5. Crosscutting

A. Cost Modeling
Oak Ridge National Laboratory

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Executive Summary

The cost modeling effort is aimed at evaluating the cost effectiveness of various technologies being considered or undertaken by the Lightweighting Materials (LM) Program. This project identifies the system-level life cycle baselines and then assesses the life cycle costs of competing materials and design options at the system level. These systems level results can be used to evaluate various whole vehicle design approaches that optimize the materials used according to system requirements and cost targets. Those assessments are then used by DOE management to aid in setting program priorities and evaluating potential impacts.

Activity and Developments

Technical Cost Modeling

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Accomplishments

Completed a report on the lightweighting (LW) potential of pickup trucks. The LW potential of pickup trucks may be somewhat lower than cars, but the total vehicle weight could be reduced by 40% even with the application of only near-term technologies.

- Completed the development of a baseline automotive system cost model for light-duty vehicles. The model was validated in terms of both mass and cost distribution using a 2002 average midsize car manufactured by domestic Original Equipment Manufacturers (OEMs).

- Completed the initial economic evaluation of linear strain extrusion machining of magnesium (Mg) sheet production technology. Economics of this technology demonstrated to date for small width sheet appear to be favorable compared to other available technologies.

Future Directions

- Using the baseline multi-material vehicle cost model developed in FY11, estimate the cost-effectiveness of 25% body and chassis mass reduction goal from a system perspective.

- Complete the comparative primary Mg cost analysis of Chinese Pidgeon process vs. solid oxide membrane process.

- Evaluate the economics of lightweight materials projects in terms of both material production and parts manufacturing processes supported by LM as necessary.

- Complete cost assessment of alternative low-cost carbon fiber manufacturing technologies.

Technology Assessment

- Target: Achieve system-level cost-effectiveness of various LM's multi-year light-duty vehicle weight reduction goals.

- Gap: Lightweight materials could be more than three times more expensive than conventional materials, in terms of both raw material and part manufacturing cost.

Introduction

The cost modeling effort comprises a single task which supports both system-level modeling of potential cost impacts of various technologies and materials replacement impacts. Individual efforts for this task are approved on a case-by-case basis at the discretion of DOE program management. In previous years, cost models were developed for the carbon fiber (CF) and Mg research portfolios. System-level models for potential mass savings have been developed and are continually refined to provide program guidance for the cost-benefit analysis of various potential LW technologies.

The LM component of the DOE Vehicle Technologies Program has a 50% weight-reduction goal for passenger vehicle body and chassis systems, with safety, performance, and recyclability comparable to 2002 vehicles. A baseline cost model for a multi-material vehicle is essential to facilitate the development and validation of cost-effectiveness of LM's various multiyear body and chassis weight-reduction goals from a system perspective. The current work uses a holistic systems approach for modeling the costs of automotive systems. The automotive cost model's capabilities have been demonstrated using a 2002 midsize car's teardown data and other industry data.

Approach

The technical cost-modeling task involves developing and modifying various component, material, and system-level models to analyze and validate the effectiveness of different technical research efforts. The goals of those modeling efforts are as follows.

- Address the economic viability of lightweight materials technologies both at the specific component level and at the complete vehicle level.

- Use cost modeling to identify specific technology improvements and major cost drivers that are detrimental to the economic viability of those new technologies.

- Derive cost estimates based on a fair representation of the technical and economic parameters of each process step.

- Provide technical cost models and/or evaluations of the “realism” of cost projections of lightweight materials projects under consideration for LM funding.
- Examine technical cost models of lightweight materials technologies that include aluminum (Al) sheet, CF precursor and precursor processing methods, and CF reinforced polymer composites (CFRP), and examine methods of producing primary Al, Mg, and titanium and Mg alloys with adequate high-temperature properties for powertrain applications.

Results and Discussion

As vehicle LW gains momentum in achieving proposed fuel economy targets, it is becoming imperative to determine how the cost-effectiveness of desired vehicle weight-reduction goals can be achieved in combination with other technology options, such as advanced powertrain technologies, being considered by the industry. Using a systematic approach that facilitates consideration of various lightweight materials and technologies for automotive systems scenarios—and the interactions among them within a scenario—an automotive cost model for a baseline midsize passenger car has been developed to examine the cost effectiveness of LM’s multi-year weight reduction goals. This approach facilitates the consideration of several LW strategies such as lightweight metals, composites, and multi-materials, each of which can be optimized at the specific component level and the vehicle system level before its cost-effectiveness can be evaluated by comparison among scenarios for determining a LW strategy. The analysis also considers the impacts of LW a component beyond the component itself to the complete vehicle retail price and life cycle/ownership costs.

The focus of this FY’s work provides not only the reference for the cost-effectiveness measure for evaluation of LW strategies, but also the mass and cost breakdown at a major vehicle-component level indicating where the most cost-effective LW opportunities exist for this specific vehicle type. Under this approach, multiple LW pathways based on technology status and timeframe in which the desired vehicle weight-reduction goal is to be achieved can be examined to determine their cost effectiveness from a systems perspective. The approach can consider an extensive use of Al for the near-term lower mass reduction goal vs. the use of carbon fiber polymer composites for the long-term higher mass reduction goal vs. a multi-materials scenario. A relative, total-system cost comparison among various pathways will determine the optimal strategy to be pursued for the desired LW goal.

