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Vehicle Lightweighting: 40% and 45% Weight Savings Analysis: Technical Cost Modeling for Vehicle Lightweighting

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EXECUTIVE SUMMARY

The U.S. Department of Energy's Vehicle Technologies Office Materials Area commissioned a study to model and assess manufacturing economics of alternative design and production strategies for a series of lightweight vehicle concepts. The strategic targets were a 40% and a 45% mass reduction relative to a standard North American midsize passenger sedan at an effective cost of $3.42 per pound (lb) saved.

The baseline vehicle was an average of several available vehicles in this class. Mass and cost breakdowns from several sources were used, including original equipment manufacturers' (OEMs') input through U.S. Department of Energy's Vehicle Technologies Office programs and public presentations, A2Mac1 LLC's teardown information, Lotus Engineering Limited and FEV, Inc. breakdowns in their respective lightweighting studies, and IBIS Associates, Inc.'s decades of experience in automotive lightweighting and materials substitution analyses. Information on lightweighting strategies in this analysis came from these same sources and the ongoing U.S. Department of Energy-funded Vehma International of America, Inc. Ford Motor Company Multi-Material Lightweight Prototype Vehicle Demonstration Project, the Aluminum Association Transportation Group, and many United States Council for Automotive Research's/United States Automotive Materials Partnership LLC lightweight materials programs.

This effort was undertaken with the goal of understanding the technical viability of 40 and 45% weight reduction, as well as the economic conditions required to meet the stated cost target. Although the target baseline was meant to be a mainstream vehicle, the analysis explored what is potentially possible with current and developmental lightweight strategies, without the constraints of previously invested capital, material supply relationships, platform commonality, market preferences of ever-increasing power and luxury, and other business pressures. The ultimate purpose of the analysis was to assess the technical viability of achieving aggressive weight reduction. This foundation dictates several important assumptions underlying the economic analysis that must be considered in context with the resulting cost comparisons:

- The full detail of the functionally equivalent, crashworthy designs is not available for many proposed advanced concepts. Therefore, the analysis results are speculative and most likely represent a best-possible-case scenario. Real-world application of these concepts may involve additional processing, performance, comfort, safety, and corrosion measures that are not fully understood at this time.

- Costing was performed in regard to fully implemented, high-volume processes, with automation and expected learning curve improvements, not as current developmental or low-volume introductory practices. Particularly in the case of carbon fiber structures, the ultimate analysis included the predictions of processing cost reductions provided by material suppliers currently engaged in automotive production. To provide a conservative estimate for the carbon case, the report also presents results with costs based on current production experience, under which the cost of weight savings is considerably beyond the stated target.

- Economic comparison was made in terms of the OEMs' direct manufacturing cost per vehicle. Most subsystems, therefore, included the margins of one or more supplier levels that would be included in the OEM purchase cost. Those systems manufactured by the OEM (such as engines and body structures) did include costs of tooling, production capital, energy, direct and indirect manufacturing labor, and material. Engineering; selling, general, and administrative costs; profit; and dealer margins were not included at this level.

The analysis indicates that a 37 to 45% reduction in a standard mid-sized vehicle is within reach if carbon fiber composite materials and manufacturing processes are available and if customers will accept a reduction in vehicle features and content, as demonstrated with the Multi-Materials and Carbon Fiber Composite – Intensive vehicle scenarios. These results, relative to the cost target, are shown in Figure ES-1. The analysis also led to the following conclusions:

- Achieving this level of mass reduction at the target cost of $3.42 /lb saved is only possible with significant improvements in processing technologies.
- Achieving 40% mass reduction will require a significant amount of advanced lightweighting, involving both moderate technical risk for high-volume production (i.e., magnesium) and high-technical-risk processes (i.e., automated and rapid-cycle-time composite forming). The price premium will remain very high until high-volume, low-cost carbon fiber is available.
  - In the case of carbon fiber composite molding, these advances will require automated high-rate, high-volume processing for material preparation, preforming, and molding. Processing must be on the order of 3-minute cycle times for complex automotive structures to reduce part-forming costs from the current $50/lb to the neighborhood of $5/lb.
  - Meeting the cost target will also require reducing the current carbon fiber price ($12.50/lb) more than 50% to $6/lb for the 40% goal and more than 65% to $4.20/lb for the 45% goal.
- Mass reduction of 45% or more will require not only extensive use of lightweight materials (such as carbon fiber and magnesium) but also next-generation electrical and interior systems. The goal could be more readily achieved if there were significant changes in market expectations of performance, comfort, and features.

Furthermore, these lightweighting technologies may potentially reduce performance in terms of OEM customer requirements such as noise, vibration, ride comfort, repairability, and safety. The full details of the functionally equivalent, crashworthy designs are not available for many proposed advanced concepts. Therefore, the analysis results are speculative and most likely represent a best possible case scenario. Real-world application of these concepts may involve additional processing, performance, comfort, safety, and corrosion measures that are not fully understood at this time

However, there are very real opportunities for significant mass reduction within acceptable costs of lightweighting. Continued exploration of lightweighting technologies will identify the best course forward in terms of optimizing the amount of mass reduced relative to the price premium.

- Through the use of established technologies, state-of-the-art designs, and some level of power and luxury downsizing (if accepted by the market), mass reduction on the order of 30% can be achieved with a moderate price premium and relatively low technical risk.

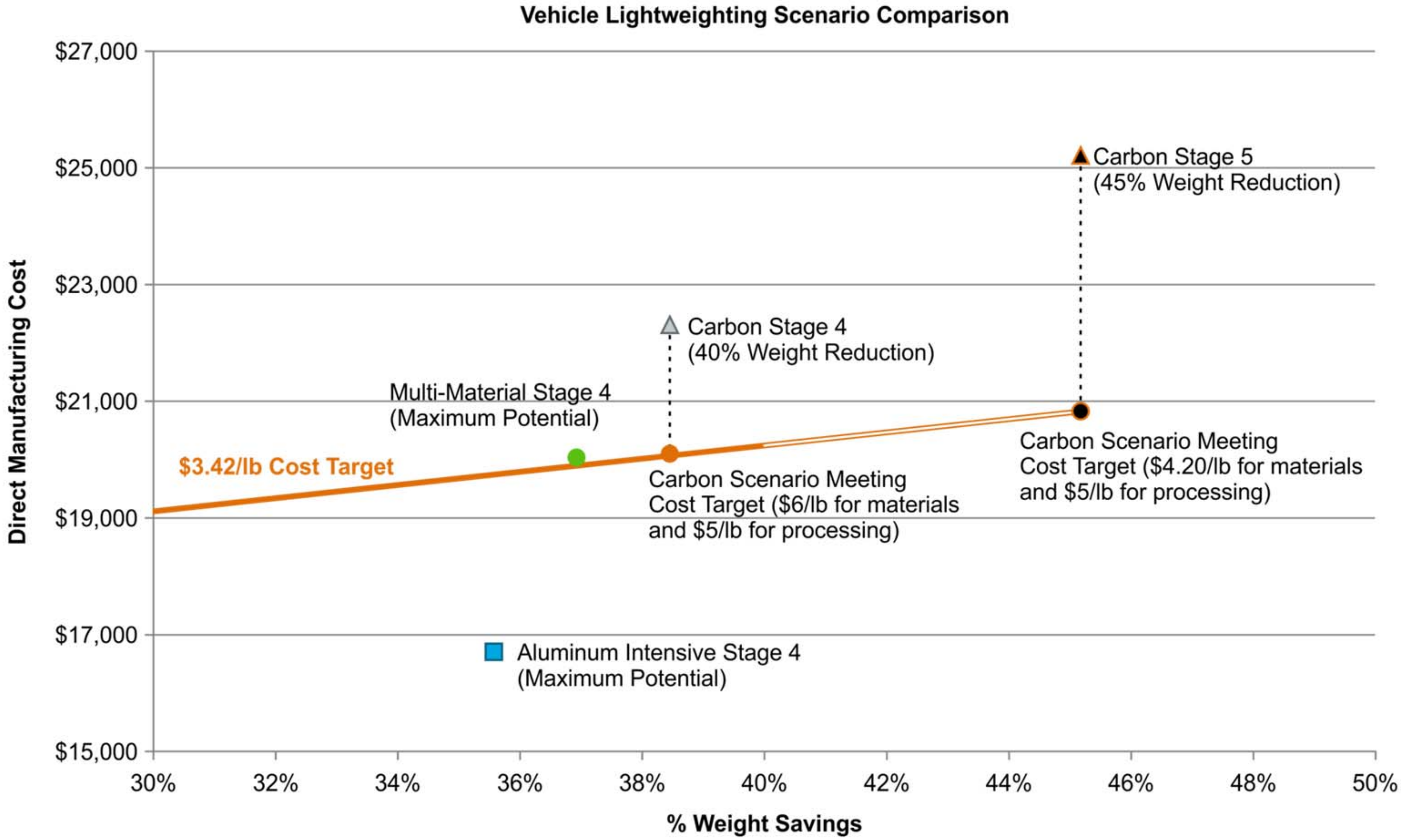

Figure ES-1. Costing results of advanced weight savings scenarios based on different material systems. Carbon scenarios assume an optimistic, projected, carbon composite processing cost of $5/lb and current carbon fiber price of $12.50/lb.

ACKNOWLEDGEMENTS

This report summarizes the results of the technical cost modeling exercise funded by the U.S. Department of Energy (DOE) to assess the manufacturing economics of alternative design and production strategies for a series of lightweight vehicle concepts to achieve a 40 and 45% mass reduction relative to a standard North American midsize passenger sedan at an effective cost of $3.42 /lb saved. The modeling and technical analysis was performed by IBIS Associates, Inc. drawing on their 25 years of experience with the automotive industry, including their manufacture and supply chain. IBIS used a systematic set of sub-tasks, each with quantifiable deliverables. Program managers and scientists of the DOE Office of Energy Efficiency and Renewable Energy's Vehicle Technologies Office provided guidance and feedback on the model results. The technical staff of Idaho National Laboratory and Energetics Incorporated also contributed to the analysis and technical content of this summary report. Particular recognition and thanks are due to the DOE-funded Vehma International of America, Inc./Ford Motor Company's Multi-Material Lightweight Vehicle program team for their expertise, experience, and system mass data.

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ACRONYMS

BIW	body in white
DOE	U.S. Department of Energy
EPA	Environmental Protection Agency
FEV	FEV, Inc.
Ford	Ford Motor Company
HVAC	heating, ventilating, and air conditioning
IBIS	IBIS Associates, Inc.
IP	instrument panel
MMLV	Multi-Material Lightweight Prototype Vehicle Demonstration
NHTSA	National Highway Traffic Safety Administration
OEM	original equipment manufacturer
USAMP	United States Automotive Materials Partnership LLC
USCAR	United States Council for Automotive Research
Vehma	Vehma International of America, Inc.
VTO	Vehicle Technologies Office

Vehicle Lightweighting: 40% and 45% Weight Savings Analysis: Technical Cost Modeling for Vehicle Lightweighting

1. INTRODUCTION

1.1 Technical Cost Modeling for Vehicle Lightweighting

Vehicle lightweighting is an integral part of the overall strategy needed to meet proposed fuel economy targets. Furthermore, cost pressures placed on automakers dictate that lightweighting options be vetted for cost effectiveness. As such, the U.S. Department of Energy (DOE) Vehicle Technologies Office (VTO) initiated a cost modeling effort to evaluate the cost effectiveness of various materials-based, weight-reduction technologies being considered or currently under development by the lightweighting program. The overall goal was to model and assess the manufacturing economics of alternative design and production strategies for a series of lightweight vehicle concepts to achieve a high level of overall mass reduction. The initial goal of this effort was to develop these concepts, achieving two tiers of overall vehicle mass reduction levels (40% and 45%) for a current baseline design. The second goal was to identify the material, processing, and economic requirements to achieve these reductions at an effective cost of $3.42 per pound (lb) saved.

These strategies consist of multiple combinations of lightweight structural materials, advanced manufacturing technologies, alternative subsystem technologies, and vehicle design approaches to reduce mass. The primary objective of this study was to conceptualize these strategies and to construct a detailed techno-economic simulation of the vehicle design and manufacturing costs, projecting the relative commercial and retail cost position of each concept.

IBIS Associates, Inc. (IBIS) conducted technical cost modeling for the current effort. IBIS's approach was developed based on decades of automotive and composite process cost analysis. IBIS has experience in modeling many of the target processes and this experience served as the starting platform for the cost-benchmarking effort discussed in this report.

Information on the current component designs for the baseline vehicle was derived from the DOE VTO materials program estimates and from the Multi-Material Lightweight Prototype Vehicle Demonstration (MMLV) Project conducted by the Vehma International of America, Inc. (referred to as Vehma) and Ford Motor Company (referred to as Ford) (co-funded by the DOE VTO Lightweight Materials Area). This information served as a starting point from which additional analysis was conducted. IBIS, Energetics Incorporated (Energetics), Idaho National Laboratory, and DOE team members have worked together throughout the project to review material, process issues, and determine the course of the analysis. Through application of this technical cost modeling tool, the program has determined quantitative, analytical answers to the following questions regarding lightweight vehicle economics and strategies:

- What are the projected costs for alternative lightweight concepts relative to program targets?
- What are the absolute and relative magnitudes of key cost drivers?
- How do the economics change with respect to the design, material pricing, production volume, and manufacturing scenarios?

1.2 This Document

Several vehicle concepts were developed to achieve a 40% mass reduction relative to a conventional midsize passenger car, followed by similar efforts to achieve a 45% mass reduction; those concepts were then assessed in terms of direct manufacturing cost. With the aim of understanding the feasibility of achieving the targeted weight savings at a cost premium of $3.42 /lb saved, these concepts were analyzed to understand the technology and economic requirements to meet this goal. The purpose of this document is to summarize these efforts.

Standard industry language, as shown in FEV Inc.'s report on lightweighting the Toyota Venza (FEV 2012) and by reports from the Aluminum Association (IBIS 2005) and Honda (Honda 2013), presents ultimate weight reduction results in dollars per mass saved. Indirect costs (e.g., original equipment manufacturer [OEM] overhead, engineering, design, testing, depreciation, etc.), which are used in calculation of the price seen by the consumer, are not incorporated into industry analyses. This standard industry practice was utilized in the technical cost model currently being discussed.

The cost target of $3.42 /lb saved was developed using a simple payback model, which calculated the weight reduction's effect on fuel consumption throughout the entire vehicle life. Based on multiple analyses reported in the literature, a 10% reduction in vehicle weight results in a 7% reduction in fuel consumption, assuming that the vehicle is re-optimized so all other vehicle performance remains constant (NHTSA 2010). It was assumed that each vehicle will travel 10,000 miles annually for a 15-year life. According to the Transportation Energy Databook, only one-third to one-half of all light vehicles remain in use after 15 years of age (ORNL 2014). An analysis of R. L. Polk & Company data performed by the National Highway Traffic Safety Association shows that vehicles that do survive to 15 years travel, on average, around 10,000 miles per year (NHTSA 2006). Finally, the fuel cost estimate used for the Annual Energy Outlook 2011 High Oil Price case projected fuel price data out to 2025 (EIA 2011).

The results provided the total gallons saved per pound over the 15-year vehicle lifetime. This cost savings was then discounted 7% each year because the vehicle owner must pay for the weight reduction up front, but must drive for 15 years to realize the complete payback (Stephens et al. 2014). The resulting estimate provides an upper boundary on acceptable price, and further reductions in the cost penalty make implementation of the technologies more likely. Further information on the derivation of the cost per pound saved target is provided in Appendix A.

While the cost target of $3.42 /lb saved was derived from consumer cost savings, the advanced material concepts evaluated were assessed in terms of direct manufacturing costs. The consumer cost is equivalent to the direct manufacturing costs to an OEM multiplied by a retail price equivalent, which is typically around 1.5 for the automotive industry. Because introduction of new technologies almost never comes with lower initial costs compared to conventional technology, to achieve volumes of scale and realize the benefits of new technologies, the OEMs often exclude the retail price equivalent multiplier when introducing new and innovative materials or technologies. This practice was followed in the work presented in this report, where the cost target of $3.42 pounds saved was derived based on consumer savings over the vehicle lifetime and then used in the cost-effectiveness comparison of the advanced materials concepts.

1.3 Data Sources

Data were collected from multiple sources for the baseline and lightweighting scenarios explored in this analysis. The primary sources are listed as follows:

- DOE target definition (DOE 2013)
- Direct interviews with OEM and supplier engineers and designers
- Published vehicle specification data (Edmunds.com 2013, Wards Auto 2013)
- IBIS databases and previous cost analyses (IBIS 2014)
- Vehma/Ford Fusion breakdown data (Skszek and Conklin 2013)
- Vehma/Ford MMLV Mach 1 and 2 data (Skszek and Zaluzec 2012)

- Lotus Phase 1 lightweighting (Lotus Engineering Inc. 2010)
- FEV, Inc. light-duty mass reduction cost analysis (FEV 2012)
- Aluminum Association Body-in-White (BIW) studies (IBIS 2008, IBIS 2005, EDAG 2013)
- Honda's study and report on a National Highway Traffic Safety Association study (Honda 20103)
- United States Council for Automotive Research (USCAR) United States Automotive Materials Partnership LLC's Automotive Composites Consortium lightweighting studies (USAMP 2011, USAMP 2006, VTO 2012).

The Vehma/Ford MMLV project team supported development of lightweighting scenarios by providing both vehicle system mass data from the project and expert guidance.

IBIS leveraged more than two decades of experience assessing direct manufacturing costs of new technologies and performing competitive economic and performance assessments of advanced materials and manufacturing practices for OEMs, materials suppliers, and technology development agencies. Furthermore, IBIS has lifecycle cost analysis experience for alternative automotive materials and vehicle designs on behalf of the American Iron and Steel Institute, the Aluminum Association, the DOE FreedomCar Program, the Partnership for a New Generation of Vehicles, USCAR, and the big three U.S. light-duty automobile manufacturers and Tier 1 suppliers; this experience was leveraged to characterize vehicle production costs.

2. BASELINE DESCRIPTION

The focus of the current lightweighting analysis program is a standard North American midsize passenger sedan. Five example vehicles of this class are shown in Figure 1: Chevrolet Malibu, Buick LaCrosse, Chrysler 200, Ford Fusion, and Honda Accord.


(a)

(b)

(c)

(d)

(e)

Figure 1. (a) Chevrolet Malibu, (b) Buick LaCrosse, (c) Chrysler 200, (d) Ford Fusion, and (e) Honda Accord.

The baseline is intended to be a generic representation of this vehicle class and is based on an amalgam of the specifications of these cars, with a target mass matching the Environmental Protection Agency (EPA) test mass for a 2012 midsize vehicle. This mass was 3,603 lb, which includes 300 lb of added occupant/cargo equivalent on top of a 3,303-lb curb weight.

Most of the vehicles in this class range from $20,000 to $25,000 manufacturer's suggested retail price, with a manufactured cost of $13,300 to $16,600 based on a 1.5 retail price equivalent for direct manufacturing cost, exclusive of engineering, warranty, and other SG&A factors.

Manufacturing costs are assumed to be those incurred by the OEM under current North American production practices. Body structures, engines, and assembly operations are direct manufacturing costs incurred at the OEM, while other systems are represented as purchased components and subsystems from Tier 2 and 3 suppliers. Furthermore, high-volume production (i.e., 200,000+/year) is assumed for a baseline model and even higher volumes for many cross-platform systems.

Descriptive information on current component designs for the baseline vehicle was provided by DOE and the Vehma/Ford MMLV team (DOE 2013). This information served as a starting point from which to collect additional data and develop a generic midsize vehicle description from available public information.

Table 1 provides a baseline summary that is broken down by subsystem. A detailed description of the subsystem constituents and costs are included in Appendix B.

Table 1. Subsystem breakdown, mass in pounds.

	Midsize Baseline 2013 Internal Combustion Engine Midsize Steel Unibody		
System		Mass (lb)	Cost ($)
Table 1			
Powertrain	**Baseline**	**998**	**$6,119**
	Engine	345	$3,162
	Energy Storage	33	$74
	Fuel System	165	$364
	Transmission	195	$1,199
	Driveshaft/Axle	55	$177
	Differential	24	$132
	Cradle	62	$107
	Thermal Management	33	$150
	Exhaust System	50	$230
	Oil and Grease	9	$81
	Powertrain Electronics	22	$400
	Emission Control Electronics	4	$43
Body		**1,006**	**$2,823**
	BIW	717	$1,287
	Closures	134	$230
	Front/Rear Bumpers	20	$126
	Glazing	81	$250
	Paint	24	$450
	Exterior Trim	8	$144
	Body Hardware	18	$312
	Body Sealers and Deadeners	4	$24

System	Midsize Baseline 2013 Internal Combustion Engine Midsize Steel Unibody	Mass (lb)	Cost ($)
Table 1			
Chassis		**663**	**$1,807**
	Suspension	270	$578
	Braking System	163	$406
	Wheels and Tires	180	$317
	Steering System	49	$506
Interior		**473**	**$3,370**
	Instrument Panel	84	$900
	Trim and Insulation	119	$390
	Door Modules	50	$300
	Seating and Restraints	172	$1,330
	Heating, Ventilation, and Air Conditioning (HVAC)	48	$450
Electrical		**112**	**$1,000**
	Interior Electrical	57	$400
	Chassis Electrical	33	$400
	Exterior Electrical	22	$200
Final Assembly		**53**	**$605**
TOTAL		**3,305**	**$15,724**

3. MASS REDUCTION TECHNOLOGIES

3.1 Technologies Considered in this Study

In addition to the myriad of materials, forming processes, and assembly technologies that are part of conventional vehicle manufacturing, many novel production technologies must be employed for the use of alternative materials, which are necessary to achieve the program's aggressive lightweighting goals. The following list outlines the technologies primarily featured in the most likely reduced-mass vehicle scenarios. This list is by no means exhaustive; it is expected to grow as the team identifies additional concepts and explores them with the cost model analysis in successive phases of this effort. Following the list, this section provides the projected levels of weight savings and costs of employing these approaches as identified from the source material.

- **Body**
  - Ultra-high-strength steel stampings
  - Aluminum stampings, extrusions, and aluminum high-pressure vacuum castings
  - Magnesium castings and stampings
  - Carbon fiber layup (tape and roving, automated), sheet molding compound, and injection molding
  - Chemically toughened glass and polycarbonate
  - Press-hardened boron steel stampings
- **Powertrain**
  - Magnesium and aluminum high-pressure vacuum die casting
  - Carbon fiber filament winding

- Increased power density from advanced engine design

- **Chassis**
  - Aluminum castings, forgings, and extrusions
  - Carbon fiber wheels
- **Assembly**
  - Adhesive bonding
  - Self-piercing rivets
  - Friction stir welding.

3.1.1 Developmental Status

Many of the technologies under consideration for the lightweight concepts in this study have not yet been deployed for the high-production volumes associated with world-class automotive manufacturing. Where possible, the manufacturing costs for these technologies are assessed because they would likely exist in such an environment, with associated levels of automation, production rate, and economies of scale.

3.2 Source Data on Lightweighting Technologies

The following section highlights mass savings data from the two most robust total vehicle lightweighting exercises with published material found to date: the EPA-sponsored FEV report (FEV 2012) and the DOE-sponsored Vehma/Ford MMLV program (Skszek and Conklin 2013; Skszek and Zaluzec 2012) currently in progress.

3.2.1 Body

3.2.1.1 Body-in-White and Panels. The BIW is the largest monolithic component of a vehicle and serves as the structural platform to which all other systems are attached. Each of the following BIW concepts has served as the foundation for respective vehicle lightweighting programs from which data were drawn for the present study.

3.2.1.1.1 High-strength steel body-in-white (Lotus/FEV, American Iron and Steel Institute) – An optimized steel BIW concept involving extensive use of advanced high-strength and ultra-high-strength steels was developed in a lightweighting study commissioned by the International Council on Clean Transportation and performed by Lotus Engineering (Lotus Engineering Inc. 2010); Figure 2 depicts the design material map for this concept. In this work, a production version 2009 Toyota Venza served as the baseline for mass reduction efforts, with the goal of producing a design with 20% savings of non-powertrain mass. The EPA then contracted with FEV for Phase II of this effort (FEV 2012) to assess and evaluate the Phase I Lotus designs, conduct validation exercises, propose additional mass reduction options for a 20% total vehicle mass reduction, and assess the differential cost impact of the lightweighting strategies. A summary of the FEV results is included in Appendix C.

The resulting Lotus/FEV designs reported in the Phase II effort yielded a 14% mass savings for the BIW structure and a 13% savings for the closure panels.

3.2.1.1.2 Aluminum-intensive (Aluminum Association) – There are many commercialized examples of individual components and substructures making use of aluminum to reduce weight, as well as a few low-volume, high-end vehicle examples made entirely of aluminum structures (IBIS 2008, IBIS 2005). The most important instance is the upcoming aluminum-bodied 2015 Ford F-150. The most useful data for the current analysis come from the Aluminum Association, which has conducted several studies and concept demonstrations of entirely aluminum body structures for high-volume standard passenger vehicles, including a recent analysis of an aluminum treatment of the same 2009 Toyota Venza addressed in the Lotus/FEV programs (see Figure 3; EDAG 2013). These analyses yielded weight reductions ranging from 35 to 47% and typically used stamped sheet, extruded rails and beams, and four to six moderately complex castings.

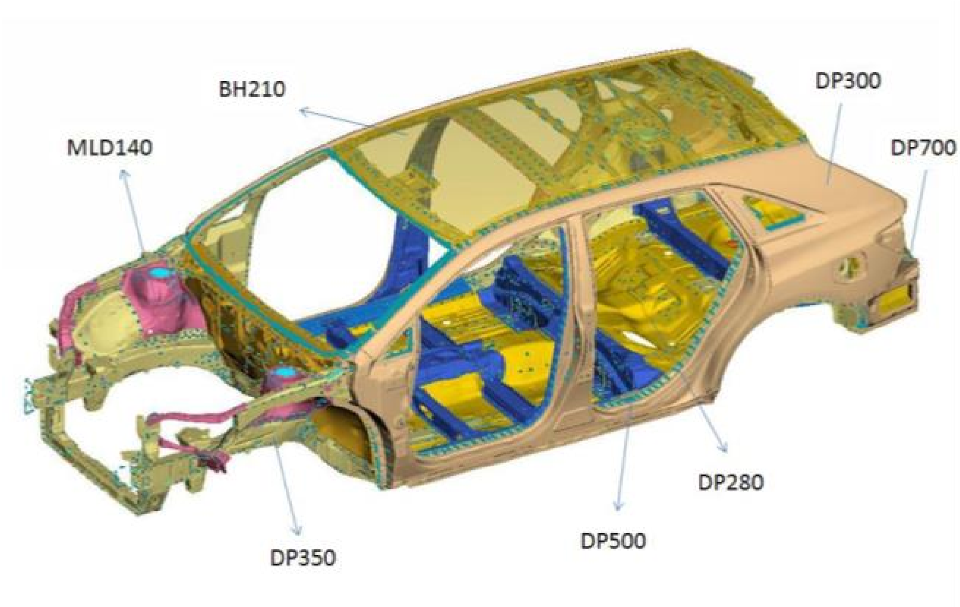

Figure 2. Lotus Engineering BIW design material map for Toyota Venza.

