9$ tonnes (t) = $10^{12}$ kilograms (kg, SI) ≈ 1.102 × $10^9$ short tons.

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## Supporting Information

Additional supporting information may be found in the online version of this article:

**Supporting Information S1:** This supplement describes modeling of other powertrain vehicles, provides a life cycle cost model for vehicles and a sensitivity analysis of manufacturing cost estimates to production volume.

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