The baseline Automotive System Cost Model (ASCM) developed for a midsize passenger car is based at the level of 35+ major components, for which specific mass and technology data has been collected. Using the component data and specific alternative component technology data available from the industry representing a specific LW scenario, LW cost-effectiveness can be estimated. It is the sizing interrelationships among various vehicle components (i.e., mass decompounding/secondary mass savings impacts) considered in ASCM that allows the systems-level examination of cost-effectiveness impacts, an approach that goes beyond one-for-one component substitution. The mass decompounding effect also allows consideration of how the heavier and expensive alternative electric powertrains can impact the cost-effectiveness of non-powertrain LW options. This effect is limited to the consideration of component-level mass and the associated cost for the hybrid and fuel cell advanced powertrain types currently included in the model. Component-manufacturing costs are estimated after components are sized after taking into account their interrelationships; to this, vehicle assembly, OEM corporate overhead, and dealer costs are added for estimating vehicle retail price. Comparison of alternative LW scenarios is finally made at the level of vehicle life cycle/ownership cost, which is estimated by adding operation cost that consists of six major cost categories, including fuel—a category strongly influenced by vehicle LW and powertrain type considered. As most LW options have high initial costs, it is the vehicle life-cycle cost, rather than the vehicle retail price on which the automotive industry currently focuses, that needs to be considered to determine each option’s economic viability. It is the systems approach that allows consideration of the impacts of a specific component-level lightweight substitution in the context of a plausible scenario of the vehicle mass and associated life cycle cost, that facilitates the for formulation of a cost-effective LW strategy.

A baseline midsize passenger car—a 2002 midsize vehicle with a curb weight of 3,249 lbs (as reported by EPA in its annual trend report), manufactured by a domestic OEM—was considered for the capability demonstration of the system-level cost model developed here. Mass data at the 35+ component level were obtained using the vehicle teardown data from the A2Mac1 database (an industry database). Intellicosting’s benchmarking cost data, based similarly on teardown data, are developed at a more detailed level to estimate costs of major components within each of the 35+ component categories considered in our cost modeling framework, as shown in Table 1. For example, the engine has been disaggregated further into seven major components. Representation of cost components at a detailed level provides additional capability to examine LW opportunities at a one-step-more-detailed level. Major subcomponent cost data represent OEM purchased cost at an annual production volume of 250,000. The model is dynamic in the sense that new component-level technology data can be added to the model database when data become available and needed for cost-effective LW strategy analyses. The total baseline manufacturing cost of a midsize passenger car is estimated to be $12,762 or $8.64/kg, with components such as engine, transmission, body-in-white (BIW), and seating and restraints form a major share of total cost.

Table 1. Mass and Cost Distribution of Major Components in a 2002 Baseline Midsize Passenger Car.

System	Component	Mass (kg)	Cost ($)
Powertrain			
Engine	Crankshaft	18.3	$274
	Cylinder Head	21.8	$274
	Cylinder Block	41.3	$500
	Oil Pan Assembly	5.5	$202
	Camshafts	3.6	$60
	Valve Roller Rocker	1.6	$208
	Other	62.4	$703
Energy Storage	Energy Storage	17.7	$40
Fuel System	Fuel Tank	58.3	$160
	Other	5.5	$57
Transmission	Case	27.3	$335
	Gears and Shaft	22.7	$280
	Clutch	33.6	$513
	Other	25.0	$17
Driveshaft/Axle	Driveshaft assembly	8.7	$62
	CV joint	19.0	$66
Differential	Drive bearings	3.2	$18
	Case	4.5	$35
	Gears	5.0	$40
Cradle	Cradle	32.3	$78
P/T Thermal	Radiator	4.8	$70
	Radiator fan assembly	6.6	$77
	Radiator fan motor	1.5	$38
	Other	5.5	$96
Exhaust System	Exhaust manifold	7.3	$46
	Catalytic converter	3.2	$289
	Muffler	5.1	$80
	Other	6.7	$12
Powertrain Electrical	Engine control module	1.4	$130
	Power electrical	4.4	$80
	Alternator	6.0	$53
Emission Control Electronics	Emission Control Electronics	1.2	$31
Oil and Grease	Oil and Grease	12.1	$59

Body			
BIW	BIW	320.5	$1,025
Panels	Panels	60.0	$197
Front/Rear Bumper	Impact module	5.5	$33
	Other	4.5	$58
Glass	Glass	21.8	$129
Paint	Paint	12.0	$450
Exterior Trim	Exterior Trim	10.9	$104
Body Hardeners	Body Hardeners	10.0	$226
Body Sealer & Deadners	Body Sealer & Deadners	2.0	$24
Chassis			
Corner Suspension	Upper front control arms	15.9	$62
	Lower front control arms	11.4	$69
	Rear control arms	7.7	$71
	Other	98.6	$425
Braking Systems	Steering Knuckle	6.2	$42
	Rotor	27.2	$48
	Assembly Calliper	15.6	$41
	Other	20.6	$163
Wheels and Tires	Wheel	28.2	$64
	Tires	29.3	$231
Steering System	Steering column assembly	39.2	$256
	Steering wheel w/ airbag	1.8	$94
Interior			
Instrument Panel	IP Cockpit	15.6	$300
	Beam assembly	9.3	$68
	Bracket assembly	4.5	$27
	Other	2.3	257
Trim and Insulation	Accessories	6.1	$72
	Carpet	19.5	$67
	Overhead trim	15.2	$283
Door Modules	Door trim assembly	18.3	$151
	Garnish	11.4	$60
Seating and Restraints	Seat assembly	65.5	$1075
	Airbag assembly	14.9	$231
	Restraints	7.3	$43
HVAC	HVAC system	9.1	$150
	Radiator	4.8	$70
	Other	7.3	$107
Electrical			
	Interior	3.1	$123
	Chassis	3.1	$123
	Exterior Lighting	17.7	$158
Assembly	Assembly	10.1	$605
Total		**1477.0**	**$12,762**

As one would expect, body and chassis vehicle systems combined contribute 50% of vehicle curb mass, whereas the powertrain alone accounts for the largest share, 30%, of vehicle mass. Because the body and chassis contribute so significantly to total vehicle mass, significant LW opportunity exists. Figure 1 shows the estimated vehicle ownership cost distribution of a 2002 midsize car. From the cost perspective, the engine, transmission, BIW, and seating and restraints are major cost items, with each costing at least $1,000. The total vehicle retail price is estimated to be $19,015, of which OEM overhead and dealer cost is estimated to be about $6,253. The estimated vehicle retail price falls into the price range ($18,515 to $20,290) of similar vehicles (by curb weight) manufactured by U.S. OEMs in that model year, although actual vehicle prices may vary widely depending on the specific options included.