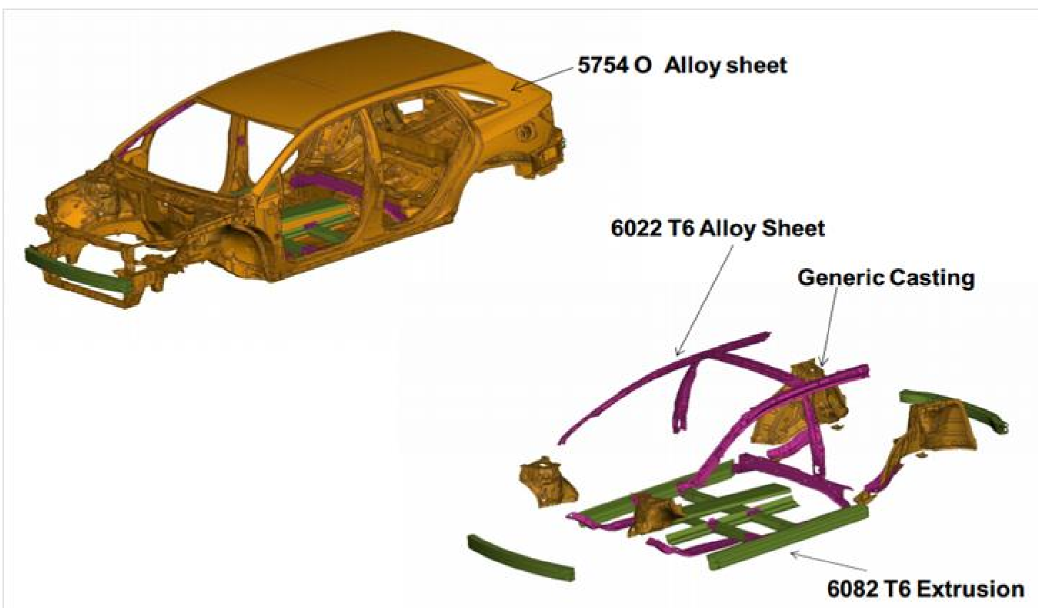

Figure 3. Aluminum Association BIW design for the Toyota Venza.

3.2.1.1.3 Multi-Material Lightweight Prototype Vehicle Demonstration (Ford/Vehma – Mach I and Mach II) – The MMLV Mach I BIW concept developed by Ford and Vehma (see Figure 4) targeted 40% vehicle mass reduction (Skszek and Conklin 2013, Skszek and Zaluzec 2012). Results indicated a potential 24% mass reduction through the application of aluminum high-pressure vacuum die castings, aluminum extrusions, aluminum stampings, boron press-hardened steel, and conventional steel stampings. The BIW baseline mass was reduced from 717 to 550 lb. The large high-pressure vacuum die castings were used for hinge pillar reinforcements, spring bucket, kick-down rail, and mid rail, resulting in both weight savings and significant part count reduction.

The Mach I panel and closure set achieved a 30% mass reduction through use of aluminum panels, aluminum extrusions, magnesium castings, and boron steel stampings.

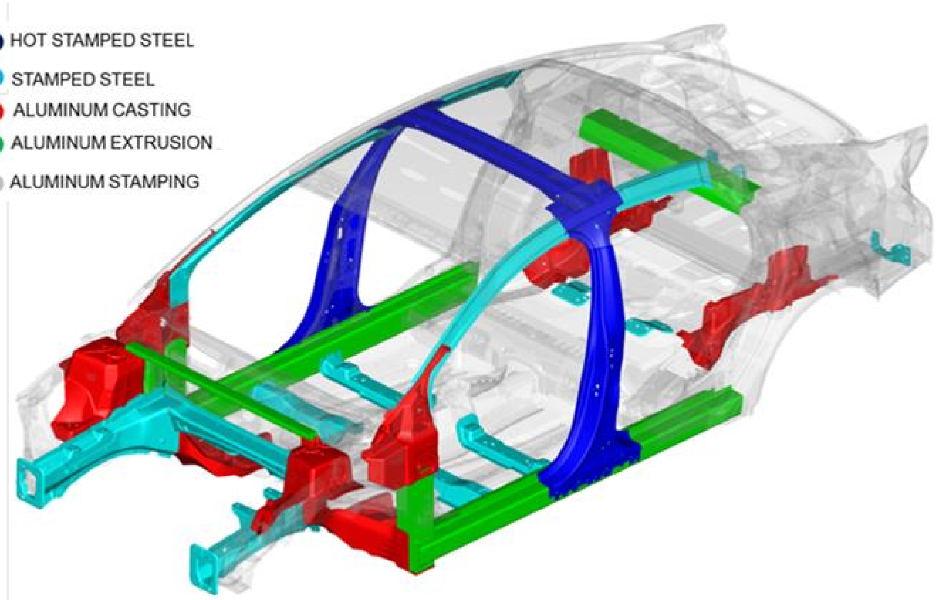

Figure 4. Vehma/Ford MMLV Mach I BIW.

The Mach II design concept (targeting a 45% vehicle mass reduction; see Figure 5) further reduces BIW mass by making extensive use of carbon fiber composites along with aluminum, ultra-high-strength steel, and press-hardened boron steel for a 44% mass reduction. Closure panels use magnesium sheet, extrusions, and castings along with aluminum sheet and boron steel intrusion beams for a 46% mass savings.

3.2.1.1.4 Carbon fiber composite BIW (USCAR and IBIS) – A high-volume production, fully carbon fiber composite body structure is a speculative concept at the present time, with the only examples of such a structure being confined to extremely low-volume custom or exotic supercars. The 2014 BMW i3 (see Figure 6) uses a carbon fiber passenger compartment, but still relies on aluminum for the substructure and skins. However, the BMW effort is informative as to how fully composite structures may be produced in the future: by employing highly automated preforming, layup, demolding, and transfer operations to reduce the cycle times and high labor content of current molding practices.

Numerous fiber and resin suppliers have been developing high-speed production processes for carbon fiber such as high-pressure resin transfer molding and sheet molding compound that seek to bring the 50% mass benefit of carbon fiber to high-volume components. USCAR’s Automotive Composites Consortium and IBIS, jointly and separately, have assessed components, structures, and processes in automotive production scenarios to explore the economic and performance potential of the current and projected carbon fiber technologies (IBIS 2014, USAMP 2011). Specifically, Focal Projects III and IV explored carbon fiber injection/compression approaches to BIW and seat structures, resulting in 60% and 58% projected mass reduction (Warren 2013).

3.2.1.2 Other Body

3.2.1.2.1 Bumpers – The FEV-optimized steel design described a high-strength steel front bumper with a mass reduction of 8% (FEV 2012). The Vehma/Ford MMLV Mach I uses extruded and stamped aluminum front and rear bumper beams, reducing mass by 32% (Szkszek and Conklin 2013). A further reduced Mach II design, also employing extruded and stamped aluminum, reported a 46% weight savings. The extruded aluminum front bumper from the Aluminum Association study reduced weight by 45%.

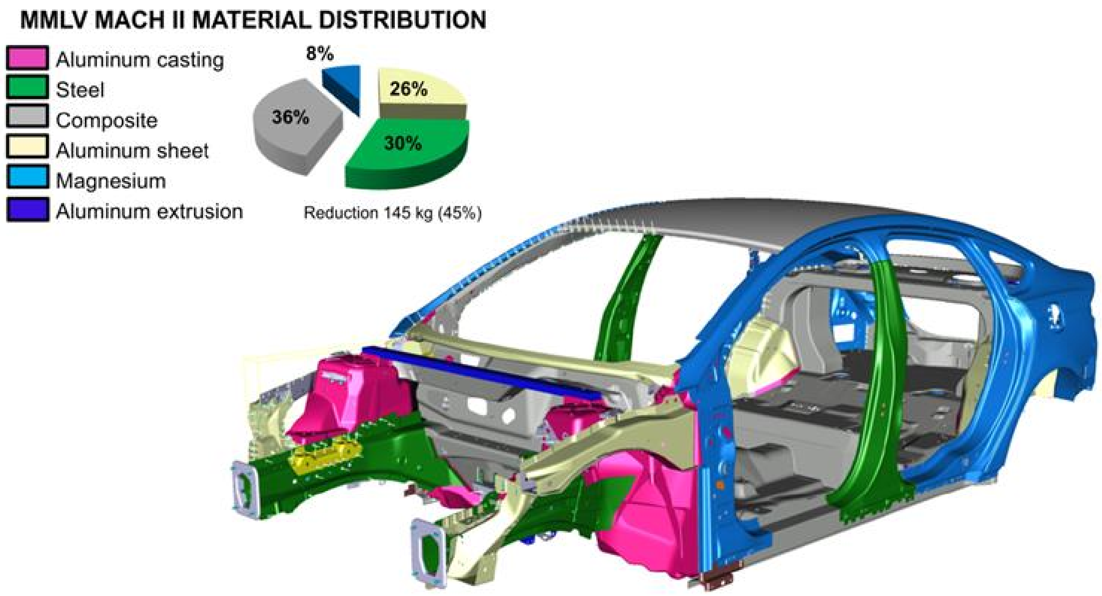

Figure 5. Ford/Vehma MMLV Mach II BIW.

Figure 6. BMW i3 passenger compartment and rolling chassis.

3.2.1.2.2 Body hardware – FEV proposed a 5.7-lb mass reduction at an increased cost of $24 through material reduction through use of Trexell's MuCell and PolyOne gas assist injection molding processes for select exterior hardware components such as side mirrors and ornamentation (FEV 2012).

3.2.1.2.3 Glazing – The FEV study proposed a 9.2-lb mass reduction at an increased cost of $14 through reduction of the inner-layer thickness of the laminated glass windshield and reduction of overall thickness for the side and backlight windows (FEV 2012).

The Vehma/Ford MMLV Mach I concept utilized a combination of lightweight alternatives such as polycarbonate for the rear window and chemically toughened glass using soda lime hybrid laminate construction for the windshield and side windows to achieve a predicted 35% weight savings (Skszek and Conklin 2013).

3.2.1.2.4 Exterior trim – The Vehma/Ford MMLV Mach I concept used MuCell and chemically foamed plastics to reduce weight by 15% for the plastic trim components, similar to proposals in the FEV program (Skszek and Conklin 2013).

3.2.2 Powertrain

3.2.2.1 Engine Lightweight Materials and Downsizing. FEV made a robust study of potential weight savings approaches to 20 different engine subsystems (FEV 2012). The approaches resulted in 66 lb saved, while simultaneously reducing cost through engine downsizing. The details can be found in the FEV report.

The Vehma/Ford MMLV program powertrain design involved both lightweight materials and a downsized powerplant. The already lightweight 1.6-liter (L) I-4 gasoline turbo direct injection engine technology was replaced with a smaller 1.0 L I3 cylinder gasoline turbo direct injection engine using both aluminum and compacted graphitic iron (Skszek and Conklin 2013). To further reduce mass to meet the Mach II goals, the turbocharger and associated components were removed.

3.2.2.2 Fuel Storage. The high-density polyethylene fuel tank in the FEV study saved 27.9 lb and $4 per vehicle (FEV 2012).

3.2.2.3 Transmission. FEV proposed replacement of the baseline aluminum transmission housing with magnesium and the carrier gear system with a high-strength steel alloy, reducing mass by 41.6 lb and increasing cost by $114 (FEV 2012).

In the Vehma/Ford MMLV Mach I transmission, steel and cast iron were replaced with aluminum and aluminum was replaced with cast magnesium, saving an additional 24.2 lb (Skszek and Conklin 2013).

3.2.2.4 Driveshaft and Axle. The FEV design reduced the mass of the driveline system by using scalloped drive hubs, hollowing the driveshaft to reduce material. Plastic and aluminum were also used for the bearing carriers. The combination was projected to save 3.3 lb with a cost reduction of $3 (FEV 2012).

3.2.2.5 Cradle. The Vehma/Ford MMLV Mach I vehicle employed hollow aluminum extrusions and castings, resulting in a 50% weight savings over the baseline steel front and rear cradles (Skszek and Conklin 2013).

3.2.2.6 Exhaust. FEV proposed using the Mubea tailor rolled tubing process for tubes, exhaust gas treatment housing, and muffler. The combined projected savings was 16.5 lb with a cost reduction of $2 (FEV 2012).

3.2.3 Chassis

3.2.3.1 Suspension. The FEV study performed an extensive exploration of the suspension subsystems and components to reduce mass by 110 lb through use of aluminum, magnesium, steel tubing, polymers, and fastener reduction (FEV 2012). Several of the mass-reduction ideas investigated are provided in Table 2.

Table 2. FEV suspension system mass reduction approach.

System	Subsystem	Sub-Subsystem	System Sub-Subsystem Description	Mass Reduction Ideas Selected for Detail Evaluation
04	01	00	Front suspension subsystem	
04	01	00	Ball joint fasteners	Use rivet ball joints and eliminate fasteners
04	01	00	Control arm mounting shaft	Use aluminum forging
04	01	00	Control arms	Combination; replace from Passat and change to aluminum welded fabrication
04	01	00	Front stabilizer link assemblies	Make right- and left-hand front stabilizer link assemblies out of forged aluminum
04	01	00	Knuckles	Use normalized cast aluninum
04	01	00	Stabilizer bar	Combination; replace from Passat and change to steel tubing (hollow)
04	01	00	Stabilizer bar mounts	Make stabilizer bar mounts out of cast magnesium
04	01	00	Stabilizer bar mount bushings	Make stabilizer bushings out of nylon
04	01	00	Strut modules and wheel carriers	Use lightweight suspension composite strut module with integrated wheel carrier
04	01	00	Balljoints	Replace from 2005 Volkswagon Passat (mass: 1.97–1.32; cost: 0.93)

In the Vehma/Ford MMLV Mach I design concept, cast and extruded aluminum control arms, linkages, and shock towers reduced mass by 66 lb relative to the baseline (Skszek and Conklin 2013). In addition, hollow shot peened coil springs reduced the weight. The Mach II design involves using composite coil springs, carbon fiber stabilizer bars, and reduced mass knuckles and calipers to realize an overall vehicle mass reduction.

3.2.3.2 Brakes. The FEV effort reduced braking system mass through use of aluminum slotted and cross-drilled rotors, aluminum calipers and mounting brackets, and system downsizing. The result was a 70-lb reduction and a reported savings of $170 (FEV 2012). The Vehma/Ford MMLV Mach I design employed aluminum brake rotors, thermally sprayed with stainless steel for wear resistance (Skszek and Conklin 2013).

3.2.3.3 Wheels and Tires. Taller, narrow tires (155/70R19) and aluminum wheels (19-in. x 5-in.) reduced mass by more than 20% compared to the baseline steel wheels for the Vehma/Ford MMLV Mach I design (Skszek and Conklin 2013). The Mach II design in progress is considering carbon fiber wheels for an even more extreme mass savings, but current prices are well beyond VTO’s target cost.

3.2.3.4 Steering. The FEV concept redesigned the steering system to save 4.0 lb through parts consolidation, design optimization, and a polymer steering wheel (FEV 2012).

3.2.4 Interior

3.2.4.1 Instrument Panel. The FEV design used a magnesium beam and the Trexell Mucell microcellular foam injection molding process for the instrument panel and center stack moldings to reduce mass by 13.9 lb (FEV 2012).

The Vehma/Ford MMLV Mach I concept used a carbon fiber instrument panel beam to reduce the number of components and to save weight.

3.2.4.2 Trim. The Vehma/Ford MMLV Mach I design used MuCell and chemically foamed plastics to reduce weight by 15% for the plastic trim components (Skszek and Conklin 2013).

3.2.4.3 Seating and Restraints. FEV examined the use of thixomolded magnesium, MuCell, PolyOne, and structural foam to achieve a projected mass savings of 53 lb per vehicle (FEV 2012).

The Vehma/Ford MMLV Mach I design used carbon fiber seat backs and redesigned cushions, foam and trim, mechanisms, and motors to reduce mass by 44 lb per vehicle (Skszek and Conklin 2013).

4. VEHICLE CONCEPT SCENARIOS – 40% WEIGHT SAVINGS TARGET

4.1 Scenario Descriptions

Countless variations of approaches to vehicle lightweighting exist. To provide a structure for examining these approaches, four different scenarios were addressed in the concept model, with each built around a common body structure architecture.

4.1.1 Optimized Steel

The optimized steel scenario was built around the body structure developed by Lotus Engineering and refined by FEV/EDAG for the EPA study (FEV 2012). The body structure utilized high-strength steels and part count reduction to reduce mass. Additionally, FEV-projected savings for the body, powertrain, chassis, interior, and electrical system were included in this optimized steel scenario.

4.1.2 Aluminum-Intensive

The aluminum-intensive scenario was assessed based on application of the mass savings of a nearly all-aluminum body structure to the baseline vehicle (IBIS 2008, IBIS 2005, USAMP 2011). In addition to the BIW, the cradle, bumpers, and wheels were aluminum. Secondary powertrain and chassis weight savings were also taken into account.

4.1.3 Multi-Material

The multi-material scenario applied the savings for each of the mass reduction technologies known to have been applied in the Vehma/Ford MMLV Mach 1 (Skszek and Conklin 2013, Skszek and Zaluzec 2012).

4.1.4 Carbon Fiber Composite-Intensive

The carbon fiber composite-intensive scenario started with the multi-material scenario and applied carbon fiber for all body, panels, bumpers, and suspension components. This scenario is less robust in terms of providing a functionally equivalent design to a mass-produced midsize passenger vehicle than the other scenarios. However, it potentially offers the greatest level of weight savings, making its assessment important in evaluating the feasibility of achieving DOE’s most aggressive mass reduction targets (USAMP 2011, VTO 2012, Warren 2013).

5. LIGHTWEIGHTING STAGES – 40% WEIGHT SAVINGS TARGET

As previously discussed, the technical cost modeling analysis conducted during this study addressed two targets for specific overall vehicle mass reduction (i.e., 40% and 45%) compared to the baseline vehicle. In addition to these weight reduction targets, the study used the available data and analytical tools to look at intermediate steps to understand the incremental costs of additional weight savings along the paths to these targets. While traditional vehicle lightweighting designs start with weight targets in mind and focus on a holistic redesign of the vehicle, this study used a stage progression for performing this exercise. This methodology was used as a way to better assimilate all data from several independent studies previously performed to explicitly quantify (1) weight savings contribution of specific lightweighting strategies and (2) the associated costs of each, both within the framework of an aggregate vehicle concept. It is not intended to suggest that the intermediate "stages" would be a design endpoint for a concept or represent the actual sequence of technology adoption by manufacturers.

- Baseline

  This is the previously defined base case study, mass, and cost list as described Section 2 and detailed in Table 2 of this document.

- Stage 1 – Body Structure

  For each scenario built around a body structure material system, a Stage 1 analysis looked at the mass and cost impact of replacing only the body structure alternatives (i.e., BIW, panels, and bumpers), while the rest of the vehicle remained the same as baseline.

- Stage 2 – Powertrain and Chassis

  In Stage 2, the powertrain and chassis components were replaced with lightweight systems from the respective lightweighting program (e.g., the optimized steel scenario was derived from the EPA/FEV and Ford/Vehma MMLV work). No powertrain or chassis mass reduction was associated with the aluminum-intensive or carbon fiber composite-intensive scenario data sources.

- Stage 3 – Other Body, Interior, and Auxiliary Systems

  Stage 3 extended the lightweighting to all the remaining systems in the respective scenarios.

- Stage 4 – "Best-in-Class" Subsystem and Component Concepts from Each Scenario

  In Stage 4, the best mass reduction data available from the two detailed vehicle lightweighting programs and other available data were applied to each of the scenarios, including the aluminum-intensive and carbon fiber composite-intensive. In the multi-material scenario, the Mach II MMLV body replaced the Mach I body. In addition, where appropriate, powertrain and chassis systems were downsized according to the reduced overall vehicle mass to maintain the same overall vehicle performance (e.g., acceleration).

5.1 Incremental Mass Savings

Figures 7 through 10 highlight the incremental mass reduction between each of the four weight-reduction stages for the multi-material scenario. First, from baseline to Stage 1, the BIW and panel mass were reduced (Figure 7). In moving from Stage 1 to Stage 2, the powertrain and chassis weight savings strategies were applied (Figure 8). Stage 3 applied reduced-weight interior systems such as instrument panel, trim, door modules, and seating (Figure 9). In Stage 4, the concept from data collection offering the greatest weight reduction for each system is applied and additional secondary mass reductions are taken into account (Figure 10). Figure 11 provides a summation of the mass breakdown of all scenarios through each stage. Table 3 provides the total mass and weight reduction relative to the baseline for each stage.

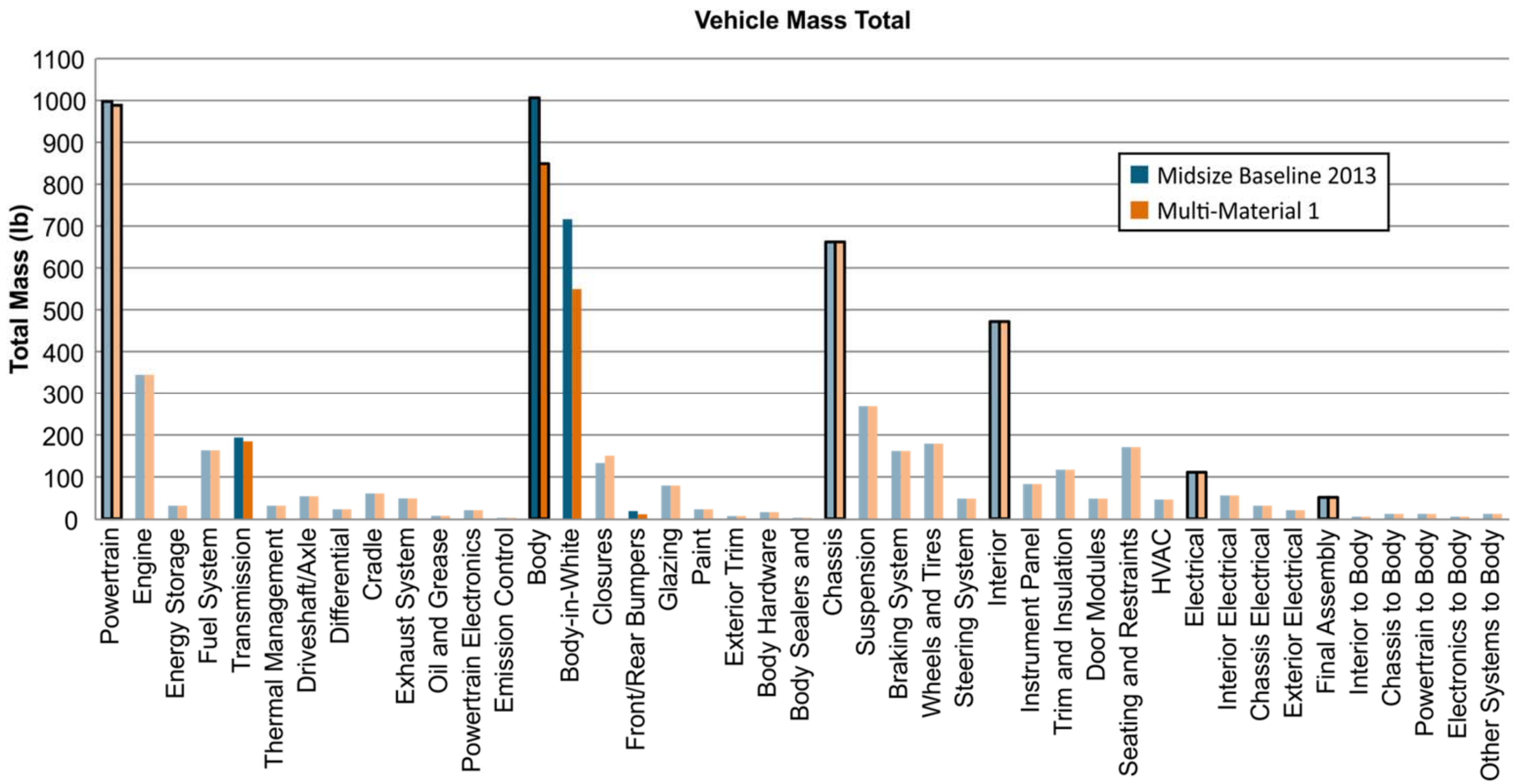

Figure 7. Baseline to Stage 1 mass reduction under the multi-material scenario focuses on weight reduction in the body system. Systems and subsystems that have NO weight changes between the baseline and Stage 1 are presented in muted colors.

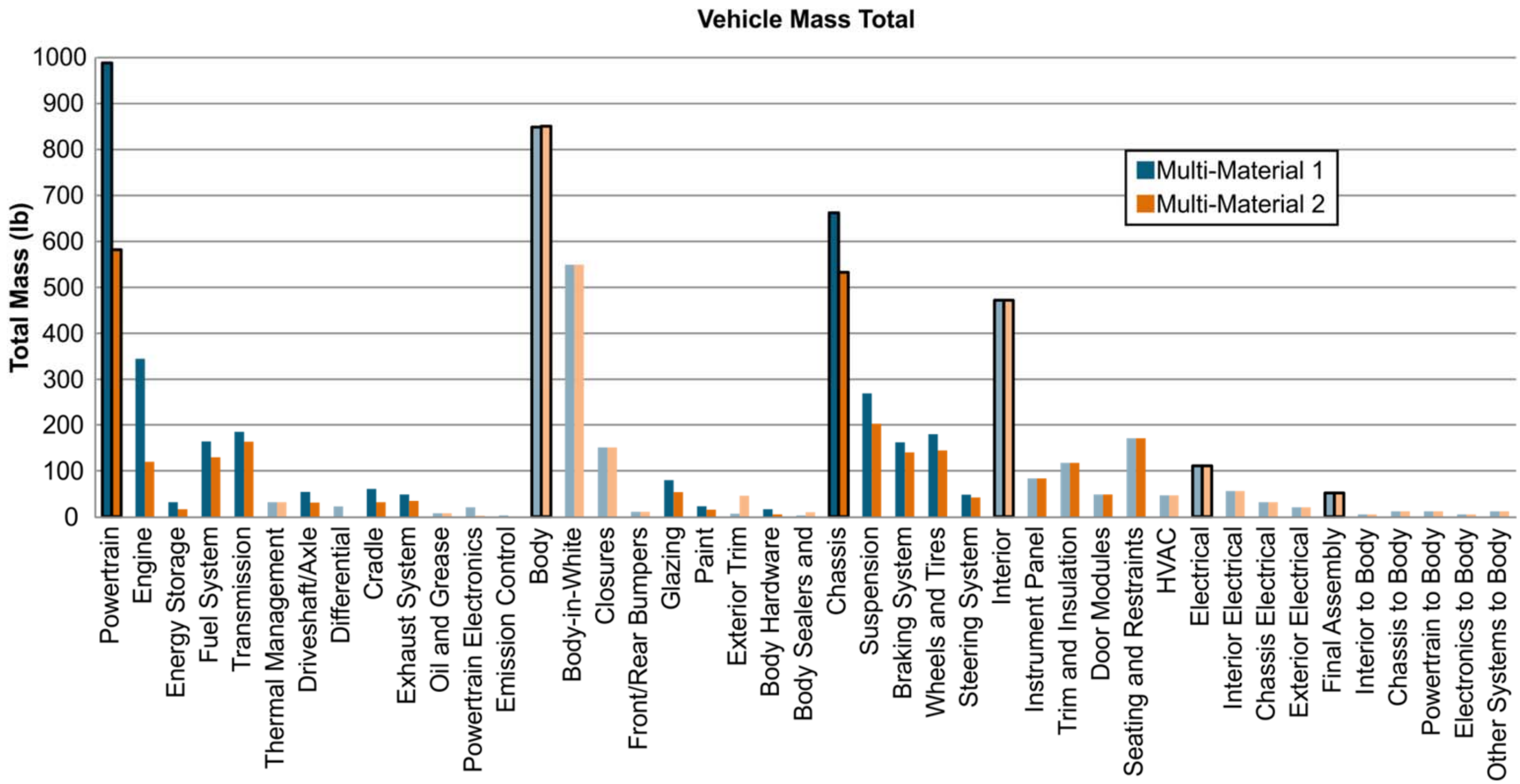

Figure 8. Stage 1 (Multi-Material 1) to Stage 2 (Multi-Material 2) mass reduction focuses on weight reduction in the powertrain system, including engine, battery, fuel, driveline, cradle, and exhaust system. The body system does show a slight increase in weight between Stage 1 and Stage 2. Systems and subsystems that have NO weight changes between Stage 1 and 2 are presented in muted colors.

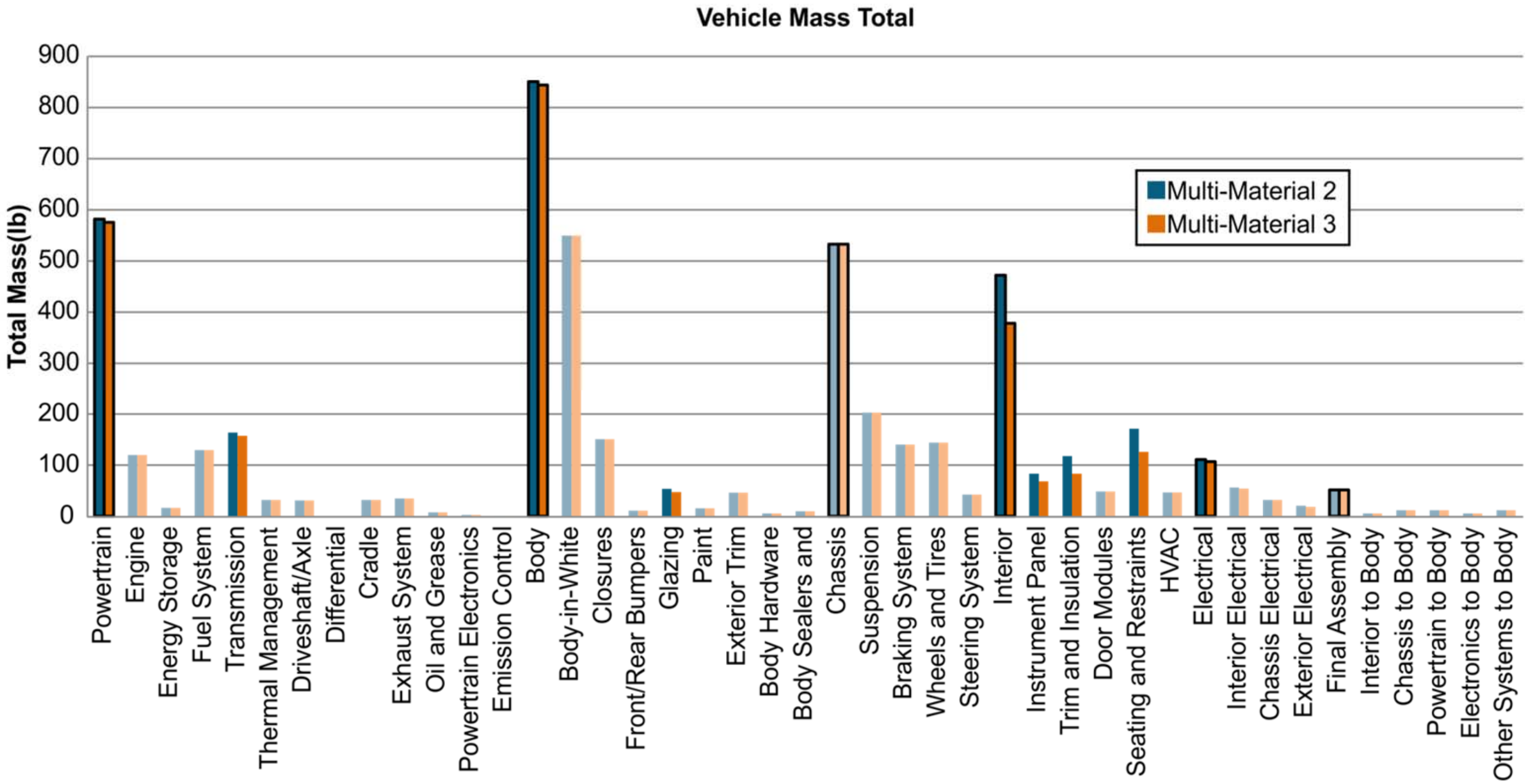

Figure 9. Stage 2 (Multi-Material 2) to Stage 3 (Multi-Material 3) mass reduction focuses on weight reduction in the interior system, including instrument panel, trim, door modules, and seating. Systems and subsystems that have NO weight changes between Stage 2 and Stage 3 are presented in muted colors.

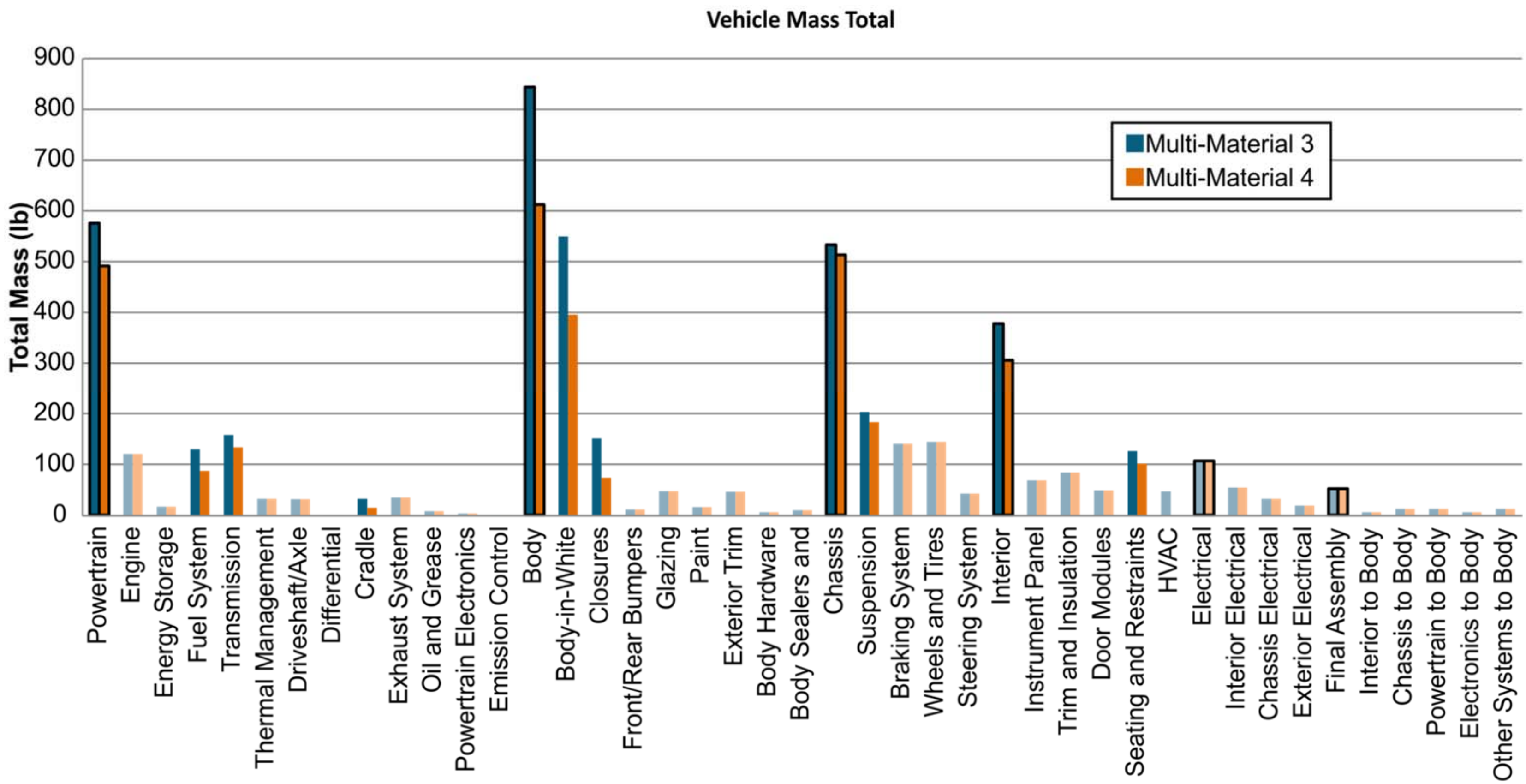

Figure 10. Stage 3 (Multi-Material 3) to Stage 4 (Multi-Material 4) mass reduction, including Mach II BIW (Section 3.2.1.1.3*)* improvements, focuses on weight reduction in the following systems: powertrain, including the fuel system, transmission, and engine cradle; body, including the BIW and panels; chassis, including the suspension; and interior, including seating. Systems and subsystems that have NO weight changes between Stage 2 and Stage 3 are presented in muted colors.

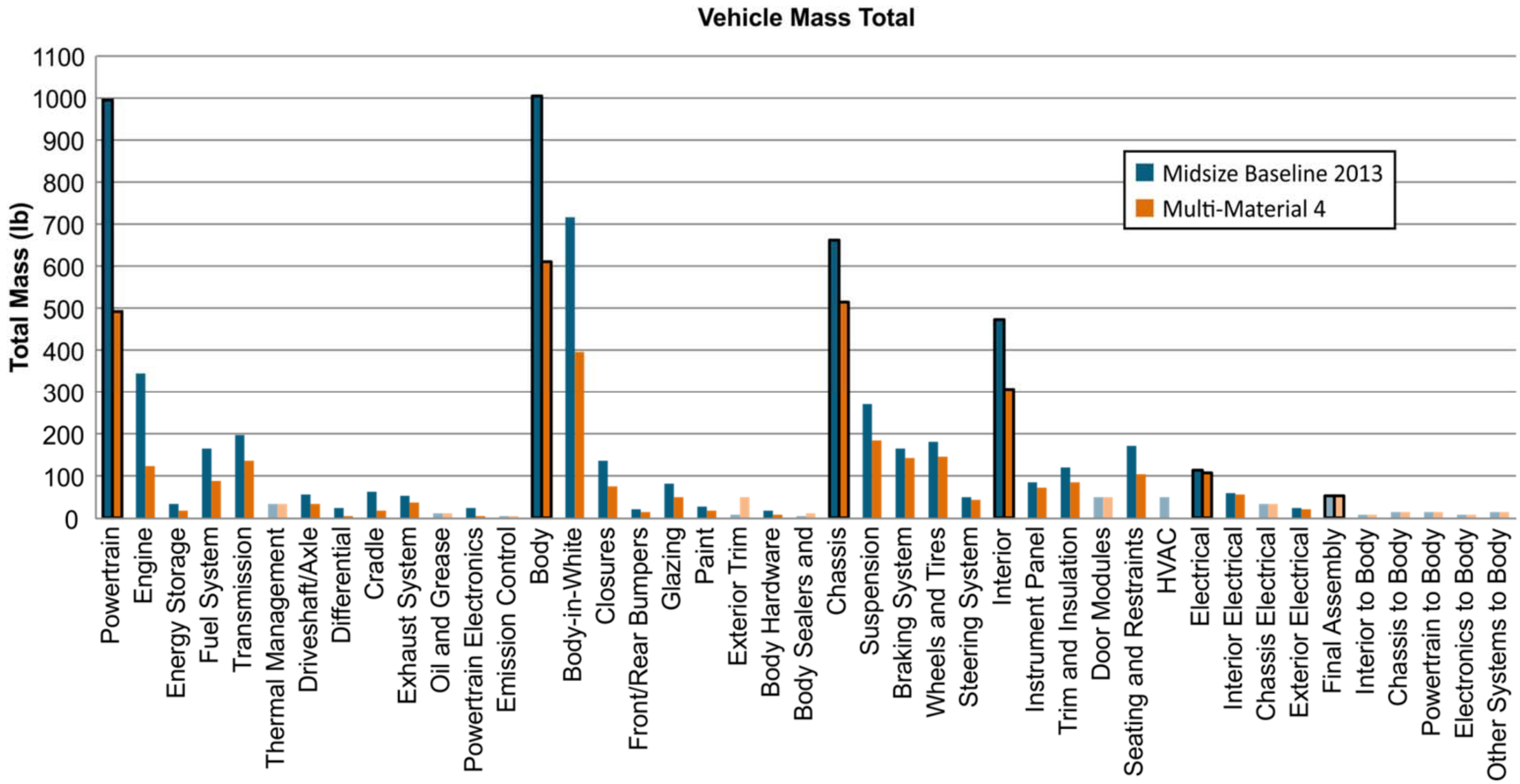

Figure 11. Cumulative mass reduction result in a single plot (superimposing Figures 7 through 10) from baseline to Stage 4 (Multi-Material 4).

Table 3. Vehicle scenario mass reduction summary.

	Ford	Ford/Vehma	DOE	IBIS	IBIS	IBIS	IBIS	IBIS	IBIS	IBIS	IBIS	IBIS	IBIS	IBIS	IBIS
	2013 Fusion	MMLV-M1	2013 Midsize Baseline	Midsize Baseline 2013	Optimized Steel 1	Optimized Steel 2	Optimized Steel 3	Aluminum Intensive 1	Aluminum Intensive 4	Multi-Material 1	Multi-Material 2	Multi-Material 3	Multi-Material 4	Carbon 1	Carbon 4
Total Mass (lbs)	**3430**	**2629**	**3303**	**3304**	**3198**	**2843**	**2758**	**2937**	**2129**	**3138**	**2604**	**2493**	**2084**	**2843**	**2034**
				lbs		lbs		lbs		lbs		lbs		lbs	
Powertrain	**836.0**	**590.7**	**1080.3**	**997.9**	**991.9**	**837.0**	**837.0**	**977.1**	**493.9**	**988.4**	**582.1**	**576.0**	**491.6**	**971.7**	**488.9**
Engine	266.2	120.8	345.5	345.4	345.4	279.4	279.4	345.4	121.0	345.4	121.0	121.0	121.0	345.4	121.0
Energy Storage	30.8	17.6	39.6	33.0	33.0	33.0	33.0	33.0	17.6	33.0	17.6	17.6	17.6	33.0	17.6
Fuel System	147.4	130.4	142.7	164.8	164.8	137.1	137.1	164.8	88.0	164.8	130.5	130.5	88.0	164.8	88.0
Transmission	193.6	169.4	242.9	195.4	189.4	147.6	147.6	174.6	136.4	186.0	164.5	158.5	134.1	169.3	131.4
Thermal Management	15.4	37.3	41.1	33.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0
Driveshaft/Axle	39.6	32.3	61.9	55.2	55.2	51.7	51.7	55.2	32.3	55.2	32.3	32.3	32.3	55.2	32.3
Differential	2.2	0.0	28.4	24.0	24.0	24.0	24.0	24.0	0.2	24.0	0.2	0.2	0.2	24.0	0.2
Cradle	59.4	32.9	72.2	62.0	62.0	62.0	62.0	62.0	15.4	62.0	33.0	33.0	15.4	62.0	15.4
Exhaust System	48.4	35.9	49.9	49.9	49.9	34.1	34.1	49.9	35.9	49.9	35.9	35.9	35.9	49.9	35.9
Oil and Grease	8.8	8.7	27.1	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8
Powertrain Electronics	19.8	3.9	26.4	22.0	22.0	22.0	22.0	22.0	4.0	22.0	4.0	4.0	4.0	22.0	4.0
Emission Control Electronics	4.4	1.4	2.7	4.4	4.4	4.4	4.4	4.4	1.3	4.4	1.3	1.3	1.3	4.4	1.3
Body	**1146.2**	**889.2**	**1000.0**	**1006.2**	**906.1**	**906.1**	**891.6**	**659.7**	**654.8**	**848.9**	**850.6**	**844.0**	**612.4**	**570.6**	**564.6**
Body-in-White	717.2	550.5	716.7	716.8	618.3	618.3	618.3	429.0	429.0	550.0	550.0	550.0	396.0	344.3	343.2
Closures	215.6	151.3	134.2	134.2	134.2	134.2	134.2	83.6	83.6	151.8	151.8	151.8	74.3	79.2	79.2
Front/Rear Bumpers	90.2	57.0	22.4	20.2	18.6	18.6	18.6	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1
Glazing	79.2	54.8	48.7	81.0	81.0	81.0	72.2	81.0	48.4	81.0	55.0	48.4	48.4	81.0	48.4
Paint	17.6	17.0	26.8	24.3	24.3	24.3	24.3	24.3	16.9	24.3	16.9	16.9	16.9	24.3	16.9
Exterior Trim	8.8	47.2	24.4	8.1	8.1	8.1	8.1	8.1	47.1	8.1	47.1	47.1	47.1	8.1	47.1
Body Hardware	6.6	0.0	22.4	17.6	17.6	17.6	11.9	17.6	6.6	17.6	6.6	6.6	6.6	17.6	6.6
Body Sealers and Deadeners	11.0	11.6	4.5	4.0	4.0	4.0	4.0	4.0	11.0	4.0	11.0	11.0	11.0	4.0	11.0
Chassis	**721.6**	**552.1**	**674.7**	**662.6**	**662.6**	**462.0**	**462.0**	**662.6**	**513.6**	**662.6**	**533.4**	**533.4**	**513.6**	**662.6**	**513.6**
Suspension	266.2	222.5	298.8	269.6	269.6	175.7	175.7	269.6	183.8	269.6	203.6	203.6	183.8	269.6	183.8
Braking System	173.8	141.2	155.6	163.1	163.1	102.4	102.4	163.1	141.2	163.1	141.2	141.2	141.2	163.1	141.2
Wheels and Tires	233.2	145.1	128.6	180.5	180.5	138.4	138.4	180.5	145.2	180.5	145.2	145.2	145.2	180.5	145.2
Steering System	48.4	43.3	91.7	49.4	49.4	45.4	45.4	49.4	43.3	49.4	43.3	43.3	43.3	49.4	43.3
Interior	**550.0**	**431.6**	**472.3**	**472.6**	**472.6**	**472.6**	**416.0**	**472.6**	**306.0**	**472.6**	**472.6**	**378.6**	**306.0**	**472.6**	**306.0**
Instrument Panel	83.6	69.6	70.9	84.5	84.5	84.5	70.6	84.5	69.5	84.5	84.5	69.5	69.5	84.5	69.5
Trim and Insulation	88.0	84.4	91.2	118.6	118.6	118.6	118.6	118.6	84.5	118.6	118.6	84.5	84.5	118.6	84.5
Door Modules	110.0	93.5	66.4	49.7	49.7	49.7	49.7	49.7	49.7	49.7	49.7	49.7	49.7	49.7	49.7
Seating and Restraints	198.0	128.4	196.1	172.0	172.0	172.0	134.6	172.0	102.3	172.0	172.0	127.2	102.3	172.0	102.3
HVAC	70.4	55.6	47.6	47.7	47.7	47.7	42.5	47.7	0.0	47.7	47.7	47.7	0.0	47.7	0.0
Electrical	**123.2**	**116.7**	**53.4**	**112.2**	**112.2**	**112.2**	**98.8**	**112.2**	**107.8**	**112.2**	**112.2**	**107.8**	**107.8**	**112.2**	**107.8**
Interior Electrical	68.2	55.3	6.9	57.2	57.2	57.2	46.9	57.2	55.2	57.2	57.2	55.2	55.2	57.2	55.2
Chassis Electrical	33.0	41.8	6.9	33.0	33.0	33.0	31.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0
Exterior Electrical	22.0	19.6	39.6	22.0	22.0	22.0	20.9	22.0	19.6	22.0	22.0	19.6	19.6	22.0	19.6
Final Assembly	**52.8**	**48.2**	**22.6**	**52.8**	**52.8**	**52.8**	**52.8**	**52.8**	**52.8**	**52.8**	**52.8**	**52.8**	**52.8**	**52.8**	**52.8**
Interior to Body	6.6	6.0	2.8	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6
Chassis to Body	13.2	12.0	5.6	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2
Powertrain to Body	13.2	12.0	5.6	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2
Electronics to Body	6.6	6.0	2.8	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6
Other Systems to Body	13.2	12.0	5.6	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2

6. TECHNICAL COST MODEL ANALYSIS

Two distinct levels of cost modeling are required for the analysis needed by this project: (1) a manufacturing process-level technical cost model to address components and assemblies and (2) a vehicle level cost model to address all automotive systems and subsystems, along with their interrelationships and sizing impact. The methodologies of these two levels of cost models are described briefly in the following subsections and in greater detail in Appendix D and Appendix E of this report.

6.1 Manufacturing Process: Component and Assembly Cost Modeling Approach

To address the program's stated objectives, technical cost models of the manufacturing and assembly processes were employed, where reported costs or projections for a given component in data collection were not available. In technical cost modeling, as employed by IBIS, process costs are addressed by performing dynamic economic simulations of manufacturing processes. In this approach, the process starts with a user-defined manufacturing scenario in terms of component geometry, production volume, and accounting assumptions. The models then assess equipment, tooling, and building capital requirements based on definitions of individual components and process parameters. Variable costs in terms of material, labor, and energy are calculated based on component geometry, scrap and yield losses, process rates, and equipment usage. Manufacturing overhead labor, maintenance cost, and the interest cost of investments and working capital are also included. This dynamic approach is particularly useful for exploring cost sensitivities, such as production rate and yield, as well as for understanding the equipment and tooling implications of material and design differences and for making projections of conceptual or developmental processes.

A more detailed discussion of process technical cost models and their constituent elements can be found in Appendix D.

6.2 Vehicle Level Cost Modeling Approach

The breakdown of vehicle mass and manufacturing costs follows the same subsystem list as established in earlier DOE cost analyses, such as the Oak Ridge National Laboratory automotive system cost model. Vehicle production is addressed under five different system groups and more than 30 subsystems, plus assembly operations. In addition, further resolution is provided in terms of several component groups for most of these subsystems, resulting in more than 60 mass and cost line items.

- Level 1: System Level (e.g., powertrain, body, chassis, etc.)
- Level 2: Subsystem Level (e.g., engine, transmission, driveline, exhaust, etc.)
- Level 3: Component Groups (e.g., engine block, cylinder head, oil pan, etc.).

Information and discussion on the methodology, including system, subsystem, and component breakdown data for the baseline, data flow and structure, sizing relationships, and scenario and data capture, are contained in Appendix E.

7. ANALYSIS RESULTS – 40% WEIGHT SAVINGS TARGET

For each of the previous scenarios and lightweighting stages, an individual case study was conducted using the vehicle lightweighting technical cost model to examine a holistic vehicle analysis of mass and cost. Each of these cases was then compared to the vehicle baseline to determine the overall mass reduction and total vehicle cost and, therefore, the cost of weight savings. The resulting breakdowns and comparisons are presented in the tables and charts in this section.

7.1 Caveats

- The full details of functionally equivalent, crashworthy designs are not available for many proposed advanced concepts. Therefore, the analysis results are speculative and most likely represent a best possible case scenario. Real-world application of these concepts may involve additional processing, performance, comfort, safety, and corrosion measures that are not fully understood at this time.
- Costing was performed in regard to fully implemented high-volume processes, with automation and expected learning curve improvements, not as current developmental or low-volume introductory practices. Particularly in the case of carbon fiber structures, the ultimate analysis includes the predictions of processing cost reductions professed by material suppliers currently engaged in automotive production. To provide a conservative estimate for the carbon fiber composite-intensive scenario, the report also presents results with costs based on current production experience, under which the cost of weight savings is considerably beyond the stated target.
- An economic comparison was made in terms of the OEMs' direct manufacturing cost per vehicle. Therefore, when considering subsystems, analysis accounted for margins of one or more supplier levels that would be included in the OEM purchase cost. Those systems manufactured by the OEM (such as engines and body structures) include the costs of tooling, production capital, energy, direct and indirect manufacturing labor, and material. Engineering costs; selling, general, and administrative costs; profit; and dealer margins are not included at this level of analysis.

Figure 12 compares the mass results of the four alternative body structure scenarios at Stage 1 savings, reflecting replacement of body structure only, relative to the baseline vehicle. As is clear when examining the comparison of the Stage 1 savings, a mass reduction of 20 to 50% in the body structure without addressing other vehicle systems will result in only 3 to 14% overall vehicle mass reduction, even though the body structure is the largest monolithic vehicle system in terms of mass and (usually) material usage.

Figure 13 shows the ultimate Stage 4 savings, involving the best weight savings of the collected data applied to the aluminum-intensive, multi-material, and carbon fiber composite-intensive structure scenarios.

All 11 structure basis and weight-saving stage scenarios are presented in Figure 14. The figure compares overall vehicle mass and system mass breakdown relative to the baseline vehicle. For the sake of comparison, the first two bars show the results of the reported data for the Ford Fusion baseline and MMLV Mach I lightweight design concept from the Ford/Vehma program. Note that the current analysis is built around a generic baseline vehicle that is similar and comparable to, but not exactly the same as, the Ford Fusion baseline used by Ford/Vehma. Figure 15 presents the same scenario totals, without the breakdown by system, in terms of pounds per vehicle.

Because of the speculative nature of high-volume carbon fiber composite manufacturing costs, two presentations of the vehicle costing results are shown. The first (Figure 16) includes carbon fiber molding costs (for structural automotive components) at approximately $50/lb, coupled with the current carbon fiber price of $12.50/lb. The $50/lb processing costs are in line with current practices, which are slow and extremely labor-intensive. The second (Figure 17), is built around a projected cost of manufacturing carbon fiber components. This projection maintains the current carbon fiber price of $12.50/lb, but takes into account the claims of carbon fiber proponents, who state that through more advanced automation, material handling, and high-speed molding technology processing costs will be drastically reduced, resulting in carbon composite processing costs of approximately $5/lb (Berger 2014). The analyses in this report include this assumption of the "projected" $5/lb processing cost, which is in line with the optimal projections for large complex automotive molding strategies pursued by USCAR/Automotive Composites Consortium (IBIS 2010). A subsequent sensitivity analysis addresses the impact of reducing carbon fiber price.

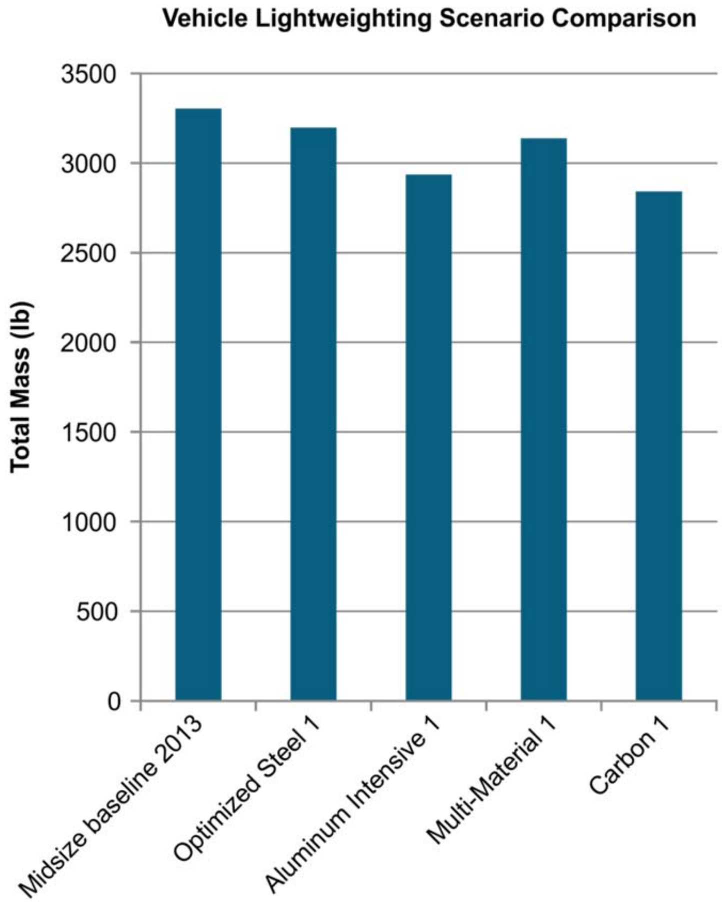

Figure 12. Comparison of mass results for the four alternative body system scenarios at Stage 1 savings, reflecting replacement of the body system only, relative to the baseline vehicle.