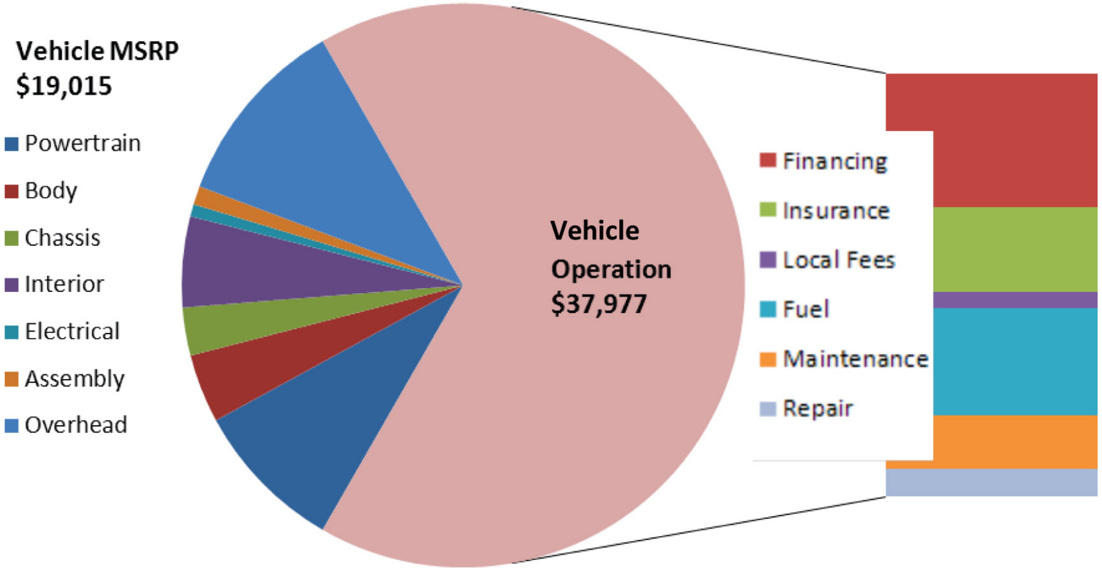

Figure 1. Vehicle ownership cost distribution of a 2002 baseline midsize car. (Note: The right side of the legend identifies operation cost categories. The stacked bar shows their relative contribution to operation cost.)

Operation cost is twice the vehicle manufacturing cost (estimated as the sum of 35+ component costs), with financing cost, insurance cost, and fuel cost the major cost drivers from among the six categories considered in the vehicle operation cost. Note that financing cost is a part of vehicle operation cost and is a function of the amount of down payment, here assumed to be $5,000. Most of vehicle operation costs such as financing, insurance, maintenance, and repair costs are sensitive to vehicle retail price, which can only be captured by a system-level vehicle cost model as developed here. Total vehicle ownership cost, represented in terms of the sum of net present values of operation cost and downpayment, is estimated to be about $43,000 or 36 cents/mile. Vehicle MSRP component of total vehicle ownership cost has been captured by downpayment and financing component of the vehicle operation cost. It is anticipated that the development of a baseline vehicle model would facilitate examining how relative cost-effectiveness would be impacted by various LM multiyear vehicle weight-reduction goals from a system perspective.

Lightweighting the Body-on-Frame Light-Duty Truck

With the new emissions and fuel economy regulations, a significant improvement in the fuel economy of pickup trucks is imperative as pickup trucks represent a major share of petroleum consumption in the light-duty truck market. OEMs' focus today has been on relatively less expensive and less risky powertrain improvements rather than LW to improve fuel economy in the highly profitable pickup truck market. To achieve the overall desired fuel economy goal, LW of pickup trucks will be essential and reflects the trend already seen in the high-volume passenger car segment of the light-duty vehicle market. The initial analysis in this report estimates the LW potential of pickup trucks based on three plausible scenarios, with the first two scenarios each focusing on one key material substitution—either metals or composites—using near-term technology. Lightweight material types considered under each scenario are those currently being considered by the automotive industry today; the LW potential estimation does not include any detailed analysis of body stiffness, modal characteristics, and impact performance for meeting the appropriate safety regulations. Advanced high strength steel, Al, and Mg have been considered in the metals scenario, whereas glass- and carbon-fiber-reinforced polymer composites (the latter to a limited extent) have been considered in the composites scenario. The third plausible scenario is a hypothetical scenario to set the boundary for the maximum weight savings potential in the longer timeframe and with the application of the best available technologies from every field, i.e., racing, aerospace, and military, applied to pickup trucks. Lightweight vehicle construction in most limited-edition, high-performance sporting cars is based on carbon fiber-reinforced polymer composites today because of its maximum mass savings potential; thus this third scenario is being referred to as CFRP. The scenario considers an extensive use of CFRP body and chassis components besides limited use of titanium in piston assemblies, valves and exhaust systems. In addition, adoption of some technology options being demonstrated in concept cars, such as lightweight CFRP engine, Li-ion battery, and high-performance tires are also considered.

Body and chassis components contribute 50% of an assumed baseline pickup truck (based on the Ford F 150 model) mass of 2,300 kg (5,060 lb) as shown in Figure 2, and, therefore, a significant LW opportunity exists. Primary mass savings using the near-term technology have been estimated to be 12% under the metals scenario and 19% under the composites scenario. Estimated maximum mass savings potential under the composites scenario is close to the extreme case scenario considered in a recent Ducker study (Schultz, 2011a) where almost all 2,225 lb of ferrous content was replaced with either Al or Mg. When secondary mass savings are taken into consideration by assuming that for every 1 kg of primary mass savings an additional 0.5 kg secondary mass savings would be obtained, the total mass savings are 18% for the metals scenario and 28% for the composites scenario. Under the metals scenario, significant increases in the use of advanced high-strength steel, Al, and Mg are projected at the expense of conventional high-strength, low-alloy steel and bake hardenable steel. For the composites scenario, primarily glass-fiber-reinforced polymer composites have been considered.