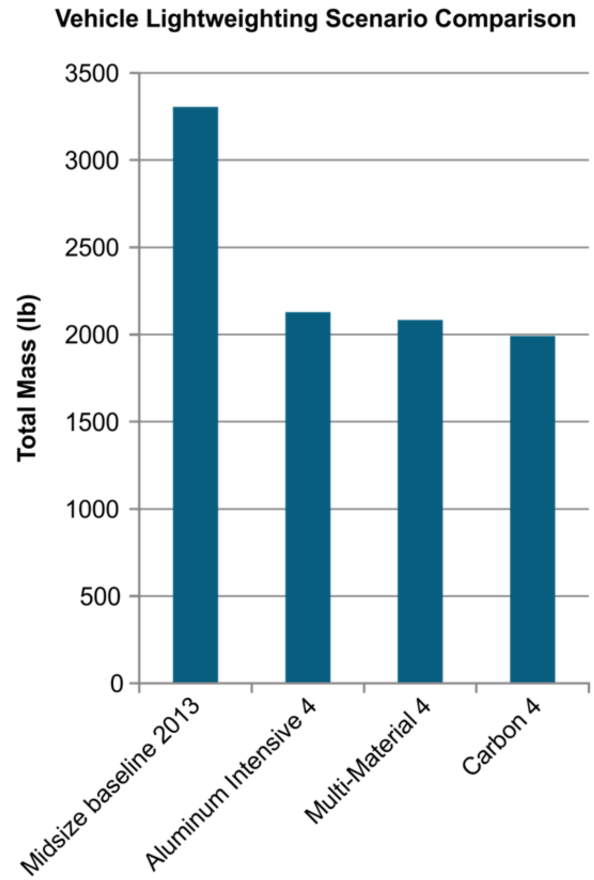

Figure 13. Complete baseline to Stage 4 savings, involving the maximum weight savings of the collected data applied to the aluminum-intensive, multi-material, and carbon fiber composite-intensive scenarios.

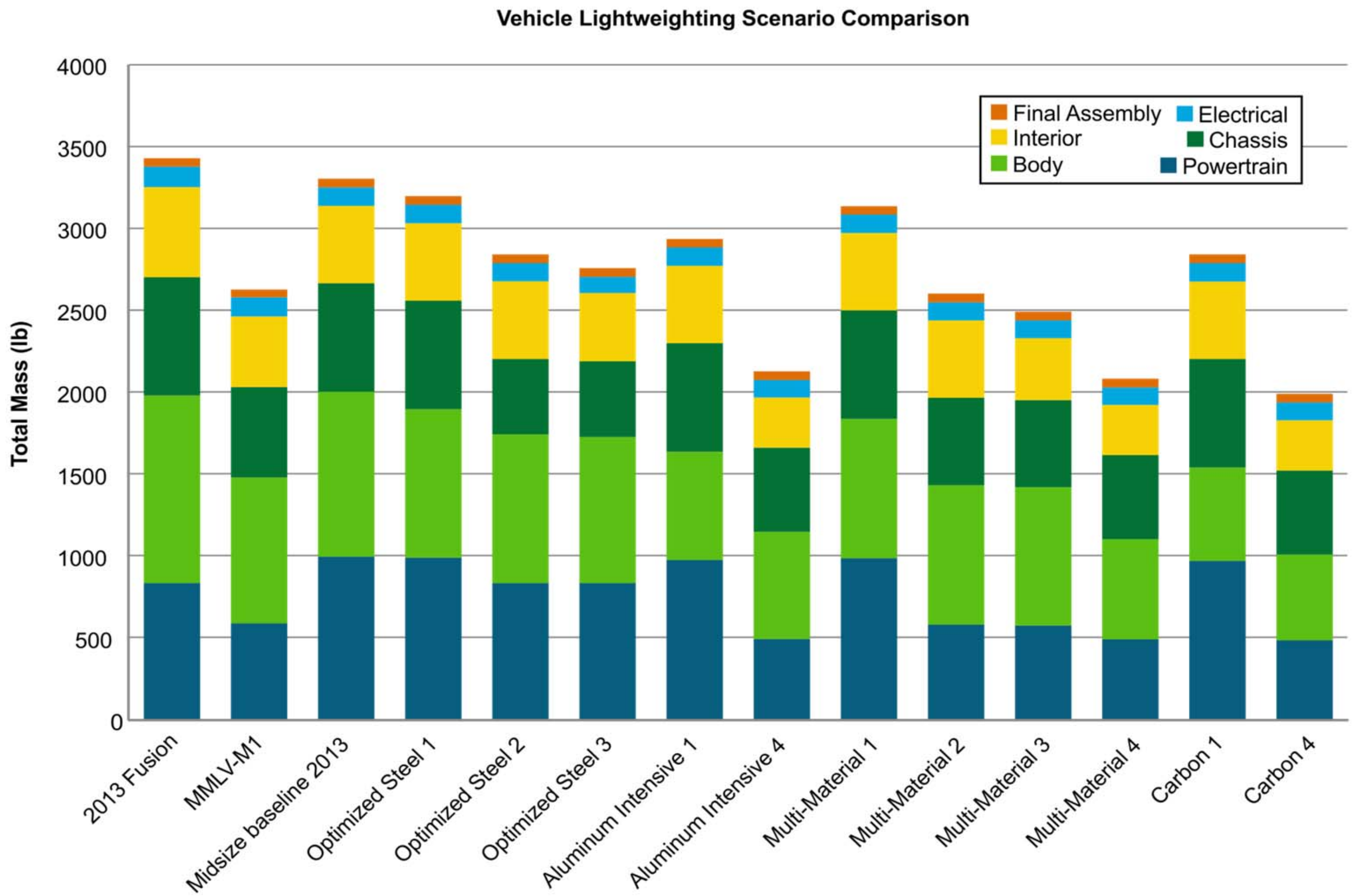

Figure 14. Overall vehicle mass and system mass breakdown comparison relative to the baseline vehicle.

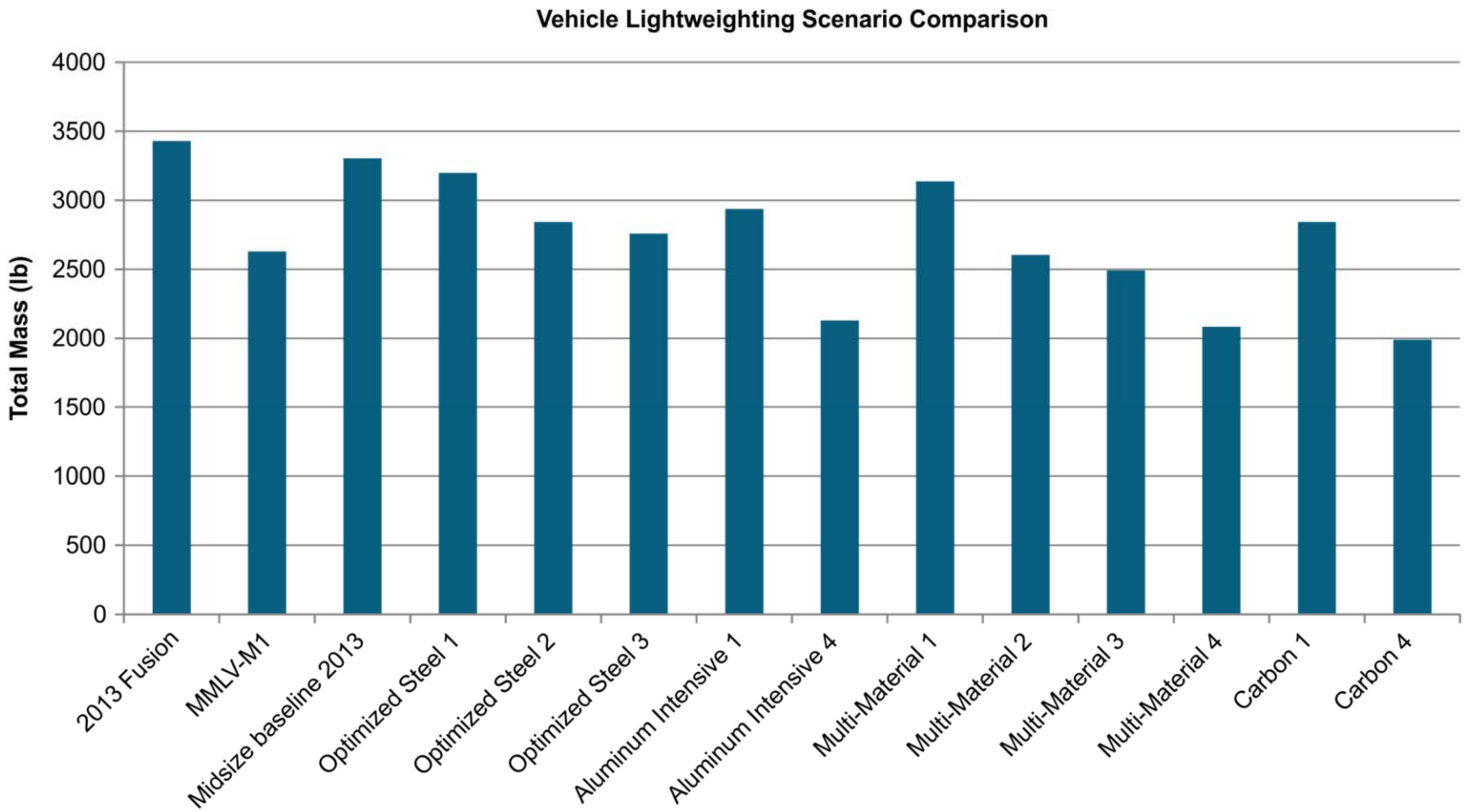

Figure 15. Cumulative mass reductions compared to the baseline vehicle without the breakdown by vehicle system.

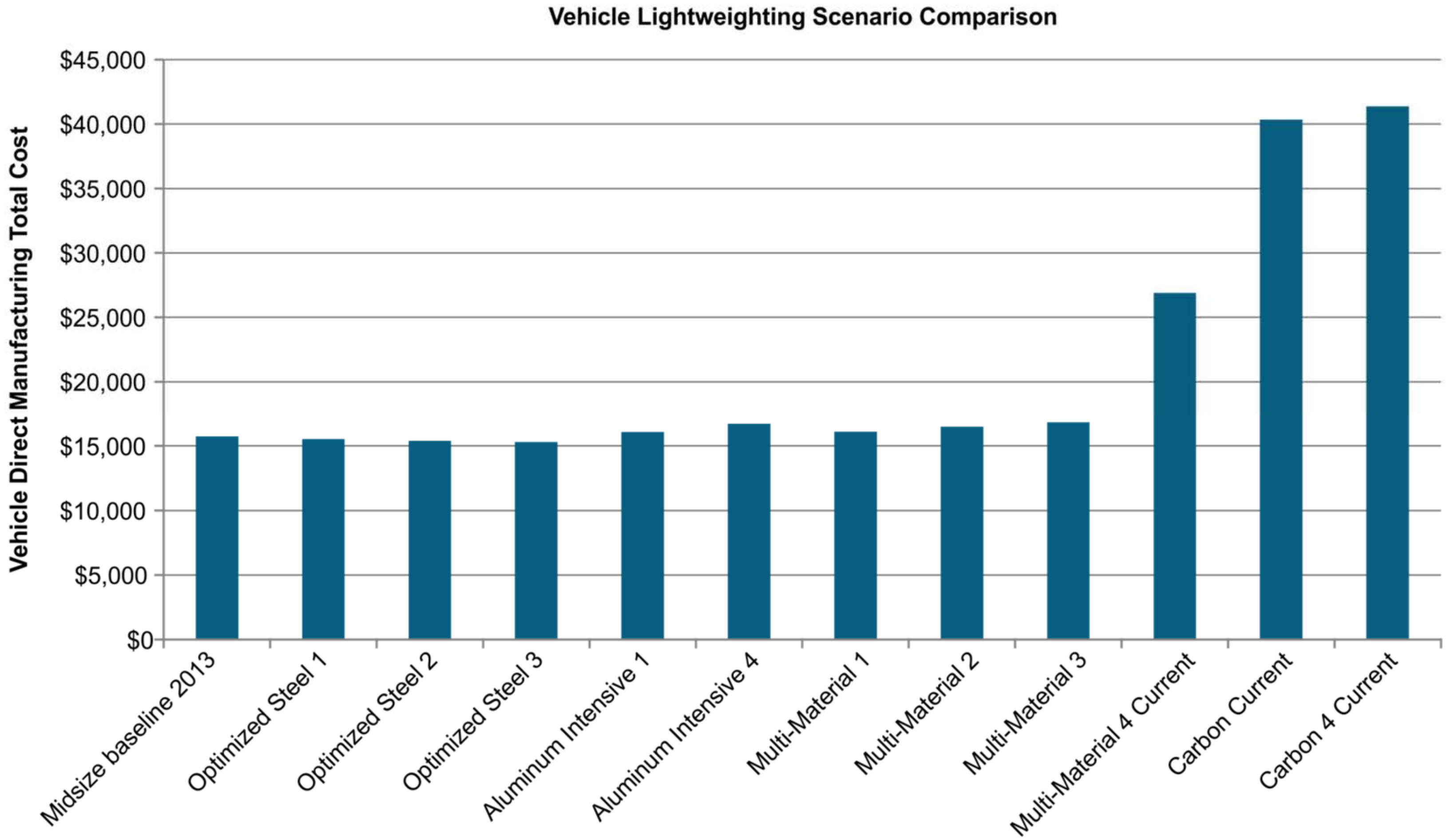

Figure 16. Scenario cost comparison using current carbon composite processing costs at approximately $50/lb and the current carbon fiber price of $12.50/lb.

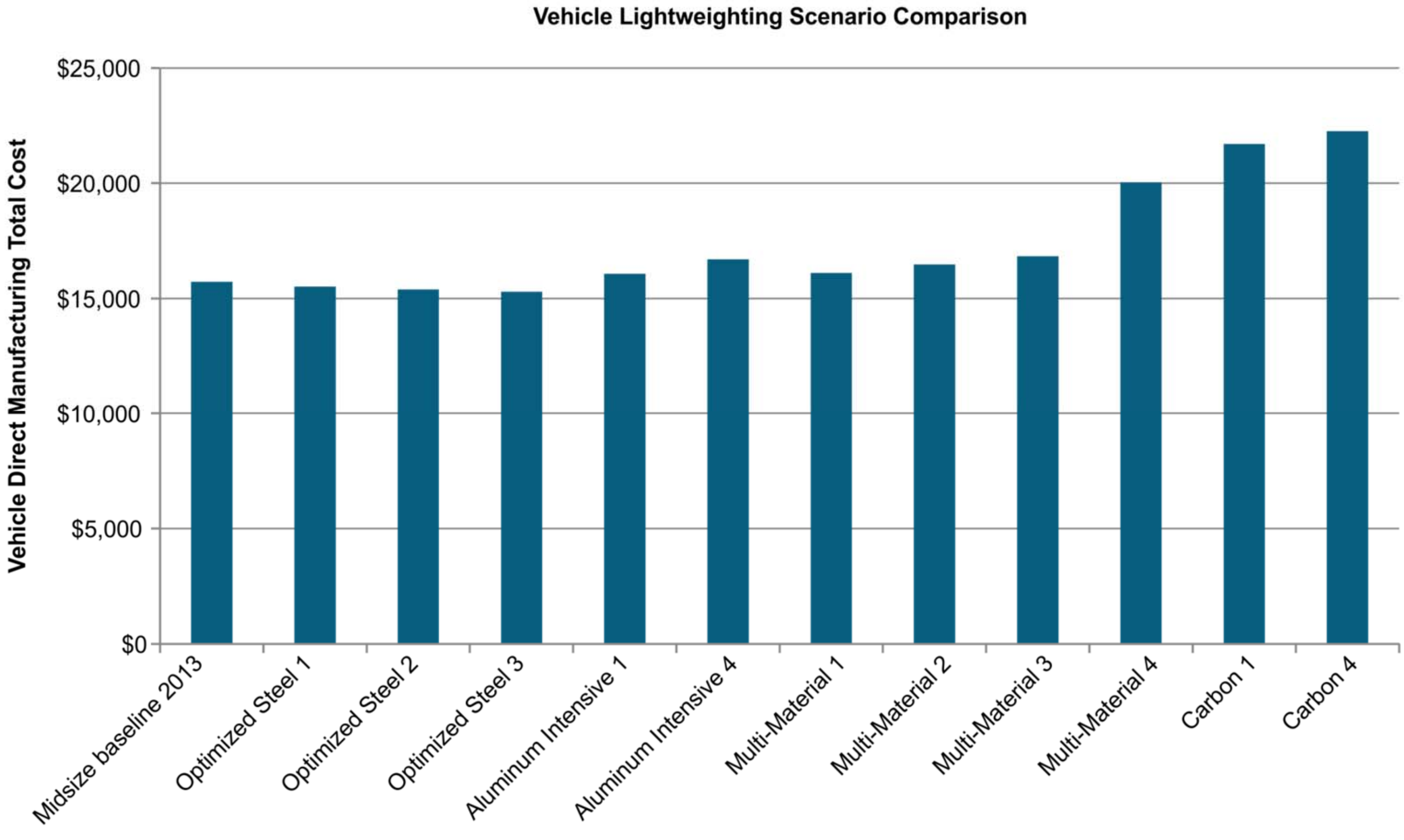

Figure 17. Scenario cost comparison at projected carbon composite processing costs of approximately $5/lb, reducing the vehicle direct manufacturing costs by almost half when compared to current carbon composite processing costs in Figure 16 (current carbon fiber price of $12.50/lb were maintained).

Figure 18 focuses on the Stage 4 savings of the aluminum-intensive, multi-material, and carbon fiber composite-intensive scenarios.

Table 4 summarizes the results of the mass and cost analysis, listing the resulting mass, in pounds, of each scenario, followed by the amount and percentage of weight saved. Below the weight savings, the direct manufacturing cost results for each scenario are shown, followed by the cost target for that scenario's amount of mass reduction (at $3.42 premium per pound of mass reduction).

Figures 19 and 20 display the data from Table 4 in a graphical format, showing the cost of each scenario plotted against the weight savings. The red line indicates the $3.42/lb target cost of weight savings for the range from 0 to 40% mass reduction from the baseline vehicle. At this target, it can be seen that a 40% reduction of the 3,304-lb baseline would result in a vehicle weighing 1,982 lb and costing $20,244. Anything below this target line represents weight reduction within the $3.42 target and anything above is more than the $3.42 target. Nearly all modeled scenarios lie below the target line. However, none of those below the target reach the 40% weight reduction goal. The Stage 4 multi-material scenario is just slightly over the target cost at 37% mass reduction, while the Stage 4 carbon fiber composite-intensive scenario approaches the weight reduction goal but, at $5.18/lb saved is significantly (i.e., 51%) above the target, even assuming optimistic projected processing costs ($5/lb).

Figure 26 (see Section 8) focuses on these same results, but zooms in on the advanced Stage 4 aluminum-intensive, multi-material, and carbon fiber composite-intensive scenarios achieving over 30% weight savings.

Given the stated task goal of identifying the path to 40% mass reduction, only the carbon fiber composite-intensive scenario is examined in further detail in Figures 20, 22, and 23 and Section 7.2.

Figure 21 breaks down the amount of weight savings in the carbon fiber composite-intensive scenario that is projected to be achieved by each subsystem. It is evident that the greatest mass reduction is from the carbon fiber body, followed by the downsized engine and suspension system. Figure 22 presents the relative cost of each subsystem for the carbon composite-intensive scenario relative to the baseline. Once again, the body structure stands out as the greatest cost increase, even under the optimistic carbon economic assumptions. Figure 23 combines the cost differential and weight savings to look at the cost of weight savings of each subsystem. Bars in the positive region above the x-axis represent a cost premium for weight savings. Conversely, bars below the x-axis represent a negative cost of weight savings. The latter case is achieved when a strategy weighs less and costs less, but most likely occurs through downsizing or eliminating systems or features.

7.2 Carbon Structure Manufacturing Issues

The preceding analyses included "current carbon **composite** manufacturing costs" and "projected carbon **composite** manufacturing costs." The projected costs were based on carbon fiber industry leader SGL Group's assertions that 90% reduction in direct processing costs will be achieved over current practices with advanced production techniques and highly automated facilities designed for automotive-level production volumes (Berger 2014). Figure 24 shows these current and projected costs for the 343-lb BIW structure of the carbon fiber composite-intensive scenario.

To meet the target $3.42/lb saved, the $6,528 BIW cost would have to be further reduced to $4,281 (i.e., a 34% decrease) (see Figure 25). The most likely path for this reduction, after achieving the previously discussed projected advances in manufacturing cost, would be a reduction in the carbon fiber price itself. The necessary reduction was determined in a sensitivity analysis of BIW cost to carbon fiber price. As shown in Figure 25, the analysis showed that the carbon fiber price would have to drop from $12.50/lb in the baseline analysis to $6.00/lb.

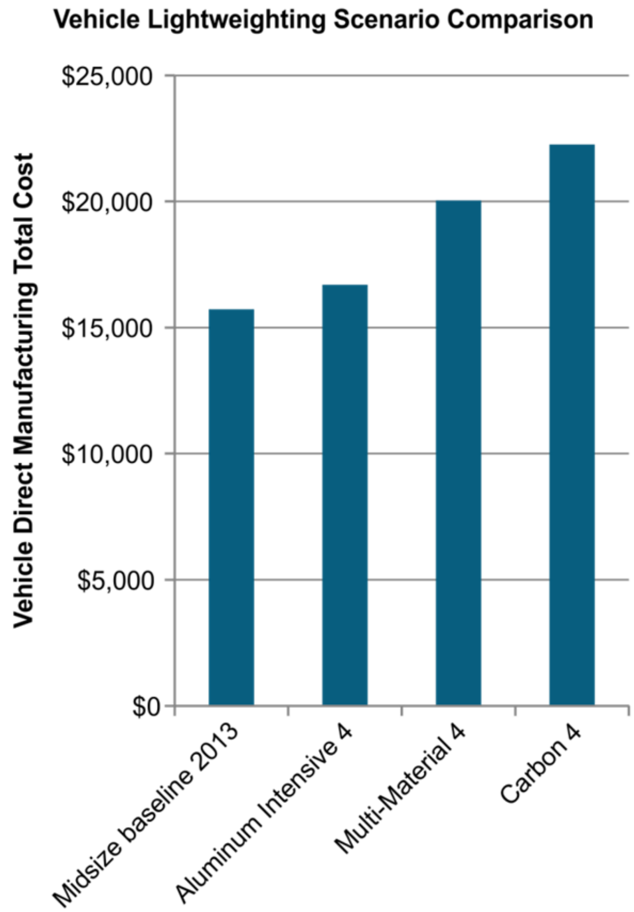

Figure 18. Stage 4 scenario costing results (baseline and Stage 4 only – "Best-in-Class" subsystem and component concepts from each scenario), assuming projected carbon composite processing costs of $5/lb and current carbon fiber price of $12.50/lb.

Table 4. Cost of weight savings data.

	2013 Ford Fusion	Vehma/Ford MMLV-M1	Midsize Baseline 2013	Optimized Steel 1	Optimized Steel 2	Optimized Steel 3	Aluminum Intensive 1	Aluminum Intensive 4	Multi-Material 1	Multi-Material 2	Multi-Material 3	Multi-Material 4	Carbon 1	Carbon 4	40% Reduction Target
Lbs	3430	2629	3304	3198	2843	2758	2937	2129	3138	2604	2493	2084	2843	2034	1983
Lbs Saved	0	801	0	106	462	546	367	1175	167	701	812	1220	462	1271	1322
% wt savings	0.0%	23.4%	0.0%	3.2%	14.0%	16.5%	11.1%	35.6%	5.0%	21.2%	24.6%	36.9%	14.0%	38.5%	40.0%
Direct Mfg Cost			$15,724	$15,522	$15,389	$15,291	$16,070	$16,706	$16,107	$16,484	$16,833	$20,036	$21,705	$22,307	
$3.42/lb Cost Target			$15,724	$16,087	$17,302	$17,591	$16,980	$19,744	$16,294	$18,120	$18,500	$19,896	$17,303	$20,069	$20,244
Project Cost of Wt. Save				-$1.90	-$0.72	-$0.79	$0.94	$0.84	$2.30	$1.09	$1.37	$3.53	$12.95	$5.18	
Target Cost Wt. Save			$3.42	$3.42	$3.42	$3.42	$3.42	$3.42	$3.42	$3.42	$3.42	$3.42	$3.42	$3.42	

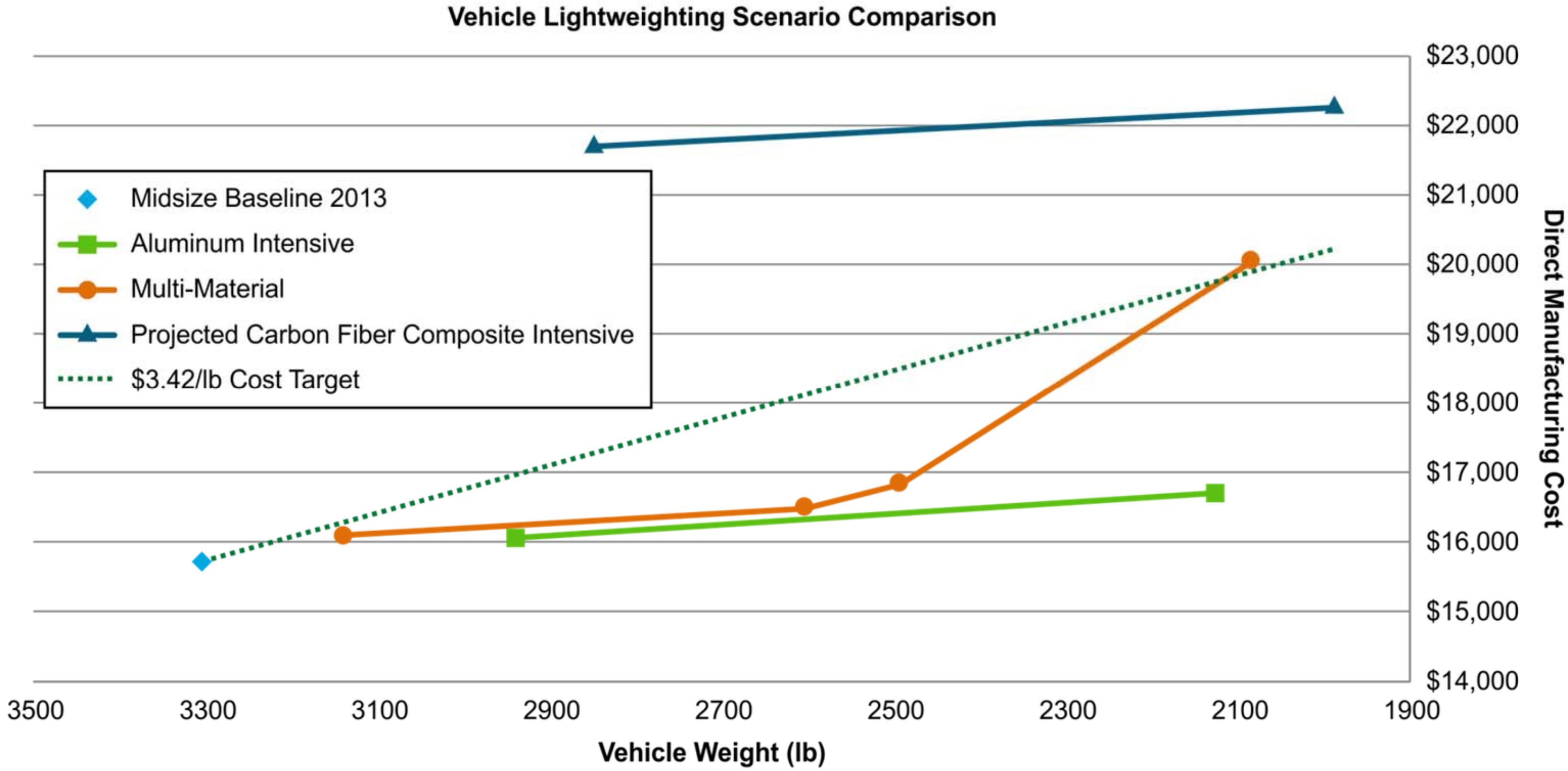

Figure 19. Progression of cost and weight savings for different lightweighting scenarios relative to target (projected carbon composite processing cost of $5/lb and current carbon fiber price of $12.50/lb are used).

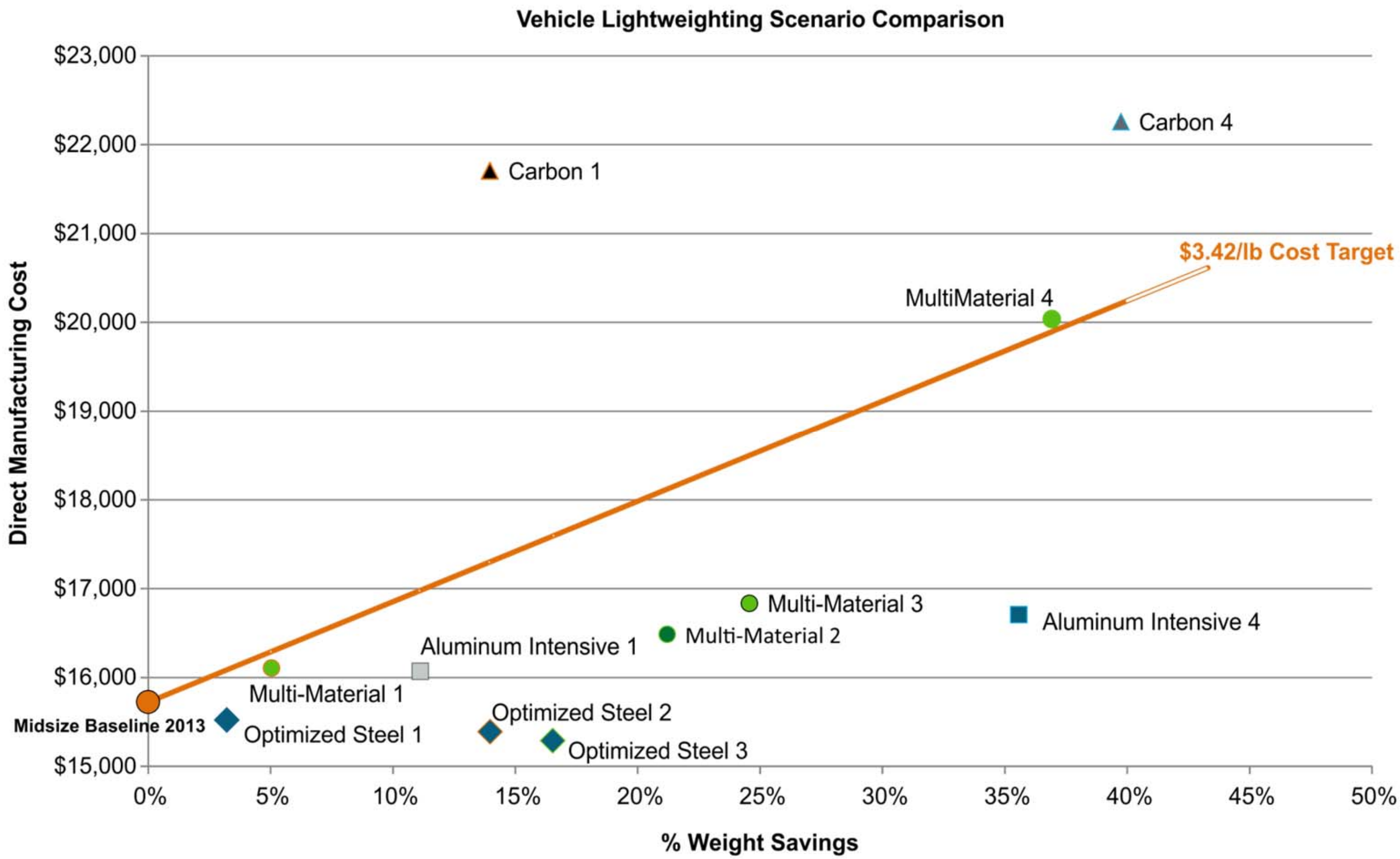

Figure 20. Mass reduction relative to vehicle cost – Carbon 1 and Carbon 4 data points assume a projected carbon composite processing cost of $5/lb and current carbon fiber price of $12.50/lb.

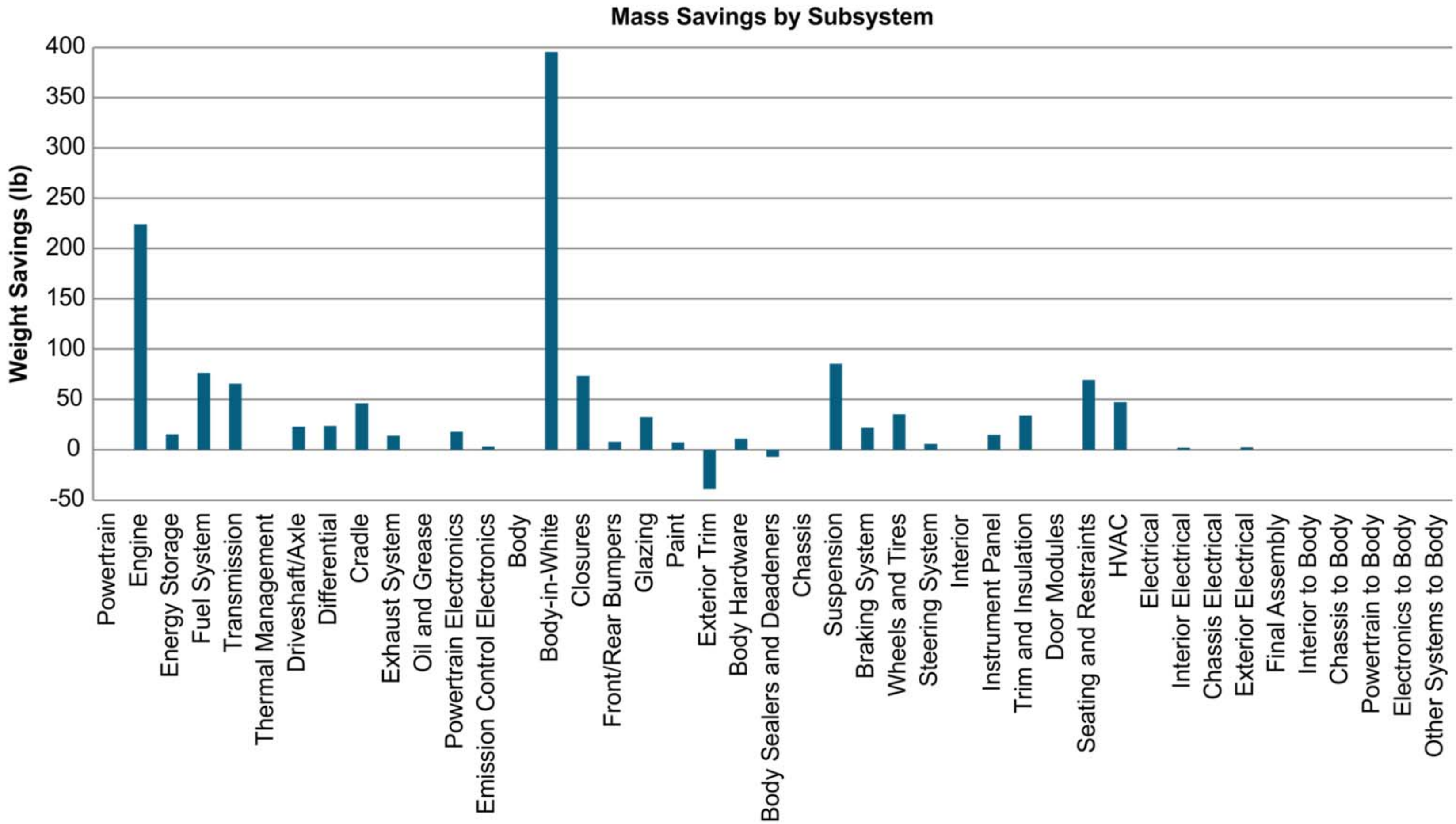

Figure 21. Carbon fiber composite-intensive scenario Stage 4 – mass reduction by system (the largest reduction comes from the carbon composite body, followed by the downsized engine and suspension system).

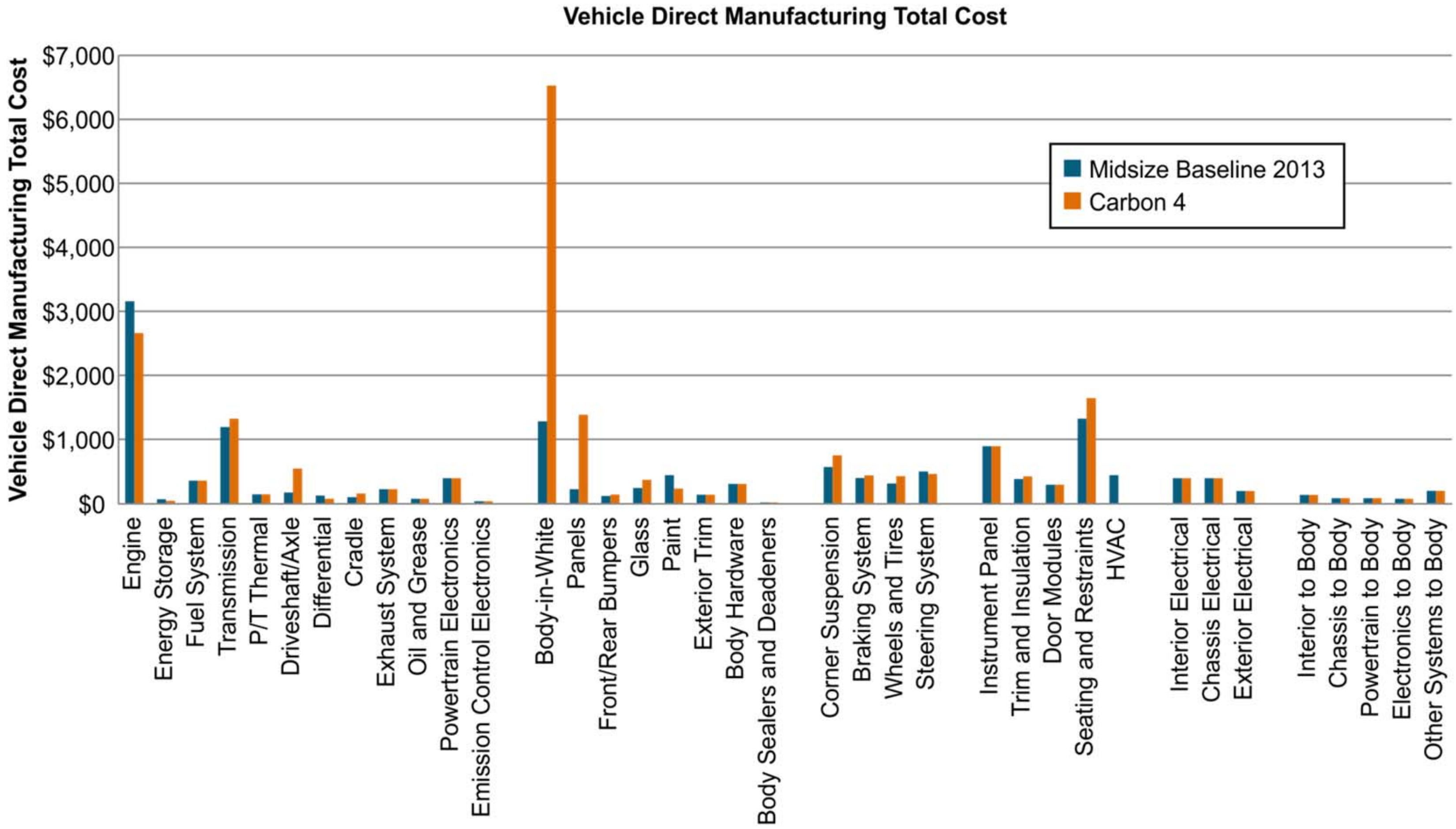

Figure 22. Carbon fiber composite-intensive scenario Stage 4 – cost relative to baseline by system (the largest cost increase comes from the BIW and panels (even under the optimistic projected carbon composite processing cost of $5/lb and current carbon fiber price of $12.50/lb).

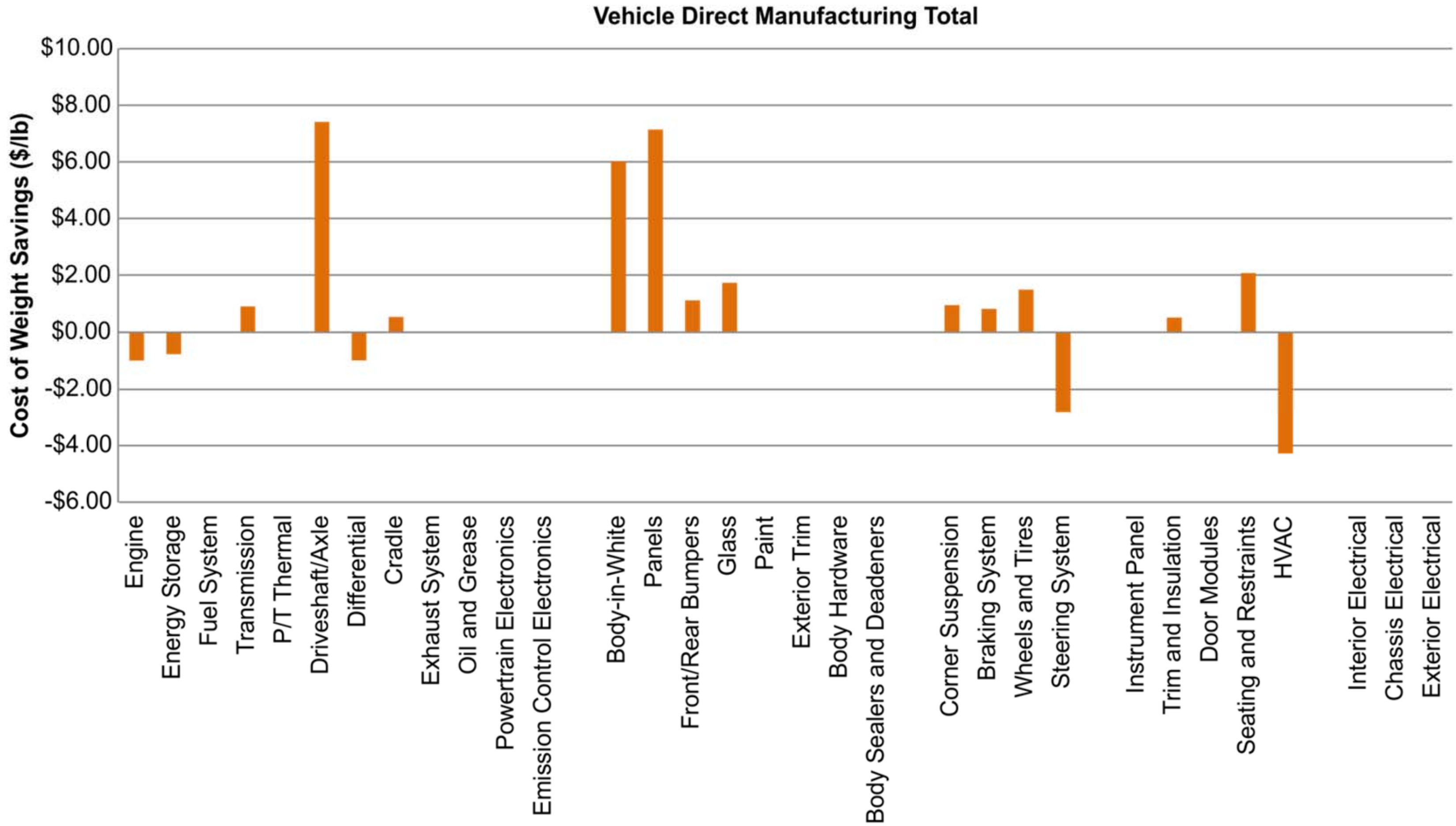

Figure 23. Carbon fiber composite-intensive scenario Stage 4 – cost of mass reduction by system (cost and weight differential are combined and presented as the cost of weight savings of each subsystem) using projected carbon fiber processing cost of $5/lb and carbon fiber price of $12.50/lb.

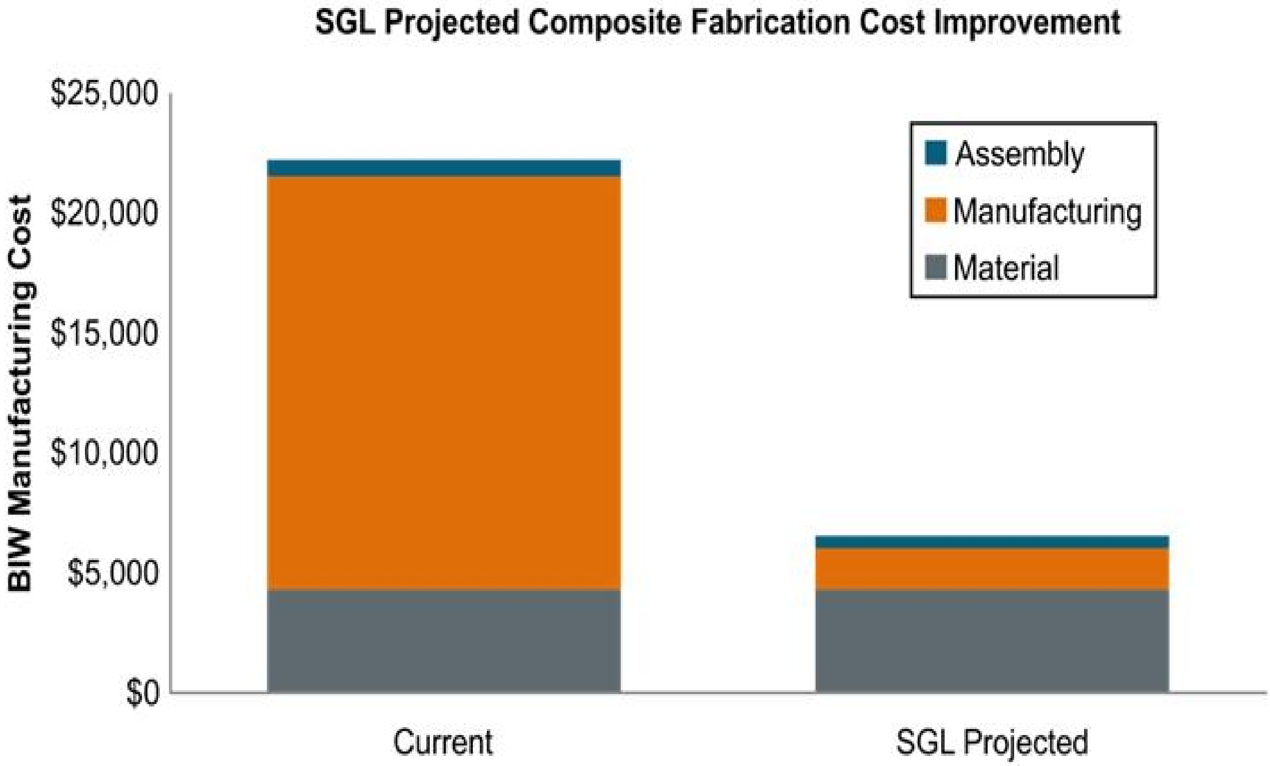

Figure 24. Carbon fiber BIW direct manufacturing cost.

8. CONCLUSION – 40% WEIGHT SAVINGS TARGET

The presented analysis shows that a 40% weight reduction in a standard midsize passenger vehicle is within reach using currently available technology, as demonstrated through the multi-material and carbon fiber composite-intensive vehicle scenarios under some specific stipulations (Figure 26). Achieving this level of mass reduction at the target cost of $3.42/lb pound saved is possible ONLY with significant improvements in processing technologies (Berger 2014).

In the case of carbon fiber composite molding, these advances will require high-rate, high-volume processing for material preparation, preforming, and molding. Processing must be on the order of 3-minute cycle times for complex automotive structures (IBIS 2010) to reduce part-forming costs from the current $50/lb to the neighborhood of $5/lb. Meeting the cost target will require reducing not only processing costs, but also the raw carbon fiber price by more than 50% to $6/lb.

Furthermore, applying some or all of these lightweighting technologies may reduce vehicle performance in terms of OEM customer requirements such as noise, vibration, ride comfort, repairability, and safety. However, there are very real opportunities for significant mass reduction within acceptable price increases. Continued exploration of vehicle lightweighting technologies will identify the best course forward in terms of optimizing the amount of mass reduced relative to the cost premium.

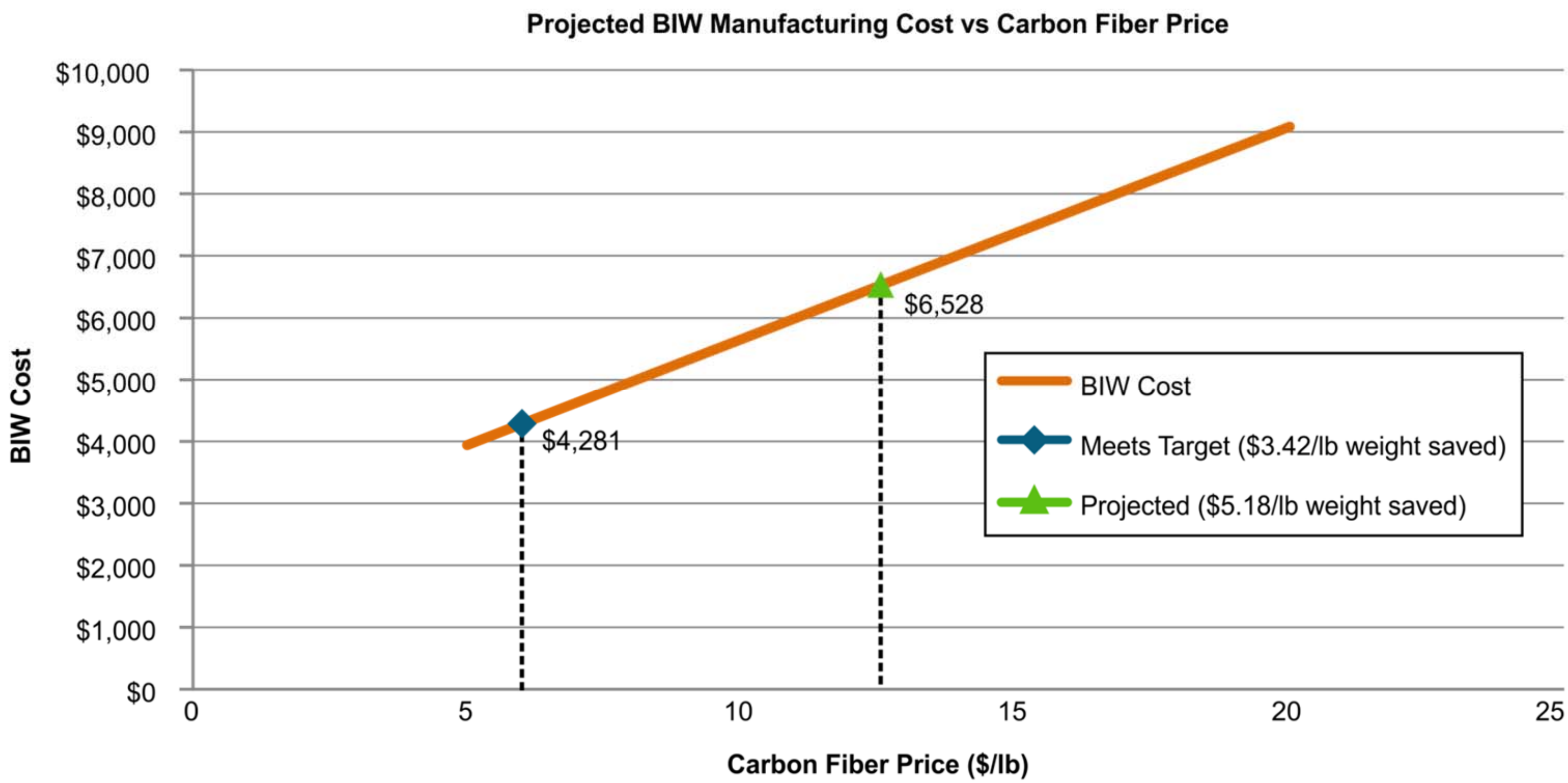

Figure 25. BIW cost versus carbon fiber price.