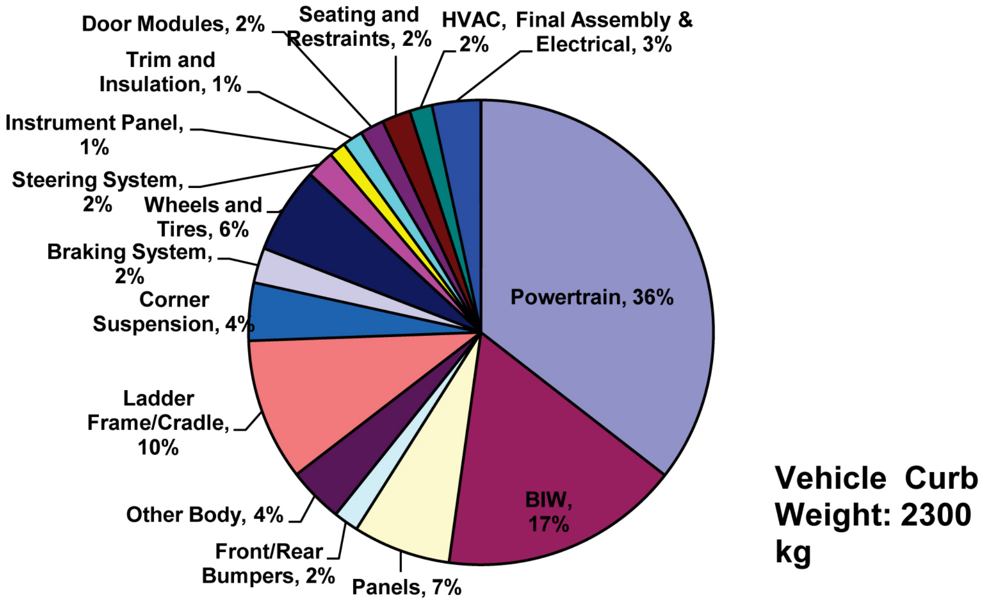

Figure 2. Weight distribution of a baseline pickup truck at the level of major components.

Powertain mass savings will mainly be achieved by engine downsizing (from V8 to V6) with the ability of turbochargers to improve both thermal efficiency and engine specific output due to improved performance or fuel economy. The latter is achieved not only by virtue of better thermal efficiency but also by engine downsizing, leading to vehicle weight reduction. In addition, substituting either Al or Mg for ferrous material has been considered in some of the powertrain components. Preliminary analysis indicates that, even assuming near-term manufacturing technology, by using lightweight powertrain components and engine downsizing, total mass savings potential would at least be 10% more than estimated for LW of body and chassis components alone (in the range of 29%–40%) for the first two scenarios. Under the CFRP scenario, maximum vehicle mass savings potential is estimated to be about 50%. Estimated maximum mass savings potential in this case of pickup trucks is conservative since its weight- to-power ratio is 4.5, compared to 3.5 kg per horsepower demonstrated in the limited-edition high performance sports car BMW M3 Carbon Racing Technology (CRT) (Reinforced Plastics 2011).

It is likely that a combination of these scenarios will be considered in the actual implementation, taking advantage of the best match between lightweight materials and specific part application, whereby a total vehicle mass savings would lie in between the two extreme ranges (i.e., 29-50%) estimated here. However, issues related to multi-material components such as the performance of the joints or nodes connecting the different components and the noise, vibration, and harshness performance need to be addressed. Practical limitations of these proposed scenarios need to be examined from a holistic system viewpoint focusing on whether the required performance and safety requirements could be met while achieving the estimated LW potential. In addition, some component-specific mass savings potential based on unibody car design is assumed to be applied to body-on-frame pickup truck designs, but it needs to be validated due to additional towing and load carrying requirements of pickups.

Estimated mass savings for pickup trucks are somewhat lower than recently published estimates for passenger cars. Estimates of mass savings in passenger vehicles such as the Lotus project, which addresses a complete passenger car without the powertrain, indicate a maximum mass savings of 38% without explicit consideration of secondary savings (Lotus 2010). It is comparatively more difficult to lightweight full frame pickup trucks because of their body-on-frame design and the towing and load carrying capability requirements. It is proposed that a multiyear mass-reduction goal be followed to achieve the desired overall estimated total mass-reduction goal for pickup trucks of at least 40%. Two intermediate mass savings goals of 15% and 25% could be set for the intervening years to achieve the overall goal. The intermediate goal-setting approach provides the opportunity to consider expensive lightweight materials options such as CFRP having the maximum savings potential but requiring time for technology maturity.

The cost of lightweight materials remains the primary hindrance to their widespread use by vehicle OEMs although the pressure to use lightweight vehicles is greater than before because of new fuel economy emission regulations. Engineers face challenges in managing the trade-offs between lightweight solutions that often cost more and incumbent materials that are cheaper. Economics will finally dictate the feasibility of various multi-material scenarios in pickup truck applications. Schultz has indicated that primary weight savings of 612 lb or 924 lb from using lightweight metals in pickup trucks corresponds to cost penalties in terms of dollars per pound saved of \$1.81 and \$2.44, respectively (Schultz 2011a, 2011b). Composites applications face a major hurdle in LW of pickup trucks because of poor economics and reliability when alternative, cost-effective options exist in this highly profitable niche market segment of the light-duty vehicle market. Because it is relatively more expensive to boost the fuel economy of light-duty trucks than it is for cars, full-sized pickups are now exempt from any fuel economy increases from the 2017 through the 2019 model year.

The Light Metal Processing and Manufacturing Initiative

The Light Metal Processing and Manufacturing initiative was undertaken to organize a comprehensive effort to prioritize and solve technical barriers in each stage of the life cycle of light metal components, including cost-effectiveness for automotive applications. The focus of this work was examination of the cost-effectiveness of several potential Mg sheet manufacturing technologies, including the linear strain extrusion machining (LSEM) process, because the improved affordability of Mg sheet would tremendously help vehicle LW efforts. LSEM Mg sheet production technology is currently being developed by Purdue University researchers. The technology uses chip formation in machining for the production of nanostructured and ultra-fine-grained materials by the imposition of very large plastic strains in a single pass of a specially designed cutting tool. Chips of controlled thickness and ultra-fine-grained microstructure can be produced by machining and extrusion imposed in a single step—similar to the wood veneer manufacturing process. Rotary and linear are the two variants of the LSEM process that have been successfully demonstrated for a small sheet size of 2 in. wide by 0.06 in. thick.