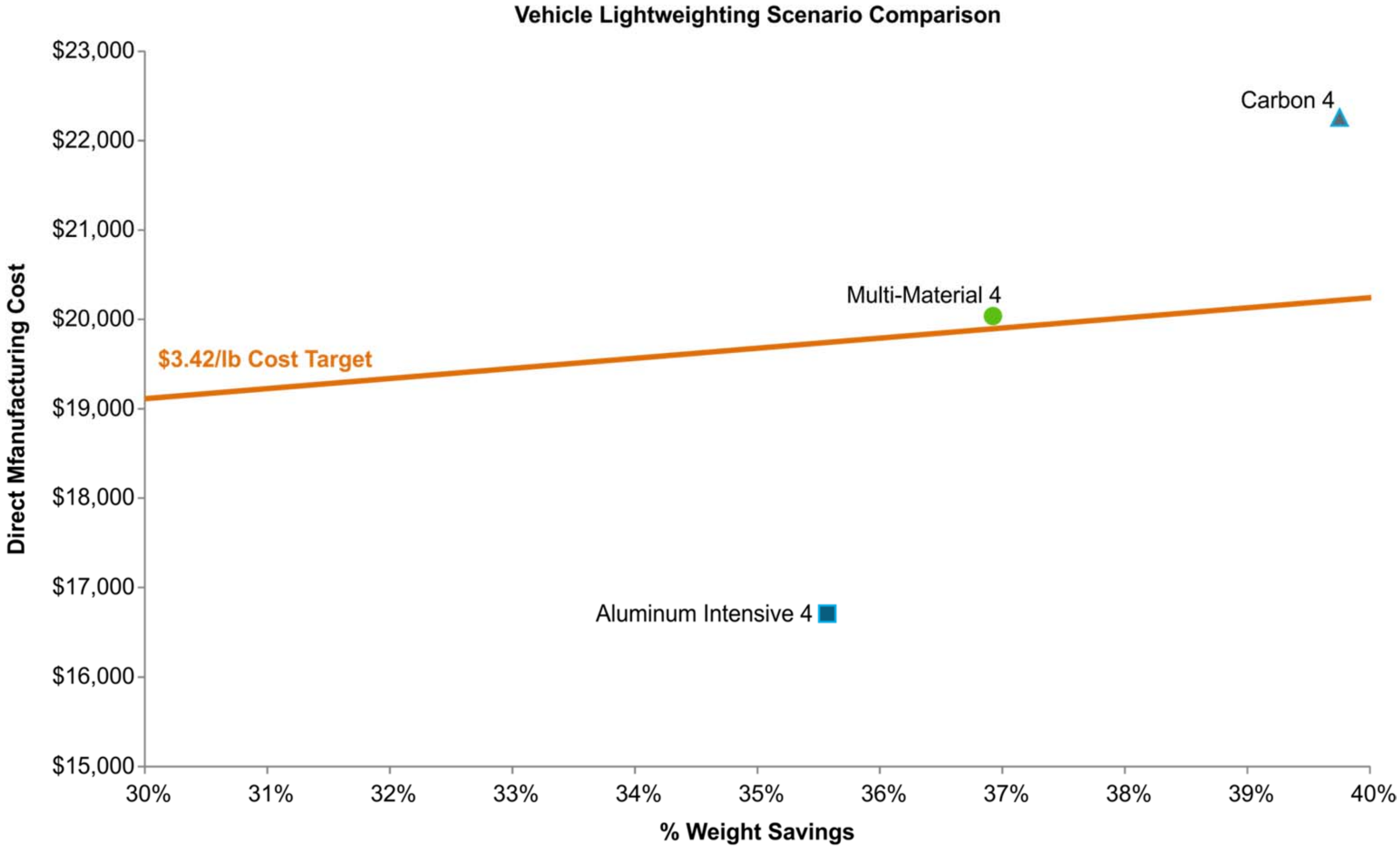

Figure 26. Advanced weight savings scenario results; carbon 4 data point assumes a projected carbon fiber processing cost of $5/lb and current carbon fiber price of $12.50/lb.

9. VEHICLE TECHNOLOGY CONCEPTS – 45% WEIGHT SAVINGS TARGET

To assess the 45% weight reduction relative to the baseline, the "Carbon 4" scenario, built around a carbon fiber composite body vehicle, served as the starting point to explore additional cost-saving strategies to further reduce the vehicle mass by an additional 165 to 1,817 lb. Meeting this mass reduction at the $3.42/lb-saved cost target would result in a direct manufactured vehicle cost of only $20,809. This number is well below the cost of the less aggressive 40% mass reduction target results, even under optimal projected process economics at current market conditions. This analysis pursued an approach similar to that for the 40% reduction targets in terms of identifying potential strategies for further weight savings and then assessing material pricing conditions required to achieve the cost-of-weight-savings target.

The 40% weight reduction analysis drew data from several well-developed full vehicle concepts, as described in Section 3.2. To achieve the weight goal, weight reduction strategies from these programs had to be combined with additional, more speculative concepts, most significantly, a high-volume-production, fully composite BIW. The more aggressive 45% mass reduction target requires additional speculative technologies to be considered.

9.1 Stage 5 Technologies Examined

For the "Stage 5 Carbon" scenario addressing this 45% weight savings target, additional magnesium, carbon fiber composite, and glass fiber composite substitution were added to the vehicle concept, along with advanced electric and electronic systems to further reduce the vehicle mass.

9.1.1 Magnesium

In addition to the many lightweight metal and multi-material programs conducted for USCAR, United States Automotive Materials Partnership has published details of many lightweighting opportunities for magnesium substitution in their "Magnesium Vision 2020" report (USAMP 2006). From this analysis of potential weight savings, several components were identified for inclusion in the Stage 5 scenario, albeit at increased material and processing cost relative to aluminum. These include extruded bumpers, body hardware, brake calipers, steering wheel and column housing, and the instrument panel beam.

9.1.2 Carbon Fiber Composites

Carbon fiber wheels represent a significant opportunity for weight savings and are currently produced for specialty high-performance and racing aftermarkets. Produced at low volumes and extremely expensive ($15,000 per set), they can save 40 to 60% of the wheel rim mass, depending on the type of material they are replacing (Carbon Revolution 2014, Halvorson 2012). In the cost analysis, it is assumed that the same optimized high-volume processing economics for the carbon fiber BIW would be achieved for wheels.

9.1.3 Glass Fiber Composites and Other

The U.S. Department of Transportation published a study through NHTSA as part of "A Safety Roadmap for Plastics and Composites Intensive Vehicles." Conducted by the National Crash Analysis Center of George Washington University, this study explores numerous strategies for using polymer composites and other strategies for reducing mass on a baseline Chevrolet Silverado pickup truck (Park et al. 2012). Many of these strategies have already been addressed from other sources in the current analysis. Other strategies incorporated into the Stage 5 concept include weight savings achieved from the long fiber polypropylene composite door modules, carbon ceramic brake disks, lightweight tires, and lithium-ion batteries.

9.1.4 Electrical

Lithium-ion batteries have significantly greater power densities than lead acid batteries, but they are much more expensive (Lithium Pros 2014). Systems manufactured for automotive use are approximately one third of the weight, but three to four times the price, of lead acid technology. In-vehicle networking connects microcontrollers throughout the vehicle to manage communication and control between sensors, processors, motors, actuators, and other mechanisms, eliminating most of the copper wiring needed for dedicated circuits, which can run several miles of wire per vehicle. As vehicle electronic systems are becoming increasingly complex, the cost and mass differential of a fully internal networked system relative to traditional wire harnesses is unclear. It has been reported that up to 150 lb can be saved at a system cost of two to five times more than a traditional system (Freescale Semiconductor 2013, D'Orazio et al. 2011). However, it has also been suggested that there will be significant assembly labor savings.

10. ANALYSIS RESULTS – 45% WEIGHT SAVINGS TARGET

10.1 Stage 5 Mass Reduction

The resulting mass distribution of the Stage 5 Scenario is shown in Figure 27. Table 5 compares the Stage 5 45% savings scenario to the baseline, reference cases, and earlier-stage scenarios.

The resulting mass reduction, relative to the baseline, is shown in Figure 28. It is clear from this depiction that the greatest single source of weight savings, by a substantial margin, is the carbon fiber BIW. The second greatest source of savings comes from the downsized engine, more from design improvements and power reduction for a lighter vehicle than from material substitution. The transmission, closures, suspension, braking, wheels/tires, and seating all represent a third group of moderate savings, achieved primarily through carbon and magnesium substitution.

Figure 29 compares the starting baseline mass with the resulting Stage 5 mass and shows the weight savings per subsystem.

10.2 Stage 5 Cost Analysis Results

The cost analysis results of the vehicle subsystem's direct manufacturing costs are presented in Figure 30. It is readily apparent that carbon fiber BIW is the largest contributor to vehicle cost, as it was to weight savings. The BIW, panels, and wheels are all based on carbon fiber usage and are all disproportionately expensive relative to the baseline compared to other subsystems employing other weight-saving strategies. For this reason, both the 40% analysis and the 45% analysis examined carbon fiber price to determine the sensitivity of its impact on reducing vehicle manufacturing cost and meeting the cost-of-weight-reduction target. Table 6 compares the manufacturing cost, the vehicle mass and weight savings, and the $3.42/lb-target cost of weight savings for each of the scenarios examined.

In Figure 31, the Stage 4 scenarios approaching 40% savings are compared with the Stage 5 scenarios. As this chart and Table 6 indicate, reaching the target cost for 45% weight savings (i.e., $20,829) requires that the Stage 5 carbon fiber composite-intensive scenario reduce overall vehicle cost by nearly $4,400. The impact of reducing carbon fiber price on overall vehicle cost is shown in Figure 32. The green triangle represents the current cost analysis results at $25,411 per vehicle using $12.50/lb. To meet the targeted $20,829 per vehicle, the material price of carbon would have to decrease to $4.20/lb. This is a greater reduction than required in the 40% savings analysis because the 45% savings scenario translates into more weight savings, requiring more costly weight-saving strategies such as use of carbon, magnesium, lithium-ion batteries, and vehicle networking.

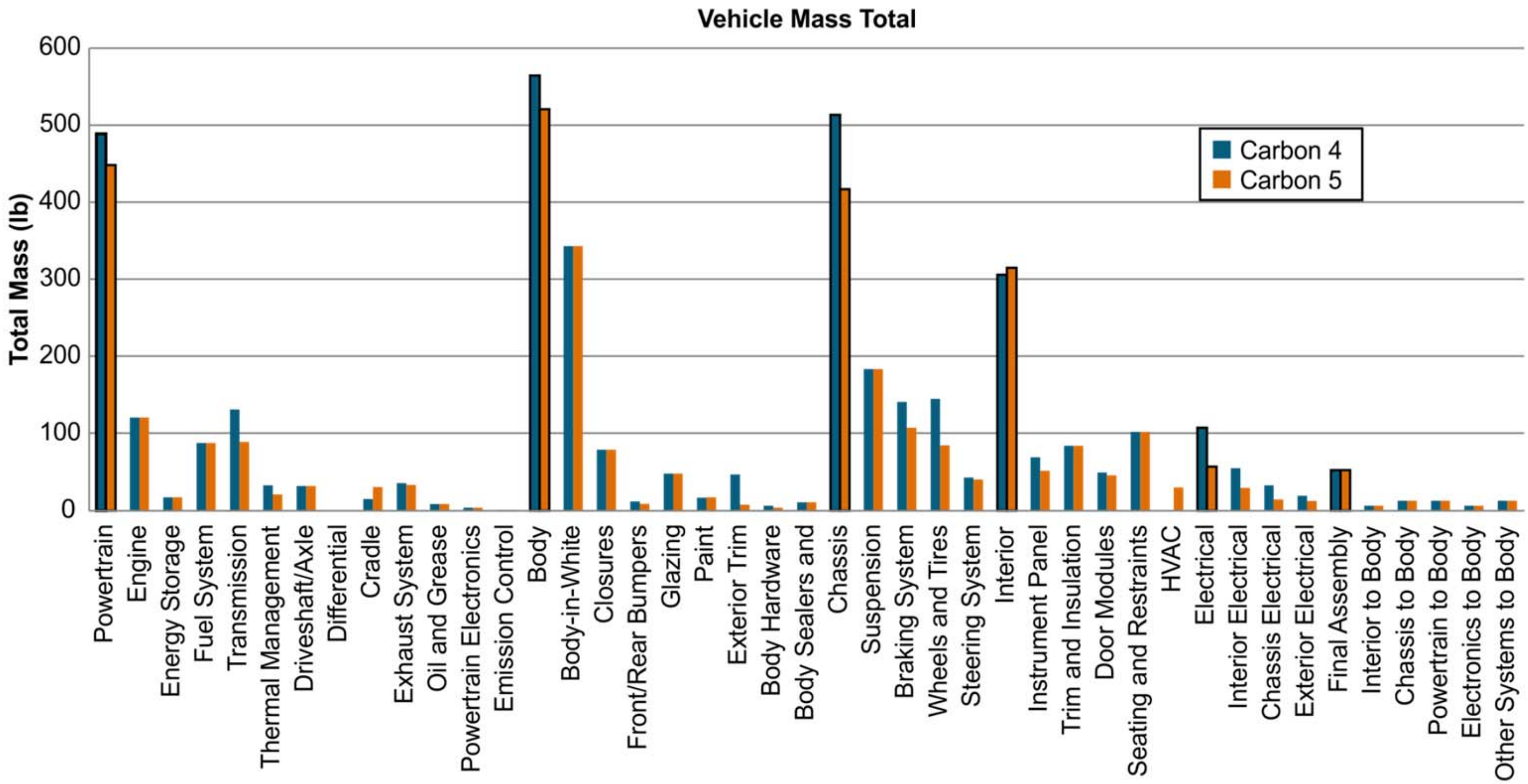

Figure 27. Stage 4 (40% weight reduction) to Stage 5 (45% weight reduction) scenario comparison.

Table 5. Scenario mass reduction summary.

	Ford	Ford/Vehma	DOE	IBIS	IBIS	IBIS	IBIS	IBIS	IBIS	IBIS	IBIS	IBIS	IBIS	IBIS	IBIS	IBIS
	2013 Fusion	MMLV-M1	2013 Midsize Baseline	Midsize Baseline 2013	Optimized Steel 1	Optimized Steel 2	Optimized Steel 3	Aluminum Intensive 1	Aluminum Intensive 4	Multi-Material 1	Multi-Material 2	Multi-Material 3	Multi-Material 4	Carbon 1	Carbon 4	Carbon 5
Total Mass (lbs)	**3430**	**2629**	**3303**	**3304**	**3198**	**2843**	**2758**	**2937**	**2129**	**3138**	**2604**	**2493**	**2084**	**2843**	**2034**	**1812**
				lbs		lbs		lbs		lbs		lbs		lbs		lbs
Powertrain	**836.0**	**590.7**	**1080.3**	**997.9**	**991.9**	**837.0**	**837.0**	**977.1**	**493.9**	**988.4**	**582.1**	**576.0**	**491.6**	**971.7**	**488.9**	**448.5**
Engine	266.2	120.8	345.5	345.4	345.4	279.4	279.4	345.4	121.0	345.4	121.0	121.0	121.0	345.4	121.0	121.0
Energy Storage	30.8	17.6	39.6	33.0	33.0	33.0	33.0	33.0	17.6	33.0	17.6	17.6	17.6	33.0	17.6	17.6
Fuel System	147.4	130.4	142.7	164.8	164.8	137.1	137.1	164.8	88.0	164.8	130.5	130.5	88.0	164.8	88.0	88.0
Transmission	193.6	169.4	242.9	195.4	189.4	147.6	147.6	174.6	136.4	186.0	164.5	158.5	134.1	169.3	131.4	89.3
Thermal Management	15.4	37.3	41.1	33.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0	21.3
Driveshaft/Axle	39.6	32.3	61.9	55.2	55.2	51.7	51.7	55.2	32.3	55.2	32.3	32.3	32.3	55.2	32.3	32.3
Differential	2.2	0.0	28.4	24.0	24.0	24.0	24.0	24.0	0.2	24.0	0.2	0.2	0.2	24.0	0.2	0.2
Cradle	59.4	32.9	72.2	62.0	62.0	62.0	62.0	62.0	15.4	62.0	33.0	33.0	15.4	62.0	15.4	31.0
Exhaust System	48.4	35.9	49.9	49.9	49.9	34.1	34.1	49.9	35.9	49.9	35.9	35.9	35.9	49.9	35.9	33.7
Oil and Grease	8.8	8.7	27.1	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8
Powertrain Electronics	19.8	3.9	26.4	22.0	22.0	22.0	22.0	22.0	4.0	22.0	4.0	4.0	4.0	22.0	4.0	4.0
Emission Control Electronics	4.4	1.4	2.7	4.4	4.4	4.4	4.4	4.4	1.3	4.4	1.3	1.3	1.3	4.4	1.3	1.3
Body	**1146.2**	**889.2**	**1000.0**	**1006.2**	**906.1**	**906.1**	**891.6**	**659.7**	**654.8**	**848.9**	**850.6**	**844.0**	**612.4**	**570.6**	**564.6**	**520.9**
Body-in-White	717.2	550.5	716.7	716.8	618.3	618.3	618.3	429.0	429.0	550.0	550.0	550.0	396.0	344.3	343.2	343.2
Closures	215.6	151.3	134.2	134.2	134.2	134.2	134.2	83.6	83.6	151.8	151.8	151.8	74.3	79.2	79.2	79.2
Front/Rear Bumpers	90.2	57.0	22.4	20.2	18.6	18.6	18.6	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	9.2
Glazing	79.2	54.8	48.7	81.0	81.0	81.0	72.2	81.0	48.4	81.0	55.0	48.4	48.4	81.0	48.4	48.4
Paint	17.6	17.0	26.8	24.3	24.3	24.3	24.3	24.3	16.9	24.3	16.9	16.9	16.9	24.3	16.9	17.6
Exterior Trim	8.8	47.2	24.4	8.1	8.1	8.1	8.1	8.1	47.1	8.1	47.1	47.1	47.1	8.1	47.1	8.1
Body Hardware	6.6	0.0	22.4	17.6	17.6	17.6	11.9	17.6	6.6	17.6	6.6	6.6	6.6	17.6	6.6	4.1
Body Sealers and Deadeners	11.0	11.6	4.5	4.0	4.0	4.0	4.0	4.0	11.0	4.0	11.0	11.0	11.0	4.0	11.0	11.0
Chassis	**721.6**	**552.1**	**674.7**	**662.6**	**662.6**	**462.0**	**462.0**	**662.6**	**513.6**	**662.6**	**533.4**	**533.4**	**513.6**	**662.6**	**513.6**	**417.1**
Suspension	266.2	222.5	298.8	269.6	269.6	175.7	175.7	269.6	183.8	269.6	203.6	203.6	183.8	269.6	183.8	183.8
Braking System	173.8	141.2	155.6	163.1	163.1	102.4	102.4	163.1	141.2	163.1	141.2	141.2	141.2	163.1	141.2	107.8
Wheels and Tires	233.2	145.1	128.6	180.5	180.5	138.4	138.4	180.5	145.2	180.5	145.2	145.2	145.2	180.5	145.2	84.8
Steering System	48.4	43.3	91.7	49.4	49.4	45.4	45.4	49.4	43.3	49.4	43.3	43.3	43.3	49.4	43.3	40.7
Interior	**550.0**	**431.6**	**472.3**	**472.6**	**472.6**	**472.6**	**416.0**	**472.6**	**306.0**	**472.6**	**472.6**	**378.6**	**306.0**	**472.6**	**306.0**	**315.0**
Instrument Panel	83.6	69.6	70.9	84.5	84.5	84.5	70.6	84.5	69.5	84.5	84.5	69.5	69.5	84.5	69.5	51.9
Trim and Insulation	88.0	84.4	91.2	118.6	118.6	118.6	118.6	118.6	84.5	118.6	118.6	84.5	84.5	118.6	84.5	84.5
Door Modules	110.0	93.5	66.4	49.7	49.7	49.7	49.7	49.7	49.7	49.7	49.7	49.7	49.7	49.7	49.7	46.0
Seating and Restraints	198.0	128.4	196.1	172.0	172.0	172.0	134.6	172.0	102.3	172.0	172.0	127.2	102.3	172.0	102.3	102.3
HVAC	70.4	55.6	47.6	47.7	47.7	47.7	42.5	47.7	0.0	47.7	47.7	47.7	0.0	47.7	0.0	30.4
Electrical	**123.2**	**116.7**	**53.4**	**112.2**	**112.2**	**112.2**	**98.8**	**112.2**	**107.8**	**112.2**	**112.2**	**107.8**	**107.8**	**112.2**	**107.8**	**57.2**
Interior Electrical	68.2	55.3	6.9	57.2	57.2	57.2	46.9	57.2	55.2	57.2	57.2	55.2	55.2	57.2	55.2	29.7
Chassis Electrical	33.0	41.8	6.9	33.0	33.0	33.0	31.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0	14.7
Exterior Electrical	22.0	19.6	39.6	22.0	22.0	22.0	20.9	22.0	19.6	22.0	22.0	19.6	19.6	22.0	19.6	12.8
Final Assembly	**52.8**	**48.2**	**22.6**	**52.8**	**52.8**	**52.8**	**52.8**	**52.8**	**52.8**	**52.8**	**52.8**	**52.8**	**52.8**	**52.8**	**52.8**	**52.8**
Interior to Body	6.6	6.0	2.8	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6
Chassis to Body	13.2	12.0	5.6	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2
Powertrain to Body	13.2	12.0	5.6	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2
Electronics to Body	6.6	6.0	2.8	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6
Other Systems to Body	13.2	12.0	5.6	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2

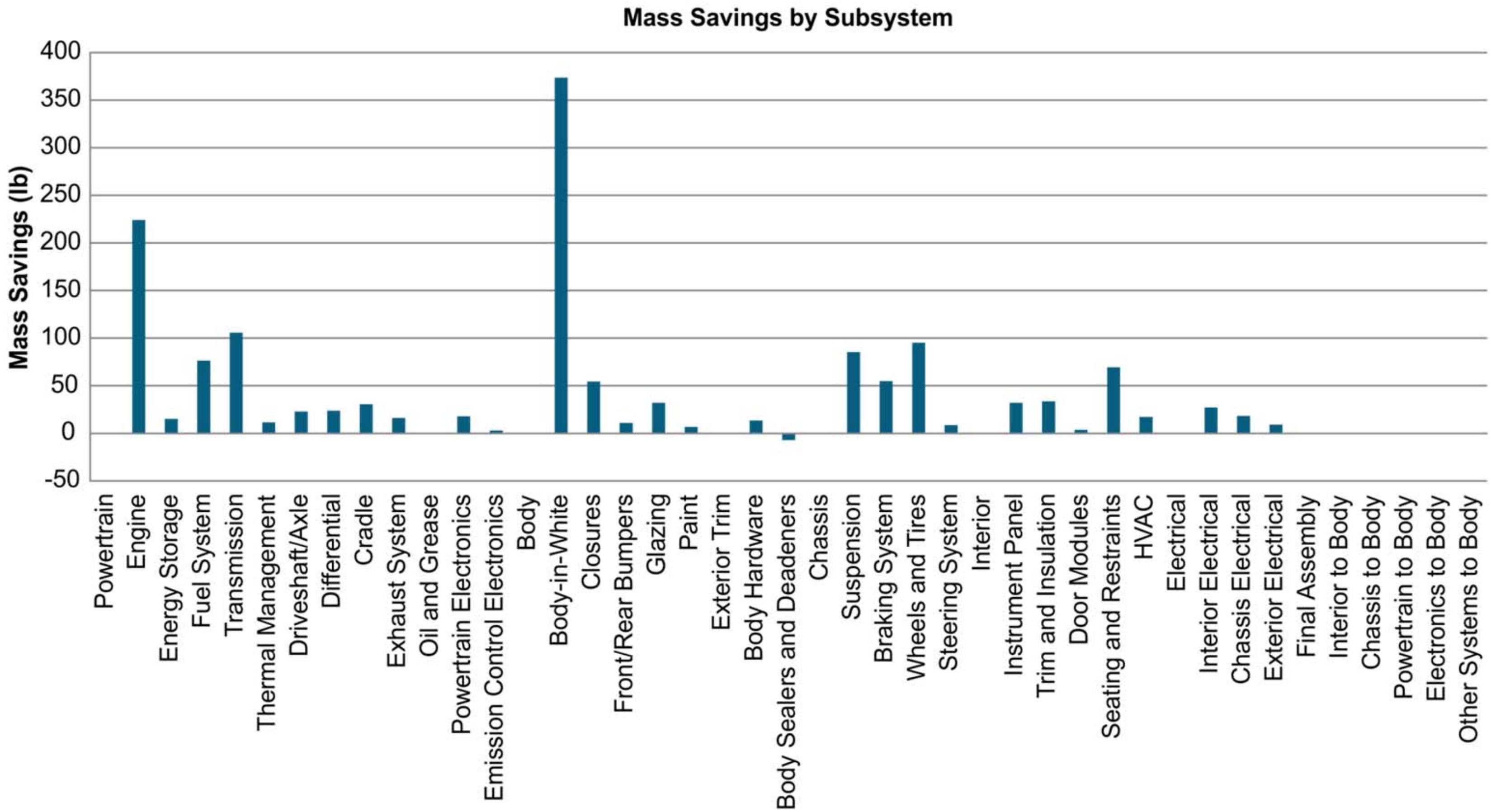

Figure 28. Forty-five percent weight reduction target (Carbon Stage 5 scenario), mass savings by system (the greatest single source of weight savings, by a substantial margin, is the carbon fiber BIW).

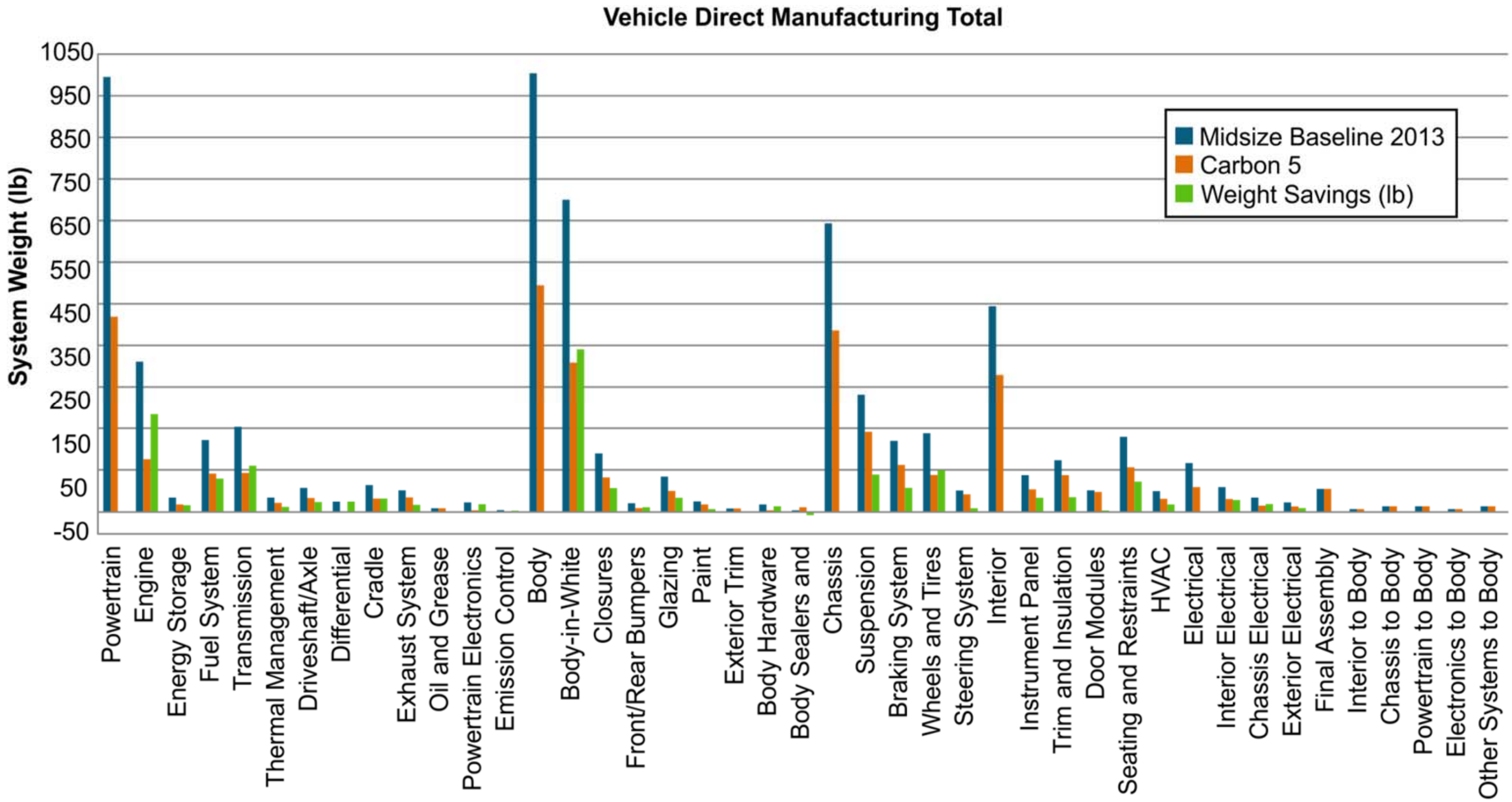

Figure 29. Baseline relative to Carbon Stage 5 (45% weight savings).