Figure 3 shows the estimated cost breakdown for LSEM-produced Mg sheet that is 2 in. wide by 0.06 in. thick, made of AZ31B alloy, and produced at an annual volume of 356 metric tonnes. Total manufacturing cost is estimated to be \$2.92/lb, about \$0.40–\$0.90/lb lower than two conventional Mg sheet production technologies: direct chill casting and twin belt casting. Raw material cost contributes more than 80% of total sheet manufacturing cost. Even with higher labor costs for the non-automated operation assumed for the smaller width sheet, LSEM appears to be competitive with the most economical technology available in the industry today, twin roll casting. Since in FY 2011, LSEM technology for wider Mg sheet production has been further developed, it is advisable now to update the economic analysis to consider both better capital utilization and automation available at economies of scale.

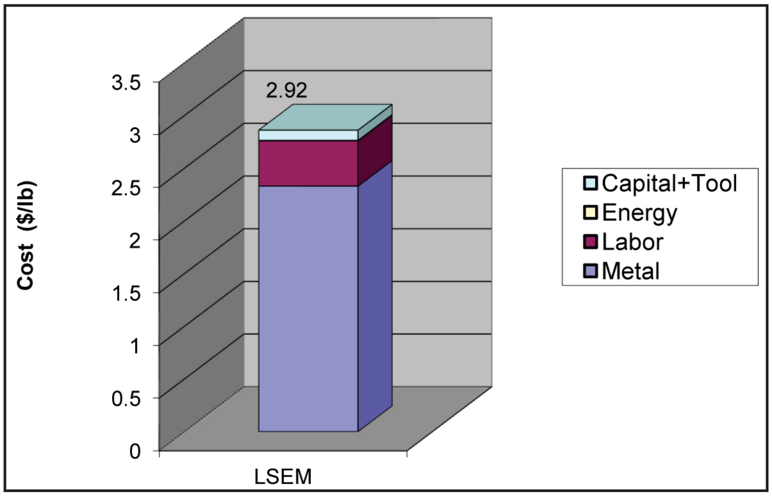

Figure 3. Estimated cost distribution for LSEM Mg sheet.

Conclusions

Determining a cost-effective, multiyear vehicle weight-reduction strategy requires development of a system-level automotive life cycle cost model that considers not only the interdependency of various components within a vehicle, but also vehicle ownership cost, including vehicle operation cost as well as the vehicle retail price. By examining several plausible scenarios, the baseline mid-size system level cost model developed contributes to determining how cost effectively multiyear LM weight reduction goals could be achieved. The LW potential of an average light-duty pickup truck may be less than that of passenger cars not only because of its body-on-frame design but also because of its towing and load carrying capability requirements. However, even using only near-term technology, total vehicle mass savings is estimated to be around 40% after taking into consideration secondary mass savings potential.

Presentations/Publications/Patents

Das, S. Battle Green. Am. Met. Mark. Oct. 2010, pp. 36–40.

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B. Safety Data and Analysis
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Contract No.: DE-AC02-05CH11231

Executive Summary

In FY2010, LBNL finalized a report comparing fatality risk per vehicle registration-year and casualty risk per police-reported crash by vehicle type and model using police-reported crash data from five states; the results from this analysis were presented at a workshop on the effect of vehicle mass and size on safety. Using an updated database of fatal crashes of MY2000 to MY2007 vehicles developed by National Highway Transportation Safety Administration (NHTSA), LBNL replicated NHTSA's findings on the effect of vehicle mass and footprint reduction on US fatality risk per vehicle mile traveled (VMT), using logistic regression analyses. LBNL also assessed the sensitivity of NHTSA's result to the data used and the variables included in the regression models. A final draft report was prepared for inclusion in the Notice of Proposed Rule Making (NPRM) for fuel economy/tailpipe greenhouse gas emission standards for 2017 to 2025 light-duty vehicles. The results of this collaborative effort with NHTSA were used to provide input assumptions concerning maximum mass reduction allowed by vehicle type in the NHTSA Volpe Model used to evaluate the costs and benefits of Corporate Average Fuel Economy (CAFÉ) stringency levels. Finally, LBNL began its analysis of fatality and casualty risk, both per VMT and per crash, using police-reported crash data from 13 states. The analysis will use similar methods as NHTSA's 2011 analysis to allow comparison of the effects of mass and footprint reduction on the two measures of risk, fatalities per VMT and casualties per crash.

Accomplishments

- Finalized a report comparing occupant risk by vehicle type and model using two measures of risk: fatality risk per vehicle registration-year and casualty risk per police-reported crash. Report also examined potential sources of bias in state crash data and summarizes the effect of accounting for driver age/gender, driving behavior, and crash location on casualty risk. (We summarized the results of this report in the FY10 Annual Report.)
- Participated in a NHTSA workshop on the effects of light-duty vehicle mass and size on vehicle safety on February 25, 2011.
- Provided formal comments on draft NHTSA report analyzing the effect of mass and footprint reduction on US fatality risk.
- Using a dataset prepared by NHTSA, replicated NHTSA's estimates of the effect of mass and footprint reduction on US fatality risk per ten billion VMT. Assessed the sensitivity of NHTSA's results to subsets of the data used and to changes in the variables included in the logistic regression models. Prepared a Final Draft report for inclusion in the docket for the NPRM for fuel economy/tailpipe greenhouse gas emission standards for 2017 to 2025 light-duty vehicles. The results of this collaborative effort with NHTSA were used to provide input assumptions concerning maximum mass reduction allowed by vehicle type in the NHTSA Volpe Model used to evaluate the costs and benefits of CAFE stringency levels.