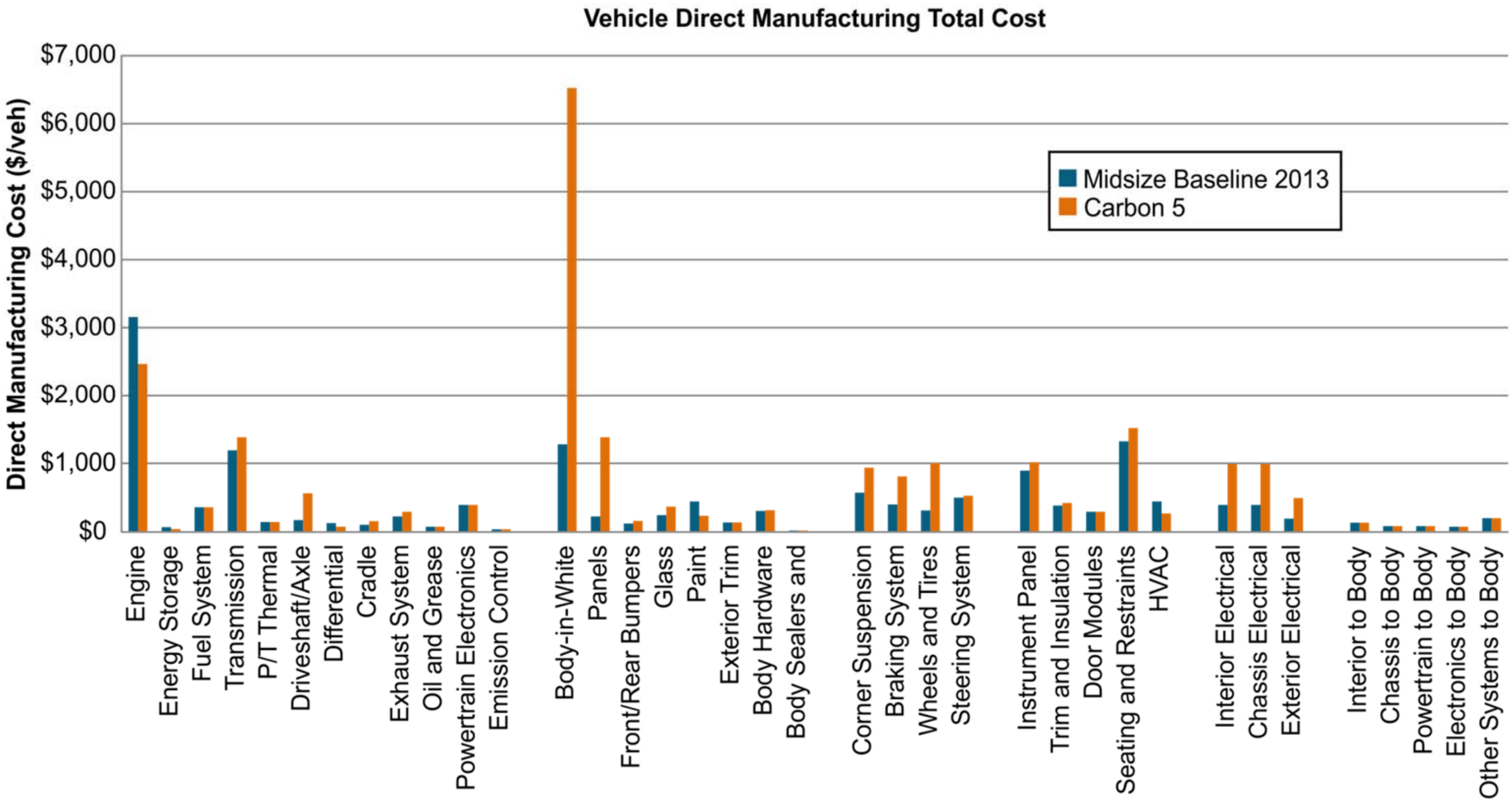

Figure 30. Cost analysis results of 45% weight reduction scenario (Carbon Stage 5) (used projected carbon composite processing cost of $5/lb and current material cost of $12.50/lb).

Table 6. Weight savings relative to target.

	2013 Ford Fusion	Vehma/Ford MMLV-M1	Midsize Baseline 2013	Optimized Steel 1	Optimized Steel 2	Optimized Steel 3	Aluminum Intensive 1	Aluminum Intensive 4	Multi-Material 1	Multi-Material 2	Multi-Material 3	Multi-Material 4	Carbon 1	Carbon 4	Carbon 5	40% Reduction Target	45% Reduction Target
Lbs	3430	2629	3304	3198	2843	2758	2937	2129	3138	2604	2493	2084	2843	2034	1812	1983	1817
Lbs Saved	0	801	0	106	462	546	367	1175	167	701	812	1220	462	1271	1493	1322	1487
% wt savings	0.0%	23.4%	0.0%	3.2%	14.0%	16.5%	11.1%	35.6%	5.0%	21.2%	24.6%	36.9%	14.0%	38.5%	45.2%	40.0%	45.0%
Direct Mfg Cost			$15,724	$15,522	$15,389	$15,291	$16,070	$16,706	$16,107	$16,484	$16,833	$20,036	$21,705	$22,307	$25,211		
$3.42/lb Cost Target			$15,724	$16,087	$17,302	$17,591	$16,980	$19,744	$16,294	$18,120	$18,500	$19,896	$17,303	$20,069	$20,829	$20,244	$20,809
Project Cost of Wt. Save				-$1.90	-$0.72	-$0.79	$0.94	$0.84	$2.30	$1.09	$1.37	$3.53	$12.95	$5.18	$6.36		
Target Cost Wt. Save			$3.42	$3.42	$3.42	$3.42	$3.42	$3.42	$3.42	$3.42	$3.42	$3.42	$3.42	$3.42	$3.42		

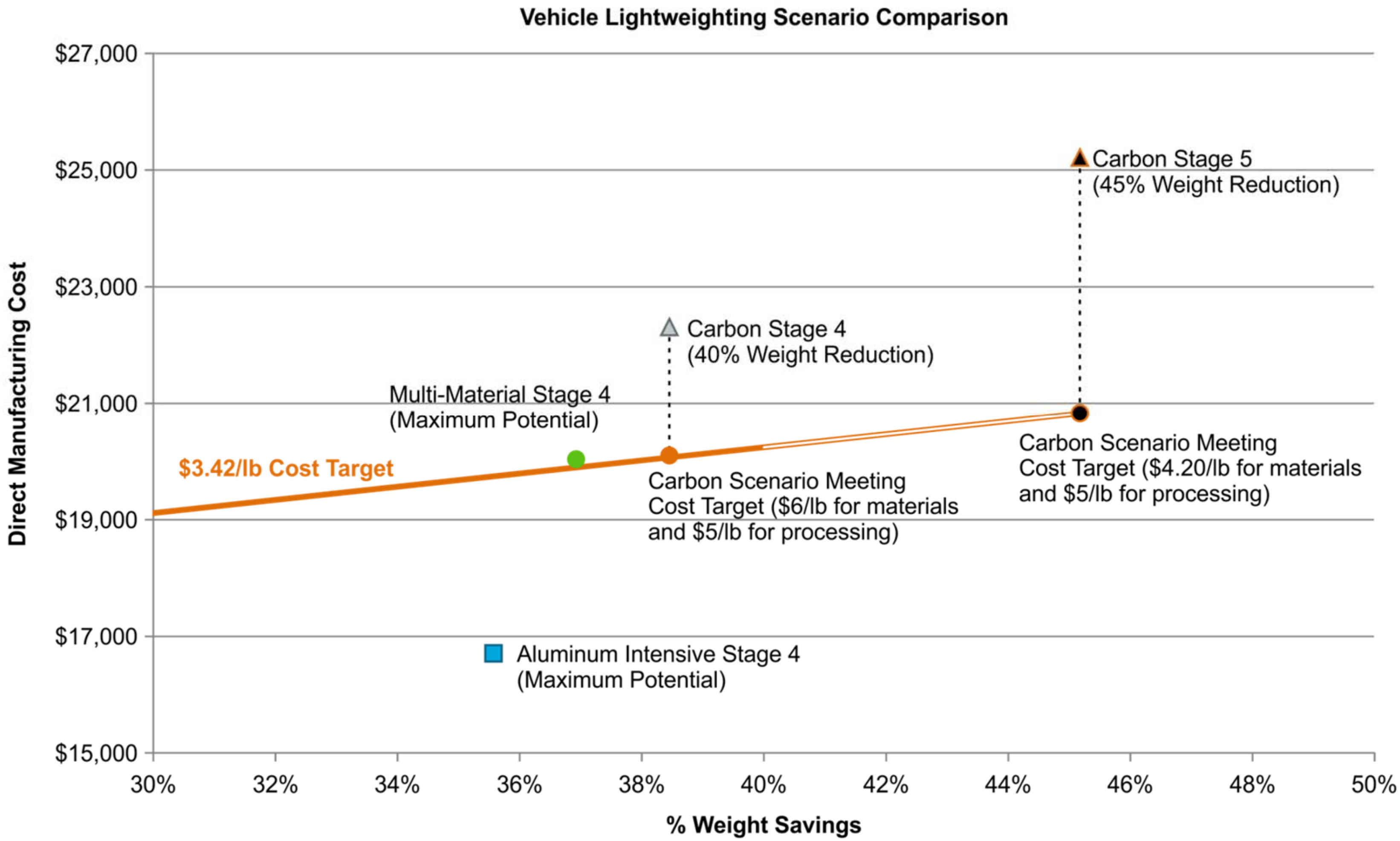

Figure 31. Forty-five percent weight savings scenario results (Carbon Stage 4 and 5 assume a carbon composite processing cost of $5/lb and carbon fiber price of $12.50/lb).

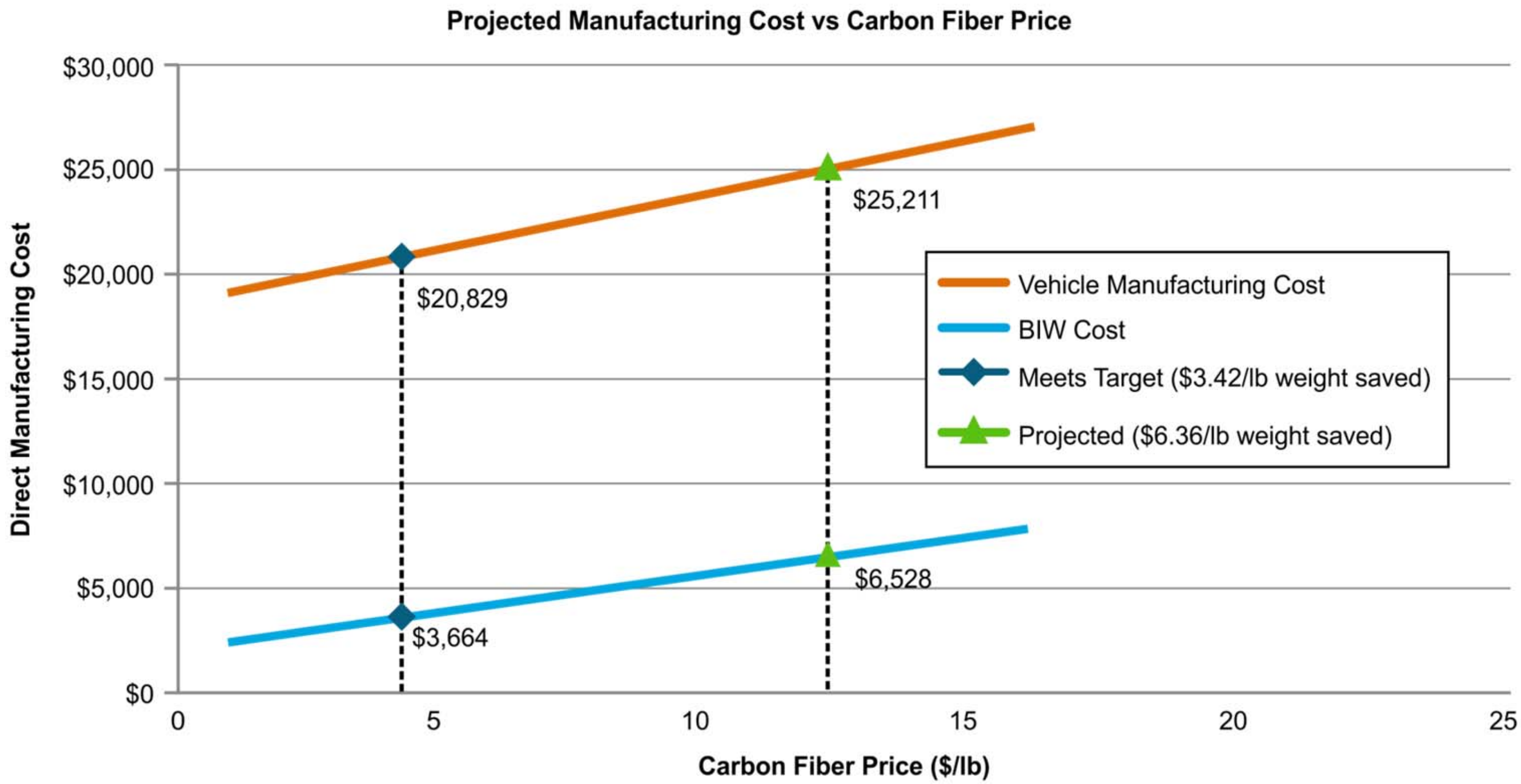

Figure 32. Carbon fiber price required to meet 45% weight savings target.

11. CONCLUSIONS – 45% WEIGHT SAVINGS TARGET

It has been shown that it is conceptually possible to reduce the mass of a baseline North American midsize passenger vehicle by 45% under some specific stipulations. The concept explored would require extensive use of carbon fiber and magnesium, as well as engine power reduction and other system downsizing. Just as in the case of the 40% target analysis, achieving this level of mass reduction at the target cost of $3.42 /lb saved is only possible with significant improvements in processing technologies (Berger 2014). In the case of carbon fiber composite molding, these advances will require high-rate, high-volume processing for material preparation, preforming, and molding on the order of 3-minute cycle times for complex automotive structures (IBIS 2010)[3] to reduce processing costs from the current $50/lb to the neighborhood of $5/lb. Furthermore, the carbon fiber price would have to be reduced to $4.20/lb because of the greater amount of carbon composites used and the expensive strategies needed to achieve additional weight savings.

From examining the broad picture of multiple technologies covering a broad range of potential weight savings, cost premiums, and technology readiness, the following conclusions have been drawn:

- Through the use of established technologies, state-of-the-art designs, and some level of power and luxury downsizing, if accepted by the market, mass reduction on the order of 30% can be achieved with a moderate price premium and relatively low technical risk.
- A significant amount of advanced lightweighting would be required for 40% mass reduction. The lightweighting would include both high-volume production (magnesium), which involves moderate technical risk, and automated and rapid cycle time composite forming, which involves high technical risk. The cost premium will remain very high until high-volume, low-cost carbon fiber is available.
- Mass reduction of 45% or more will require not only extensive use of lightweight materials, such as carbon fiber and magnesium, but also next-generation electrical and interior systems. The goal could be more readily achieved if there were significant changes in market expectations of performance, comfort, and features.

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Appendix A
Derivation of Cost Target Used in this Study

The acceptable price penalty for weight reduction of a passenger vehicle is a complicated function of the manufacturer's internal costs, the perceived value of a light vehicle among the car-buying public, the fuel price paid by consumers, and the fuel economy benefits achieved by reducing weight. In order to establish the penalty target used in this study, DOE VTO performed an analysis, balancing the fuel savings over the life of a vehicle against the incremental price of lightweight material technologies.

Based on multiple analyses reported in the literature, a 10% reduction in vehicle weight results in a 7% reduction in fuel consumption, assuming that the vehicle is re-optimized such that all other vehicle performance remains constant (Cheah 2010, Broda and Casadei 2007, Bandivadekar et al. 2008). Therefore, the value of weight reduction for consumers is tied to reduced lifetime fuel costs and a break-even point exists as a function of the cost penalty for weight reduction and the price of fuel. As fuel price increases, total lifetime fuel cost savings increase and the acceptable price penalty for weight reduction increases.

In order to establish a quantitative target, it is assumed that each vehicle will travel 10,000 miles annually for a 15-year life. These assumptions are consistent with historical data; according to the Transportation Energy Databook, fewer than one-third of all light vehicles remain in use after 15 years (ORNL 2014). An analysis of R. L. Polk Company data performed by NHTSA shows that vehicles that do survive to 15 years have traveled on average around 10,000 miles per year, but only 7,500 miles in year 15 (NHTSA 2006). We use a baseline vehicle weighing 3,500 lb and achieving 28.4 mpg fuel economy. The fuel cost estimate in this analysis uses the Annual Energy Outlook 2011 High Oil Price case projected fuel price data out to 2025 (EIA 2011), which ranges from $4.13/gallon in 2014 to $5.12/gallon in 2025.

Using the assumptions and vehicle baseline described above, the total lifetime fuel savings per pound of weight saved is calculated to be 1.1 gallon. Multiplying this value by the projected fuel price for a given year yields the lifetime fuel cost savings per pound of weight saved over the 15-year vehicle lifetime. Finally, this cost savings is discounted 7% each year (i.e., value used for the DOE Vehicle Technologies Government Performance and Results Act Report for Fiscal Year 2015 [Stephens et al. 2014]) because the vehicle owner must pay for the weight reduction up front, but drive for 15 years to realize the complete payback.

While these material targets are described as cost to the manufacturer, consumer return on investment is based on the purchase price, which includes a manufacturer mark-up. This markup is included in the resulting estimate, which provides an upper boundary on acceptable price, and further reductions in the penalty amount make implementation of the technologies more likely.

Estimates of future fuel prices and interest rates, which determine appropriate discount rates, are notoriously inaccurate. The Annual Energy Outlook estimate of crude oil cost, which is the key determinate of fuel price, for the last 15 years has substantially underestimated the actual cost (EIA 2014). Thus, while the logic described above seems to determine an upper bound for acceptable price, the historic trends in estimates of the underlying values suggests that these acceptable estimates may be too low.

Appendix B
Vehicle System Descriptions

Powertrain

Engine

Description: In this model, "engine" refers to conventional internal combustion engines. In addition to basic power plant and auxiliary systems and components, engine cooling systems, lubrication, fluid containers, and pumps are included.

Baseline: In-line, 4-cylinder, naturally-aspirated, 2.5-L gasoline engine.

Engine	Crankshaft	$390
	Cylinder Head	$390
	Cylinder Block	$699
	Oil Pan Assembly	$264
	Camshafts	$77
	Valve Roller Rocker	$234
	Other	$719

Battery

Baseline: Lead-acid, standard.

Energy Storage	Battery	$74

Fuel System

Description: The system comprises the fuel tank, gauge, tank shield, access door, mounting straps, rails, and injectors and includes the mass of the fuel itself.

Baseline: Gasoline, 17-gallon.

Fuel System	Fuel Tank	$269
	Other	$96

Transmission

Description: In this analysis, the transmission refers to the gearbox, clutch, and controls. Note that in some literature, the transmission refers to the clutch, gearbox, driveshaft, and differential. These are each treated as separate components/subsystems in this model.

Baseline: 4-speed automatic transmission.

Transmission	Case	$351
	Gears and Shaft	$293
	Clutch	$537
	Other	$18

Driveline

Description: The driveline includes the driveshaft/axle and the differential. The driveshaft/axle system includes two assemblies: (1) the driveshaft assembly that couples with the gearbox and differential and (2) the axles, including the axle shaft, housing, boots, and couplings to the wheels. The differential transmits mechanical energy from the driveshaft to the axles and allows for different rotational speeds at each wheel.

Driveshaft/Axle	Driveshaft assembly	$86
	CV joint	$91
Differential	Drive bearings	$26
	Case	$50
	Gears	$57

Cradle

Description: The cradle is a front subframe that attaches to the BIW and supports the mounting of the engine.

Cradle	Cradle	$107

Thermal Management

Description: Thermal management refers to the systems and controls involved in measuring and regulating engine temperature through coolant and heat exchangers.

Thermal Management	Radiator	$37
	Radiator fan assembly	$41
	Radiator fan motor	$20
	Other	$51

Exhaust System

Description: The system includes all exhaust equipment after the exhaust manifold, including the exhaust pipe, catalytic converter(s), and muffler(s).

Exhaust System	Exhaust manifold	$25
	Catalytic converter	$156
	Muffler	$43
	Other	$6

Powertrain Electrical

Description: This system comprises the engine control wiring, sensors, and electronic control unit(s). The electric motor(s) controller(s) for hybrid electric vehicles may be considered as part of the electric motor or could be included here if desired.

Powertrain Electrical	Engine control module	$198
	Power electrical	$122
	Alternator	$81

Emission Control

Description: This system comprises the sensors, electronic control unit(s), and engine feedback equipment that maintain exhaust emissions within specified limits.

Emission Control Electronics	Emission Control Electronics	$43

Lubrication Fluids

Description: Fluids include engine oil, transmission oil, and other miscellaneous lubricants.

Oil and Grease	Oil and Grease	$81

Body

BIW

Description: The BIW is the primary vehicle structure, usually a single-body assembly, consisting of engine compartment, passenger cabin, and storage. Closure panels and hang-on panels (e.g., fenders) are included, even if non-structural. In the model discussed in this study, the doors are included as well.

Baseline: Stamped steel unibody.

BIW	BIW	$1,287

Closures

Closures	Panels	$230

Bumpers

Description: Bumpers include the impact bar, energy absorber, and other miscellaneous mounting hardware.

Baseline: Sheet steel.

Front/Rear Bumper	Impact module	$46
	Other	$80

Glazing

Description: Glazing includes the front laminated glass windshield, tempered rear windows, door windows, and rear quarter windows.

Glazing	Glass	$250

Paint

Description: The cost and mass of the total painting operation is included (i.e., e-coat, priming, base coats, color coats, and clear coats).

Paint	Paint	$450

Exterior Trim

Description: Trim includes the bumper cover, air deflectors, ground effects, side trim, mirror assemblies, nameplates, etc.

Exterior Trim	Exterior Trim	$144

Body Hardware

Description: Hardware includes handles, external mirrors, appearance trim, and other miscellaneous items.

Body Hardware	Body Hardeners	$312

Sound and Vibration Control

Description: This system comprises sound and vibration deadening materials and inserts incorporated into the structure to reduce noise, vibration, and harshness.

Body Sealer & Deadners	Body Sealer & Deadners	$2

Chassis

Suspension

Description: This system comprises control arms, ball joints, spring, shock absorber, steering knuckle, and stabilizer shaft.

Suspension	Upper front control arms	$57
	Lower front control arms	$64
	Rear control arms	$65
	Other	$391

Braking

Description: Braking includes the hub, brake discs/drums, bearings, splash shield, and brake calipers.

Braking Systems	Steering Knuckle	$58
	Rotor	$66
	Assembly Calliper	$57
	Other	$225

Wheels and Tires

Description: Wheel rims, tires, and spare wheel/tire assembly are included.

Wheels and Tires	Wheel	$101
	Tires	$216

Steering

Description: Steering is a complex system, including the steering wheel, column, joints, linkages, bushings, housings, and potentially hydraulic-assisted or electrically assisted equipment.

Steering System	Steering column assembly	$370
	Steering wheel & accessories	$136

Interior

Instrument Panel

Description: The instrument panel (IP) module consists of an underlying panel structure, knee bolsters and brackets, the instrument cluster, exterior surface, wiring, console storage, glove box panels, glove box assembly and exterior, and a top cover.

Instrument Panel	IP Cockpit	$414
	Beam assembly	$94
	Bracket assembly	$37
	Other	$355

Trim and Insulation

Description: Trim and insulation includes the emergency brake cover, switch panels, ash trays, arm rest, and cup holders, sometimes grouped with seating. The headliner is actually the overhead system containing acoustical sound absorption, assist handles, coat hooks, modular headliner assemblies, overhead console assemblies, small item overhead storage, pillar trim, sun visors, and retainer. Also included are the molded or formed panel behind the rear seat (sometimes containing the center high-mounted stop lamp), acoustical sound absorption padding, carpet, insulation, and accessory mats.

Trim and Insulation	Accessories	$67
	Carpet	$62
	Overhead trim	$262

Door Modules

Description: This door panel system includes door insulation, door trim assemblies/panels, map pocket trim, cup holders, ashtrays, seatbelt retractor covers, speaker grills, armrests, switch panels, and handles.

Door Modules	Door trim assembly	$215
	Garnish	$85

Seating and Restraint

Description: The seating system includes seat tracks, seat frames, foam, trim, map pockets, restraint anchors, head restraint, and arm rests. The restraint system includes seat belts, tensioners, clips, air bags, and sensor assemblies.

Seating and Restraints	Seat assembly	$1,060
	Airbag assembly	$228
	Restraints	$42

HVAC

Description: HVAC comprises the cooling module (including the radiator, condenser, and fan assembly), heater, ducting, and controls.

HVAC	HVAC system	$303
		$0
	Other	$147

Electrical

Interior Electronics

Description: This system includes wiring and controls for interior lighting, instrumentation, and power accessories.

Chassis Electronics

Description: Included is the ABS electrical system (i.e., wiring, sensors, and processors), as well as suspension control systems if present.

Exterior Electronics

Description: This system includes head lamps, fog lamps, turn signals, side marker lights, and tail light assemblies.

Appendix C
EPA-FEV Lightweighting and Cost Data

Table C-1. EPA/FEV system/subsystem mass reduction and cost analysis summary (1 of 3).