- Using data on police-reported crashes from thirteen states, LBNL began to estimate the effect of mass and footprint reduction on casualty (fatality plus serious incapacitating injury) risk per crash. Analyzed the causes of differences based on whether risk is measured as fatalities per VMT or as casualties per crash. Assessed the sensitivity of the results to changes in the data used and to changes in the variables included in the logistic regression models. Began writing up results in a draft report.

Future Directions

- Finalize report on effect of mass and footprint reduction on casualty risk per crash.
- Respond to and/or incorporate comments from peer reviewers and public into final versions of two reports.

Introduction

NHTSA recently completed a logistic regression analysis updating its 2003 and 2010 studies of the relationship between vehicle mass and US fatality risk per VMT. The new study updates the previous analyses in several ways: updated Fatality Analysis Reporting System (FARS) data from 2002 to 2008 for MY00 to MY07 vehicles are used; induced exposure data from police reported crashes in several additional states are added; a new vehicle category for car-based crossover utility vehicles (CUVs) and minivans is created; crashes with other light-duty vehicles are divided into two groups based on the crash partner vehicle's weight, and a category for all other fatal crashes is added. Also, new control variables for new safety technologies and designs, such as electronic stability controls (ESC), side airbags, and methods to meet voluntary agreement to improve light truck compatibility with cars, are included. LBNL replicated the 2011 NHTSA analysis and examined the data in slightly different ways to get a deeper understanding of the relationship between vehicle weight/footprint and safety.

LBNL has begun analysis for a second report that compares the logistic regression results of the NHTSA analysis of US fatality risk per VMT with an analysis of 13-state casualty risk per crash. This analysis differs from the NHTSA analysis in two respects: first, it analyzes risk per crash using data on all police-reported crashes from thirteen states rather than risk per estimated VMT; and second, it analyzes casualty (fatality plus serious injury) risk as opposed to fatality risk. There are several good reasons to investigate the effect of mass and footprint reduction on casualty risk per crash. First, the data can be used to isolate the two components that influence whether a person is killed or seriously injured in a crash: how well a vehicle can be driven (based on its handling, acceleration, and braking capabilities) to avoid being involved in a serious crash (crash avoidance) and, once a serious crash has occurred, how well a vehicle protects its occupants from fatality or serious injury (crashworthiness). Use of the state crash data allows the separate analysis of the effect of mass or footprint reduction on crash frequency (the number of crashes per VMT) as well as crashworthiness (the number of fatalities or casualties per crash). Second, drawing both the outcomes (fatality or casualty) and the measure of exposure (police-reported crashes) from the same dataset minimizes any bias that might be introduced by drawing the outcomes or exposure from a different dataset. Third, extending the analysis to include serious or incapacitating injuries reduces the statistical uncertainty of analyzing just fatalities per crash. In addition, a serious incapacitating injury can be just as traumatic to the victim and family and as costly, from an economic perspective, as a fatality. Limiting the analysis to the risk of fatality, which is an extremely rare event, ignores the effect vehicle design may have on reducing the large number of incapacitating injuries that occur each year on the nation's roadways.

Casualty risk per crash is not necessarily a better metric than fatality risk per VMT; rather, it provides a different perspective in assessing the benefits or drawbacks of mass and footprint reduction on safety in vehicles.

Approach

For its analysis, NHTSA used FARS data on fatal crashes for MY00 to MY07 light-duty vehicles between 2002 and 2008. NHTSA used a subset of nonculpable vehicles in two-vehicle crashes from police-reported crash data from 13 states as a measure of induced exposure; these records provide distributions of on-road vehicles by vehicle year, make, and model; driver age and gender; and crash time and location (day vs. night, rural vs. urban counties, and high-speed roads). Each induced exposure record is then given a registered vehicle weighting factor, so that each induced exposure record represents a number of national vehicle registrations; the sum of the weighting factors equals the number of vehicles registered in the country. Each record is also given a VMT weighting factor, based on vehicle year, make/model, and age, using odometer data provided by R.L. Polk. The data can be used to estimate US fatality risk per registered vehicle or VMT.

NHTSA compiled a database of the following vehicle attributes, by model year, make and model: curb weight and footprint (wheelbase times track width), as well as the presence of all-wheel drive and automated braking systems. NHTSA added several new variables for new safety technologies and designs: ESC, four types of side airbags, and two methods to comply with the voluntary manufacturer agreement to better align light truck bumpers to make them more compatible with other types of vehicles.

To reflect changes in the vehicle mix since the 2003 study, NHTSA added a third vehicle category, car-based crossover utility vehicles (CUVs) and minivans. It also added two new crash types, for a total of nine: crashes with other light-duty vehicles are divided into two groups based on the crash partner vehicle's weight, and all other fatal crashes (involving more than two vehicles, etc.). The analysis involves running a logistic regression model with total crash fatalities as the dependent variable for each of the nine crash types and the three vehicle types, for a total of 27 regressions. Because all fatalities in the crash are used, the risks reflect societal risk rather than just the risk to the occupants of the case vehicle. The induced exposure cases are weighted by the number of vehicle registrations and the annual mileage so that the models are estimating the effect of changes in the control variables on US fatalities per VMT.

Rather than reporting coefficients for the variables of interest (curb weight and footprint) from a single regression model across all crash types, NHTSA reports a weighted average of the coefficients from the nine regression models run for each of the nine crash types. NHTSA uses a "baseline" distribution of fatalities across the crash types to represent the expected distribution of fatalities in the 2017 to 2025 timeframe of the new CAFE and GHG emission standards. Similar to the 2003 study, NHTSA derives the baseline fatalities from MY04-09 vehicles in crashes between 2004 and 2008. NHTSA then adjusts this baseline distribution downward to account for the assumption that all vehicles in the 2017-2025 timeframe will have ESC installed. The assumptions used for this adjustment are taken from a NHTSA analysis that found that ESC reduces fatal rollovers by 56% in cars and 74% in light trucks; fixed-object impacts by 47% in cars and 45% in light trucks; and other non-pedestrian crashes by 8% in both cars and light trucks. These assumptions treat crossover SUVs and minivans as light trucks rather than cars. This "post-ESC" distribution of fatalities by crash type is then multiplied by the regression coefficients for each crash type to create the weighted average effect of each control variable on risk.

For our analysis of fatality and casualty risk per crash, we used all of the police-reported crashes from thirteen states, both for the number of fatalities or casualties and for the measure of exposure, the total number of reported crashes. To the extent possible, we will use the same assumptions as in the NHTSA analysis, in many cases using the same SAS programs. However, it will be necessary to diverge from the NHTSA analysis in several respects. The most important of these is the need to control for differences among the states in what types of crashes are reported to police and included in the databases. Risks per crash vary substantially by state, because of either different definitions of "incapacitating", "serious", or "major" injuries, or different reporting requirements or reporting bias in certain states. For this reason it is crucial to account for state reporting requirements when analyzing risks per crash using state crash databases. Therefore, we replaced the singe variable for high-fatality states (HIFAT_ST) that NHTSA used for its analysis of US fatalities per VMT with 12 variables identifying each state except Florida for our analysis of fatality and casualty risks per crash.

Results and Discussion

The effect of mass reduction on risk that NHTSA calculated in 2011 is much smaller than in its 2003 and 2010 studies, particularly for cars. NHTSA attributes this reduction in the importance of mass reduction on safety to the phase-out of relatively light cars that had unusually high fatality risk, an observed improvement in how light, small cars are driven which reduces their tendency to be involved in serious crashes, and voluntary improvements made to light trucks to improve their compatibility with other vehicles. The 2011 NHTSA analysis finds that reducing vehicle footprint by one square foot while holding mass fixed would increase fatality risk per VMT by 1.89% in cars and 1.73% in CUVs and minivans (the effect on risk in light trucks is small and not statistically significant).

Rather than relying on the confidence intervals output by the logistic regression models, NHTSA estimates the uncertainty around its point estimates using a jack-knife technique that accounts for the sampling error in the FARS fatality and state crash data. These uncertainty estimates are larger than the confidence intervals output by the logistic regression models included in this report. As a result, in its report NHTSA finds that only the 1.44% increase in risk from mass reduction in lighter than average cars is statistically significant.

This report replicates the 2011 NHTSA analysis and examines the data in slightly different ways to get a deeper understanding of the relationship between vehicle weight/footprint and safety. We found that:

- NHTSA's (reasonable) assumption that all vehicles will have ESC installed by 2017 slightly increases the detrimental effect of mass reduction, but slightly decreases the detrimental effect of footprint reduction, on risk in cars, CUVs and minivans. This is because NHTSA projects ESC to substantially reduce the number of fatalities in rollovers and crashes with stationary objects and mass reduction reduces risk, while footprint reduction increases risk in these types of crashes, particularly in cars and CUVs/minivans.
- Many of the control variables NHTSA includes in its logistic regressions are statistically significant and have a large effect on fatality risk. For example, a car's mass could be reduced by 800 lbs. while adding ESC without increasing its fatality risk. Increasing the amount of vehicle travel on highways with speed limits greater than 55 miles per hour by 0.35% would result in the same increase in risk as reducing the mass of all cars by 100 lbs. While the effect of mass reduction may result in a statistically-significant increase in risk in certain cases, the increase is small and is overwhelmed by other known vehicle, driver, and crash factors.
- Vehicle mass and footprint are correlated, but only strongly for passenger cars. NHTSA includes both variables in their regression models, introducing the possibility that multi-collinearity may create biased results. When footprint is allowed to vary along with weight, mass reduction results in a larger increase in risk than when footprint is held constant. Similarly, when mass is allowed to vary along with footprint, footprint reduction results in larger increases in risk. To isolate the effect of mass reduction from footprint reduction on risk, NHTSA estimates the effect of mass reduction on risk for deciles of vehicles with similar footprint. Mass reduction does not consistently increase risk across all footprint deciles for any combination of vehicle type and crash type. Mass reduction increases risk in a majority of footprint deciles for 13 of the 27 crash and vehicle combinations, but few of these increases are statistically significant (the increases are statistically significant only for light-duty trucks in rollovers). On the other hand, mass reduction decreases risk in a majority of footprint deciles for 9 of the 27 crash and vehicle combinations. In some cases these risk reductions are large and statistically significant (such as in cars in rollovers and crashes with stationary objects; light-duty trucks in crashes with light and heavy cars; and CUVs and minivans in crashes with heavy cars).
- Logistic regression does not allow a statistic, such as the model R2 in a linear regression model, to measure how much variability in risk by vehicle model is explained by the control variables included in the model. Analysis of pseudo-R2 and R2 from a linear regression model suggests that much of the variance in risk remains unexplained, even after accounting for many important vehicle, driver, and crash variables. After accounting for all of the variables in NHTSA's logistic regression model, except for vehicle mass and footprint, we find that the correlation between fatality risk by vehicle model and mass is very low. There also is no significant correlation between the residual, unexplained risk and vehicle weight. These results indicate that, even after accounting for many vehicle, driver, and crash factors, the variance in risk by vehicle model is quite large and unrelated to vehicle weight.
- Changes in the data and variables NHTSA used in its regression models have only slight changes on NHTSA's results. Calculating risk as fatal crashes, rather than total fatalities, per VMT, as suggested by one of the independent reviewers of the previous NHTSA reports, increases the detrimental effect of mass reduction on risk in cars, but has no effect on mass reduction in light trucks or CUVs/minivans or on footprint reduction in any vehicle type. Calculating risk as total fatalities per induced exposure crash, rather than per VMT, reverses the sign of the effect of mass reductions on risk in cars and the lighter light trucks, with mass reduction leading to a reduction in risk in all vehicle types. Footprint reduction continues to result in large increases in risk per induced exposure crash for cars and CUVs/minivans, but leads to a large reduction in fatality risk per induced exposure crash for light trucks.
- Adding control variables for vehicle manufacturer tends to increase the effect of mass reduction but decrease the effect of footprint reduction on risk for cars and light trucks and makes mass reduction detrimental and footprint reduction slightly beneficial for CUVs/minivans.

- NHTSA included control variables for the calendar year in which the crash occurred to reflect reducing risk from changes to vehicles, driver behavior, and driving conditions over time. However, including these calendar year variables in the regression models appear to weaken the benefit of curtain side air bags in cars, CUVs, and minivans and compatibility measures and ESC in light trucks. These variables also appear to minimize the increased risk of SUVs and heavy-duty pickup trucks. Excluding these calendar year variables from the regression models increases the detrimental effect of mass reduction on risk in light trucks.

- Excluding crashes involving alcohol or drugs, or drivers with poor driving records, also increases the detrimental effect of mass reduction on risk, but reduces the detrimental effect of footprint reduction on risk. Including all-wheel-drive, sports, and police cars increases the effect of mass reduction, but reduces the effect of footprint reduction, on risk for cars; while including fullsize vans reduces the effect of mass reduction and increases the effect of footprint reduction on risk for light trucks.

- As mentioned above, for its baseline fatalities NHTSA assumes that all vehicles will have ESC installed by 2017, which will reduce the fraction of fatalities in rollovers and crashes with stationary objects, and thus will increase the detrimental overall effect of mass reduction, but decrease the detrimental overall effect of footprint reduction, on risk. However, other recent trends that are likely to continue through 2017 may also affect the distribution of crashes in that year. For example, side airbags in cars will likely reduce the fraction of fatalities in side-impact crashes, and better alignment of light truck bumpers with those of other vehicles appears to reduce the risk imposed on car occupants, at least in side impact crashes. However, it appears that mass reduction has less of a detrimental effect on risk when cars are struck in the side than when they are involved in frontal or rear-end crashes, so any future reduction in fatalities in car side impact crashes will not necessarily influence the effect of mass reduction on risk. And it is not clear whether full adoption of side airbags or compatibility measures for light trucks will reduce fatality risk when light-duty trucks, CUVs or minivans are struck in the side.

- Finally, in part because of high gas prices and the poor economy, households have been purchasing smaller and lighter vehicles in the last decade. For example, the explosion of CUVs appears to have led to a reduction in the market share of minivans, cars, and, in recent years (MY05 to MY07), SUVs and pickups. It is likely that these trends would continue, even in the absence of stronger CAFE and GHG emission standards. Any future market shifts from SUVs or pickups to cars or car-based CUVs and minivans will result in much larger reductions in fatality risk than the relatively small increases in risk expected from mass or footprint reduction. For example, we estimate that a large-scale shift in the market share of pickups and SUVs to CUVs, minivans, and cars will reduce overall fatalities by nearly 4%.

We compared the results from NHTSA's 2003, 2010, and 2011 analyses with the alternative model specifications examined in this report. NHTSA's 2011 analysis of a simultaneous reduction in mass and footprint (i.e. excluding a control variable for footprint in the regression model) results in a smaller increase in fatalities than in NHTSA's 2003 analysis, particularly for lighter cars (a 2.64% increase rather than a 4.39% increase) and light trucks (a 0.52% increase rather than a 2.90% increase). When footprint is held constant (i.e. when a control variable for footprint is included in the regression model), we find a similar reduction in additional fatalities for cars. However, holding footprint constant increases the effect of mass reduction slightly in light trucks (a 0.52% increase rather than a 0.17% increase in fatalities for lighter light trucks, and a 0.40% reduction rather than a 1.90% reduction in fatalities for the heavier light trucks). This small increase in light truck risk may be due to NHTSA analyzing crossover utility vehicles and minivans as a separate vehicle class, rather than as light trucks, in the 2011 analysis.

The results of the alternative model specifications examined in the LBNL 2011 report are, in all cases, lower than the results of the 2003 NHTSA report, and often lower than the results of the 2010 and 2011 analyses.

Conclusions

The 2011 NHTSA study and our report conclude that the effect of mass reduction on US fatality risk is small. Our report indicates that although the effect is sensitive to what variables and data are included in the regression analysis, in nearly all cases the effect is less, in some cases dramatically less, than reported in the 2003 NHTSA study. We also find that the effect on risk of other control variables, such as vehicle type, specific safety technologies, and crash conditions such as whether the crash occurred at night, in a rural county, or on a high-speed road, on risk is much larger than the effect of mass or footprint reduction on risk. Finally, we show that after accounting for the many vehicle, driver, and crash variables NHTSA used in its regression analyses, there remains a wide variation in risk by vehicle make and model and this variation is unrelated to vehicle mass.

It should be recognized that the results of the NHTSA study and our assessment of it are based on the relationship of vehicle mass and footprint on risk for recent vehicle designs (model year 2000 to 2007). These relationships may or may not continue into the future as manufacturers utilize new vehicle designs and incorporate new technologies, such as more extensive use of strong lightweight materials and specific safety technologies.

In FY12, LBNL will complete its analysis of fatality and casualty risk, both per VMT and per crash, using police-reported crash data from 13 states. To the extent possible, the analysis will use similar methods as NHTSA's 2011 analysis to allow comparison of the effects of mass and footprint reduction on the various measures of risk.

Presentations/Publications/Patents

Wenzel, T.P. Analysis of Casualty Risk per Police-Reported Crash for Model Year 2000 to 2004 Vehicles, using Crash Data from Five States. Final report prepared for EERE, US DOE, October, 2010. LBNL-4897E.

Wenzel, T.P. "Analyzing Casualty Risk using State Data on Police-Reported Crashes". Presentation at NHTSA's workshop on the effects of light-duty vehicle mass and size on vehicle safety, February 25, 2011.

Wenzel, T.P. Assessment of NHTSA's Report "Relationships Between Fatality Risk, Mass, and Footprint in Model Year 2000-2007 Passenger Cars and LTVs". Draft final report prepared for EERE, US DOE, September, 2011.

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