System	Subsystem	Sub-Subsystem	Description	System/ Subsystem/ Sub-Subsystem Weight "kg"	Estimate Mass Reduction "+" Mass Decrease, "-" Mass Increase "kg"	% System/ Subsystem Mass Reduction "%"	% Vehicle Mass Reduction	Estimated Cost Impact "+" Cost Decrease, "-" Cost Increase "$"	Tooling Cost "$" (x1000)	Average Cost/ Kilogram W/O Tooling $/kg	Average Cost/ Kilogram W/ Tooling $/kg
01	00	00	**Engine System**	172.60	30.25	17.53%	1.77%	33.69	5,892.20	1.11	1.22
01	00	00	*Engine System Roll-up ((Eng Down Size))*	172.60	10.37	6.01%	0.61%	38.42	0.00	3.71	3.71
01	02	00	Engine Frames, Mounting, and Brackets Subsystem	15.27	1.11	7.29%	0.07%	(0.09)	(2,778.60)	(0.08)	(1.43)
01	03	00	Crank Drive Subsystem	24.73	0.69	2.78%	0.04%	6.88	302.80	10.00	10.24
01	04	00	Counter Balance Subsystem	7.22	0.00	0.00%	0.00%	0.00	0.00	0.00	0.00
01	05	00	Cylinder Block Subsystem	30.13	7.11	23.58%	0.42%	(32.33)	(2,918.00)	(4.55)	(4.77)
01	06	00	Cylinder Head Subsystem	21.12	1.05	4.96%	0.06%	11.89	2,199.60	11.35	12.49
01	07	00	Valvetrain Subsystem	9.78	3.71	37.90%	0.22%	(11.13)	(2,171.00)	(3.00)	(3.32)
01	08	00	Timing Drive Subsystem	4.31	1.45	33.72%	0.08%	4.79	3,522.40	3.29	4.60
01	09	00	Accessory Drive Subsystem	0.55	0.00	0.00%	0.00%	0.00	0.00	0.00	0.00
01	10	00	Air Intake Subsystem	13.99	0.51	3.65%	0.03%	3.01	1,924.70	5.90	7.94
01	11	00	Fuel Induction Subsystem	0.54	0.11	21.32%	0.01%	2.13	1,533.40	18.51	25.73
01	12	00	Exhaust Subsystem	7.39	0.00	0.00%	0.00%	0.00	0.00	0.00	0.00
01	13	00	Lubrication Subsystem	3.34	0.23	7.00%	0.01%	(0.20)	26.50	(0.86)	(0.80)
01	14	00	Cooling Subsystem	14.10	2.59	18.38%	0.15%	4.62	2,977.60	1.78	2.40
01	17	00	Breather Subsystem	0.90	0.22	24.24%	0.01%	4.93	1,720.10	22.52	26.76
01	60	00	Engine Management, Engine Electronic, Electrical Subsystem	2.65	0.39	14.64%	0.02%	1.00	341.00	2.57	3.05
01	70	00	Accessory Subsystems (Start Motor, Generator, etc.)	16.56	0.71	4.28%	0.04%	(0.23)	(788.30)	(0.33)	(0.93)
02	00	00	**Transmission System**	92.76	18.90	20.37%	1.10%	(114.15)	(7,650.80)	(6.04)	(6.26)
02	00	00	*Transmission System Roll-up*	0.00	0.00	0.00%	0.00%	0.00	0.00	0.00	0.00
02	01	00	External Components	0.02	0.00	0.00%	0.00%	0.00	0.00	0.00	0.00
02	02	00	Case Subsystem	24.57	7.75	31.52%	0.45%	(11.03)	0.00	(1.42)	(1.42)
02	03	00	Gear Train Subsystem	41.44	3.49	8.42%	0.20%	(119.68)	0.00	(34.29)	(34.29)
02	05	00	Launch Clutch Subsystem	9.75	4.90	50.32%	0.29%	45.16	(7,650.80)	9.21	8.36
02	06	00	Oil Pump and Filter Subsystem	6.53	1.03	15.84%	0.06%	0.90	0.00	0.87	0.87
02	07	00	Mechanical Controls Subsystem	6.30	0.00	0.00%	0.00%	0.00	0.00	0.00	0.00
02	08	00	Electrical Controls Subsystem	0.78	0.00	0.00%	0.00%	0.00	0.00	0.00	0.00
02	09	00	Parking Mechanism Subsystem	0.90	0.00	0.00%	0.00%	0.00	0.00	0.00	0.00
02	20	00	Driver Operated External Controls Subsystem	2.48	1.73	69.55%	0.10%	(29.49)	0.00	(17.08)	(17.08)
03	00	00	**Body System (Group -A-)**	528.88	68.32	12.92%	3.99%	(227.45)	(22,900.00)	(3.33)	(3.51)
03	00	00	*Body System (Group -A-)*	0.00	0.00	0.00%	0.00%	0.00	0.00	0.00	0.00
03	01	00	Body Structure Subsystem	435.53	43.46	9.98%	2.54%	(109.78)	(22,900.00)	(2.53)	(2.81)
03	02	00	Front End Subsystem	70.96	16.69	23.52%	0.98%	(80.70)	0.00	(4.84)	(4.84)
03	03	00	Body Closures Subsystem	14.94	7.24	48.46%	0.42%	(29.96)	0.00	(4.14)	(4.14)
03	19	00	Bumpers Subsystem	7.45	0.35	4.70%	0.02%	(10.71)	0.00	(30.60)	(30.60)
03	00	00	**Body System (Group -B-)**	220.61	42.00	19.04%	2.45%	122.98	9,966.15	2.93	3.06
03	00	00	*Body System (Group -B-)*	0.00	0.00	0.00%	0.00%	0.00	0.00	0.00	0.00
03	05	00	Interior Trim and Ornamentation Subsystem	65.20	8.92	13.69%	0.52%	37.72	0.00	4.23	4.23
03	06	00	Sound and Heat Control Subsystem (Body)	4.50	0.27	5.95%	0.02%	0.38	0.00	1.40	1.40
03	07	00	Sealing Subsystem	8.23	2.03	24.67%	0.12%	15.70	0.00	7.74	7.74
03	10	00	Seating Subsystem	92.55	23.39	25.28%	1.37%	84.55	14,507.05	3.61	3.95
03	12	00	Instrument Panel and Console Subsystem	32.69	6.33	19.36%	0.37%	(12.49)	(5,317.90)	(1.97)	(2.43)
03	20	00	Occupant Restraining Device Subsystem	17.44	1.06	6.08%	0.06%	(2.88)	777.00	(2.71)	(2.32)
03	00	00	**Body System (Group -C-)**	26.57	2.37	8.92%	0.14%	7.52	0.00	3.17	3.17
03	00	00	*Body System (Group -C-)*	0.00	0.00	0.00%	0.00%	0.00	0.00	0.00	0.00
03	08	00	Exterior Trim and Ornamentation Subsystem	13.38	1.15	8.57%	0.07%	2.31	0.00	2.01	2.01
03	09	00	Rear View Mirrors Subsystem	2.76	0.22	7.90%	0.01%	0.73	0.00	3.33	3.33
03	23	00	Front End Modules	5.03	0.49	9.75%	0.03%	2.24	0.00	4.56	4.56
03	24	00	Rear End Modules	5.39	0.51	9.54%	0.03%	2.32	0.00	4.52	4.52

Table C-2. EPA/FEV system/subsystem mass reduction and cost analysis summary (2 of 3).

System	Subsystem	Sub-Subsystem	Description	System/ Subsystem/ Sub-Subsystem Weight "kg"	Estimate Mass Reduction "+" Mass Decrease, "-" Mass Increase "kg"	% System/ Subsystem Mass Reduction "%"	% Vehicle Mass Reduction	Estimated Cost Impact "+" Cost Decrease, "-" Cost Increase "$"	Tooling Cost "$" (x1000)	Average Cost/ Kilogram W/O Tooling $/kg	Average Cost/ Kilogram W/ Tooling $/kg
03	00	00	**Body System (Group -D-) Glazing & Body Mechatronics**	63.46	6.16	9.71%	0.36%	(15.25)	0.00	(2.48)	(2.48)
03	00	00	*Body System (Group -D-)*	0.00	0.00	0.00%	0.00%	0.00	0.00	0.00	0.00
03	11	00	Glass (Glazing), Frame and Mechanism Subsystem	48.01	6.06	12.63%	0.35%	(15.67)	0.00	(2.59)	(2.59)
03	14	00	Handles, Locks, Latches and Mechanisms Subsystem	4.93	0.00	0.00%	0.00%	0.00	0.00	0.00	0.00
03	15	00	Rear Hatch Lift assembly	4.56	0.00	0.00%	0.00%	0.00	0.00	0.00	0.00
03	16	00	Wipers and Washers Subsystem	5.96	0.10	1.68%	0.01%	0.42	0.00	4.18	4.18
04	00	00	**Suspension System**	265.91	66.83	25.13%	3.91%	144.71	(7,544.37)	2.17	2.10
04	00	00	*Suspension System*	24.42	0.00	0.00%	0.00%	0.00	0.00	0.00	0.00
04	01	00	Front Suspension Subsystem	32.89	11.57	35.18%	0.68%	3.04	(5,172.38)	0.26	0.02
04	02	00	Rear Suspension Subsystem	23.58	8.32	35.28%	0.49%	4.91	(2,459.05)	0.59	0.43
04	03	00	Shock Absorber Subsystem	42.94	14.11	32.86%	0.82%	57.99	87.06	4.11	4.11
04	04	00	Wheels And Tires Subsystem	142.07	32.83	23.11%	1.92%	78.77	0.00	2.40	2.40
05	00	00	**Driveline System**	33.66	1.50	4.47%	0.09%	(0.16)	(685.86)	(0.11)	(0.36)
05	00	00	*Driveline System*	0.00	0.00	0.00%	0.00%	0.00	0.00	0.00	0.00
05	02	00	Rear Drive Housed Axle Subsystem	8.63	0.00	0.00%	0.00%	0.00	0.00	0.00	0.00
05	03	00	Front Drive Housed Axle Subsystem	6.35	0.73	11.54%	0.04%	1.54	(6.50)	2.10	2.09
05	04	00	Front Drive Half-Shafts Subsystem	18.67	0.77	4.12%	0.04%	(1.70)	(679.36)	(2.21)	(2.69)
06	00	00	**Brake System**	86.71	32.75	37.77%	1.91%	169.56	(1,426.12)	5.18	5.15
06	00	00	*Brake System*	0.00	0.00	0.00%	0.00%	0.00	0.00	0.00	0.00
06	03	00	Front Rotor/Drum and Shield Subsystem	32.97	12.65	38.36%	0.74%	35.91	(2,182.66)	2.84	2.75
06	04	00	Rear Rotor/Drum and Shield Subsystem	23.44	6.24	26.62%	0.36%	17.44	(1,897.51)	2.79	2.63
06	05	00	Parking Brake and Actuation Subsystem	13.40	9.63	71.88%	0.56%	82.98	1,526.28	8.61	8.70
06	06	00	Brake Actuation Subsystem	5.54	2.98	53.90%	0.17%	31.87	1,253.15	10.68	10.91
06	07	00	Power Brake Subsystem (for Hydraulic)	2.83	1.24	43.89%	0.07%	1.35	(125.39)	1.09	1.03
06	09	00	Brake Controls Subsystem	8.53	0.00	0.00%	0.00%	0.00	0.00	0.00	0.00
07	00	00	**Frame and Mounting System**	43.73	16.34	48.54%	0.95%	(3.28)	(3,700.39)	(0.20)	(0.32)
07	00	00	*Frame and Mounting System*	0.00	0.00	0.00%	0.00%	0.00	0.00	0.00	0.00
07	01	00	Frame Sub System	43.73	16.34	37.36%	0.95%	(3.28)	(3,700.39)	(0.20)	(0.32)
09	00	00	**Exhaust System**	26.62	7.52	28.25%	0.44%	2.47	0.00	0.33	0.33
09	00	00	*Exhaust System*	0.00	0.00	0.00%	0.00%	0.00	0.00	0.00	0.00
09	01	00	Acoustical Control Components Subsystem	11.74	2.79	23.75%	0.16%	(0.21)	0.00	(0.07)	(0.07)
09	02	00	Exhaust Gas Treatment Components Subsystem	14.87	4.73	31.79%	0.28%	2.68	0.00	0.57	0.57
10	00	00	**Fuel System**	24.28	12.70	52.33%	0.74%	3.91	1,625.30	0.31	0.38
10	00	00	*Fuel System*	0.00	0.00	0.00%	0.00%	0.00	0.00	0.00	0.00
10	01	00	Fuel Tank And Lines Subsystem	21.02	12.21	58.08%	0.71%	2.70	1,492.80	0.22	0.29
10	02	00	Fuel Vapor Management Subsystem	3.26	0.50	15.26%	0.03%	1.21	132.50	2.44	2.59
11	00	00	**Steering System**	24.23	1.82	7.50%	0.11%	11.05	1,352.70	6.08	6.48
11	00	00	*Steering System*	0.00	0.00	0.00%	0.00%	0.00	0.00	0.00	0.00
11	01	00	Manual Steering Gear Subsystem	8.82	0.12	1.39%	0.01%	0.24	0.00	1.99	1.99
11	02	00	Power Steering Subsystem	7.48	0.21	2.81%	0.01%	0.10	186.80	0.46	0.94
11	04	00	Steering Column Subsystem	5.08	1.15	22.58%	0.07%	10.39	(1,910.00)	9.05	8.15
11	05	00	Steering Column Switches Subsystem	0.55	0.00	0.00%	0.00%	0.00	0.00	0.00	0.00
11	06	00	Steering Wheel Subsystem	2.29	0.34	14.69%	0.02%	0.32	3,075.90	0.94	5.89

Table C-3. EPA/FEV system/subsystem mass reduction and cost analysis summary (3 of 3).

System	Subsystem	Sub-Subsystem	Description	System/ Subsystem/ Sub-Subsystem Weight "kg"	Estimate Mass Reduction "+" Mass Decrease, "-" Mass Increase "kg"	% System/ Subsystem Mass Reduction "%"	% Vehicle Mass Reduction	Estimated Cost Impact "+" Cost Decrease, "-" Cost Increase "$"	Tooling Cost "$" (x1000)	Average Cost/ Kilogram W/O Tooling $/kg	Average Cost/ Kilogram W/ Tooling $/kg
12	00	00	**Climate Control System**	15.66	2.44	15.55%	0.14%	9.34	386.00	3.83	3.92
12	00	00	*Climate Control System*	0.00	0.00	0.00%	0.00%	0.00	0.00	0.00	0.00
12	01	00	Air Handling/Body Ventilation Subsystem	12.81	2.03	15.88%	0.12%	7.27	146.00	3.58	3.61
12	02	00	Heating/Defrosting Subsystem	1.03	0.39	38.03%	0.02%	2.03	240.00	5.16	5.49
12	03	00	Refrigeration/Air Conditioning Subsystem	1.33	0.00	0.00%	0.00%	0.00	0.00	0.00	0.00
12	04	00	Controls Subsystem	0.48	0.01	1.84%	0.00%	0.04	0.00	4.21	4.21
13	00	00	**Information, Gage and Warning Device System**	1.90	0.08	4.01%	0.00%	0.19	0.00	2.45	2.45
13	00	00	*Information, Gauge and Warning Device System*	0.00	0.00	0.00%	0.00%	0.00	0.00	0.00	0.00
13	01	00	Instrument Cluster Subsystem	1.40	0.08	5.44%	0.00%	0.19	0.00	2.45	2.45
13	06	00	Horn Subsystem	0.50	0.00	0.00%	0.00%	0.00	0.00	0.00	0.00
14	00	00	**Electrical Power Supply System**	18.96	0.00	0.00%	0.00%	0.00	0.00	0.00	0.00
14	00	00	*Electrical Power Supply System*	0.00	0.00	0.00%	0.00%	0.00	0.00	0.00	0.00
14	01	00	Service Battery Subsystem	18.96	0.00	0.00%	0.00%	0.00	0.00	0.00	0.00
15	00	00	**In-Vehicle Entertainment System**	4.59	1.07	23.39%	0.06%	2.35	1,175.60	2.19	2.79
15	00	00	*In-Vehicle Entertainment System*	0.00	0.00	0.00%	0.00%	0.00	0.00	0.00	0.00
15	01	00	Receiver and Audio Media Subsystem	3.15	1.02	32.55%	0.06%	1.66	1,175.60	1.62	2.24
15	02	00	Antenna Subsystem	0.16	0.05	30.82%	0.00%	0.69	0.00	14.17	14.17
15	03	00	Speaker Subsystem	1.28	0.00	0.00%	0.00%	0.00	0.00	0.00	0.00
17	00	00	**Lighting System**	10.04	0.53	5.29%	0.03%	(0.76)	400.00	(1.42)	(1.01)
17	00	00	*Lighting System*	0.00	0.00	0.00	0.00%	0.00	0.00	0.00	0.00
17	01	00	Front Lighting Subsystem	6.09	0.53	8.73%	0.03%	(0.76)	400.00	(1.42)	(1.01)
17	03	00	Rear Lighting Subsystem	3.83	0.00	0.00%	0.00%	0.00	0.00	0.00	0.00
17	05	00	Lighting Switches Subsystem	0.13	0.00	0.00%	0.00%	0.00	0.00	0.00	0.00
18	00	00	**Electrical Distribution and Electronic Control System**	23.94	0.89	3.71%	0.05%	1.35	103.50	1.52	1.58
18	00	00	*Electrical Distribution and Electronic Control Sys.*	0.00	0.00	0.00	0.00%	0.00	0.00	0.00	0.00
18	01	00	Electrical Wiring and Circuit Protection Subsystem	23.94	0.89	3.71%	0.05%	1.35	103.50	1.52	1.58
			Sub-Total Vehicle Weight =	1685.10	312.48		18.26%	148.06	(23,006.09)	0.47	0.43
			Weight Reconcile								
			Fluids -	68.52							
			NVH (Body Mastic) -	8.00							
			Misc. -	(50.24)							
			Net Calculated Vehicle Weight -	1711.38							
			Vehicle Weight As Purchased=	1710.53							
					(Decrease)			(Decrease)	(Increase)	(Decrease)	(Decrease)

Appendix D
Technical Cost Modeling Methodology

Technical cost modeling, developed by students and faculty of Massachusetts Institute of Technology's Materials Systems Laboratory and pioneered for commercial application by IBIS Associates, provides a powerful tool for estimating and simulating manufacturing costs. The technique is an extension of conventional process modeling, with particular emphasis on capturing the cost implications of material and process variables and changing economic scenarios.

In a technical cost model, cost is assigned to each unit operation from a process flow diagram. For each of these unit operations, total cost is broken down into separately calculated elements:

- Variable cost elements
  - Materials, labor, and utilities (i.e., energy)
- Fixed cost elements
  - Equipment, tooling, and building
  - Maintenance, overhead labor, and cost of capital

By breaking cost down in this way, the complex task of cost estimation is reduced to a series of more simple engineering and economic calculations.

Technical cost modeling can be implemented in either a descriptive or predictive manner. With descriptive models, the user directly inputs intermediate parameters such as production rate, equipment cost, and tooling cost. In the predictive approach, these parameters are calculated by the model as a function of the product material and geometry. These predictive functions are derived from the analysis of a continually expanding range of case studies and are updated routinely. It is this predictive nature of technical cost models that separates them from other cost-estimating tools.

The use of technical cost models can be both strategic and operational. A strategic (long-term) use might be material and process selection. This selection would depend on specific production/market scenarios and the technology under consideration. An operational (near-term) use, on the other hand, might be in the areas of process optimization or purchasing and sales. In a sales application, the user would demonstrate to a customer the cost of the customer's product with an alternative technology. In a purchasing application, the model might be used to confirm or verify a price being charged by a supplier.

More broadly, technical cost models can be used to accomplish tasks that include the following:

- Simulate the costs of manufacturing products
- Establish direct comparisons between material, process, and design alternatives
- Investigate the effect of changes in the process scenario on overall cost
- Identify limiting process steps and parameters
- Determine the merits of specific process and design improvements (research efforts).

Cost Model Output Description

In dividing cost into its contributing elements, a distinction can be made between cost elements that depend on the amount of product manufactured annually and those that do not. For example, in most instances, the cost contribution of the material is the same regardless of the number produced unless the material price is discounted, owing to high volume. On the other hand, the piece cost for tooling will vary with changes in production volume. These two types of cost elements are called variable and fixed costs, respectively.

Variable Costs

Variable cost elements are those elements of piece cost whose values are independent of the number of pieces produced. The principal variable costs include the following:

Material Cost

The cost of material is directly estimated from the design weight of a part produced and/or the price of material used. The cost for scrap or reject losses and any miscellaneous materials used in processing are also included.

Direct Labor Cost

The cost of direct labor is a function of the wages paid, the amount of time required to produce a piece, the number of laborers directly associated with the process, and the productivity of this labor (rejected parts and downtime).

Utility Cost

Utility cost is estimated from the amount of power consumed by each piece of equipment utilized in the process and is applied on a per-piece basis as a function of cycle time. Reject and scrap losses are also accounted for.

Fixed Costs

Fixed costs are those elements of piece cost that are a function of the annual production volume. Fixed costs are called fixed because they are typically one-time capital investments or annual expenses, distributed over the number of components manufactured. The main elements of fixed cost are as follows:

Equipment Cost

Equipment cost accounts for all equipment, both primary and auxiliary, involved in the manufacture of a product. The equipment cost also incorporates costs associated with installation. Equipment cost per piece is derived from equipment investment (discussed below) using equipment life and runtime as allocation factors.

Tooling Cost

Tooling costs are capital expenditures for tools, elements, shields, boats, or special fixtures necessary for manufacturing a specific product. These expenditures are dedicated to a single product and may need to be replaced several times over a production run for reasons of wear. Tool cost per piece is derived from total tooling investment (discussed below) using product life (years of production) as an allocation measure.

Building Cost

Building space costs can be estimated given the amount of space required for each process operation and the price per square foot of factory floor space. Building piece cost is derived from building investment (discussed below) in the same manner as equipment cost.

Maintenance Cost

This cost reflects the expenditures necessary to maintain capital investments, including primary and auxiliary equipment, tooling, and the building. It is expressed as a percentage of the overall allocated equipment investment.

Overhead Labor Cost

Overhead labor cost accounts for those costs associated with the overall manufacturing operation. This category includes activities such as supervision, engineering, maintenance, quality control, material and part handling, inspection, and other direct manufacturing support.

Cost of Capital

The cost of capital is a fixed cost element that accounts for the time value of money. A cost of capital is incurred for each investment that ties up money and includes shorter-term investments such as material inventories and payrolls.

Investment Costs

Investment cost is calculated using the “greenfield” assumption; that is, it is assumed that equipment and building space must be built and installed from scratch. These investments are then allocated on a per-year basis by dividing the investment by its physical life and multiplying by the runtime allocation. Investment cost per piece is then determined by dividing by the annual production volume.

Equipment Investment

Equipment investment is calculated by multiplying the cost per machine by an adjustment factor for auxiliary equipment and installation. This total is then multiplied by the NSTAT factor to account for multiple numbers of machines.

Tooling Investment

Tooling investment is calculated by multiplying the cost per tool set by the number of machines required to meet production. This number is then adjusted upward if necessary to account for tools wearing out.

Building Investment

Building investment is arrived at by multiplying the required workspace for all machines (including idle space) by the initial construction cost of that space.

Appendix E
Vehicle Level Cost Modeling Approach

The breakdown of vehicle mass and manufacturing costs follows the same subsystem list as established in earlier DOE analyses such as the Oak Ridge National Laboratory Automotive System Cost Model, in which vehicle production is addressed under five different system groups and more than 30 subsystems, plus assembly operations. In addition, further resolution is provided in terms of several component groups for most of these subsystems, resulting in more than 60 mass and cost line items.

- Level 1: System Level (e.g., powertrain, body, chassis, etc.)
- Level 2: Subsystem Level (e.g., engine, transmission, driveline, exhaust, etc.)
- Level 3: Component Groups (e.g., block, cylinder head, oil pan, etc.).

Level 1 Detail: Systems

Table E-1. Baseline system level cost.

	Mass (kg/vehicle)	Cost ($/vehicle)
Powertrain	454	$6,119
Body	457	$2,823
Chassis	301	$1,807
Interior	215	$3,370
Electrical	51	$1,000
Final Assembly	24	$605
TOTAL MANUFACTURING	1,502	$15,724

Level 2 Detail: Subsystems

Table E-2. Baseline subsystem level cost.

	Midsize Baseline 2013 ICE Midsize Steel Unibody		
System		Mass (kg)	Cost ($)
Powertrain	**Baseline**	**454**	**$6,119**
	Engine	157	$3,162
	Energy Storage	15	$74
	Fuel System	75	$364
	Transmission	89	$1,199
	Driveshaft/Axle	25	$177
	Differential	11	$132
	Cradle	28	$107
	Thermal Management	15	$150
	Exhaust System	23	$230
	Oil and Grease	4	$81
	Powertrain Electronics	10	$400
	Emission Control Electronics	2	$43
Body		**457**	**$2,823**
	Body-in-White	326	$1,287
	Closures	61	$230
	Front/Rear Bumpers	9	$126
	Glazing	37	$250
	Paint	11	$450
	Exterior Trim	4	$144
	Body Hardware	8	$312
	Body Sealers and Deadeners	2	$24
Chassis		**301**	**$1,807**
	Suspension	123	$578
	Braking System	74	$406
	Wheels and Tires	82	$317
	Steering System	22	$506
Interior		**215**	**$3,370**
	Instrument Panel	38	$900
	Trim and Insulation	54	$390
	Door Modules	23	$300
	Seating and Restraints	78	$1,330
	HVAC	22	$450
Electrical		**51**	**$1,000**
	Interior Electrical	26	$400
	Chassis Electrical	15	$400
	Exterior Electrical	10	$200
Final Assembly		**24**	**$605**

Level 3 Detail: Component Groups

Table E-3. Baseline component group level cost (1 of 2).

Powertrain		
Engine	Crankshaft	$390
	Cylinder Head	$390
	Cylinder Block	$699
	Oil Pan Assembly	$264
	Camshafts	$77
	Valve Roller Rocker	$234
	Other	$719
Energy Storage	Battery	$74
Fuel System	Fuel Tank	$269
	Other	$96
Transmission	Case	$351
	Gears and Shaft	$293
	Clutch	$537
	Other	$18
Driveshaft/Axle	Driveshaft assembly	$86
	CV joint	$91
Differential	Drive bearings	$26
	Case	$50
	Gears	$57
Cradle	Cradle	$107
Thermal Management	Radiator	$37
	Radiator fan assembly	$41
	Radiator fan motor	$20
	Other	$51
Exhaust System	Exhaust manifold	$25
	Catalytic converter	$156
	Muffler	$43
	Other	$6
Powertrain Electrical	Engine control module	$198
	Power electrical	$122
	Alternator	$81
Emission Control Electronics	Emission Control Electronics	$43
Oil and Grease	Oil and Grease	$81

Body		
BIW	BIW	$1,287
Closures	Panels	$230
Front/Rear Bumper	Impact module	$46
	Other	$80
Glazing	Glass	$250
Paint	Paint	$450
Exterior Trim	Exterior Trim	$144
Body Hardware	Body Hardeners	$312
Body Sealer & Deadners	Body Sealer & Deadners	$2

Table E-4. Baseline component group level cost (2 of 2).

Chassis		
Suspension	Upper front control arms	$57
	Lower front control arms	$64
	Rear control arms	$65
	Other	$391
Braking Systems	Steering Knuckle	$58
	Rotor	$66
	Assembly Calliper	$57
	Other	$225
Wheels and Tires	Wheel	$101
	Tires	$216
Steering System	Steering column assembly	$370
	Steering wheel & accessories	$136

Interior		
Instrument Panel	IP Cockpit	$414
	Beam assembly	$94
	Bracket assembly	$37
	Other	$355
Trim and Insulation	Accessories	$67
	Carpet	$62
	Overhead trim	$262
Door Modules	Door trim assembly	$215
	Garnish	$85
Seating and Restraints	Seat assembly	$1,060
	Airbag assembly	$228
	Restraints	$42
HVAC	HVAC system	$303
		$0
	Other	$147

Electrical		
	Interior	$400
	Chassis	$400
	Exterior Lighting	$200

Assembly		
	Assembly	$605

Vehicle-Level Cost Model Data Structure

The IBIS automotive lightweighting technical cost model is designed to allow comparison of multiple vehicle concepts and configurations from the perspective of mass and direct manufacturing cost. In addition to the three levels of vehicle detail outlined in the previous section, the model structure can be described as having three levels of function. One functional level is the system definition, in which there is a page for each major vehicle system and the user selects from a database or directly inputs the subsystem or component group parameters. The middle functional level is the aggregation of all system data for the current vehicle case study and the calculation of intermediate factors used for sizing some systems. The top functional level is the scenario management function, which allows the user to save a current configuration, recall and edit a previous scenario, or make comparisons between multiple vehicle concepts.

The model is constructed in Microsoft Excel, with a substantial level of Visual Basic code for operating the scenario management function. Each of the boxes in Figure E-1 represents a separate worksheet in the Microsoft Excel model.

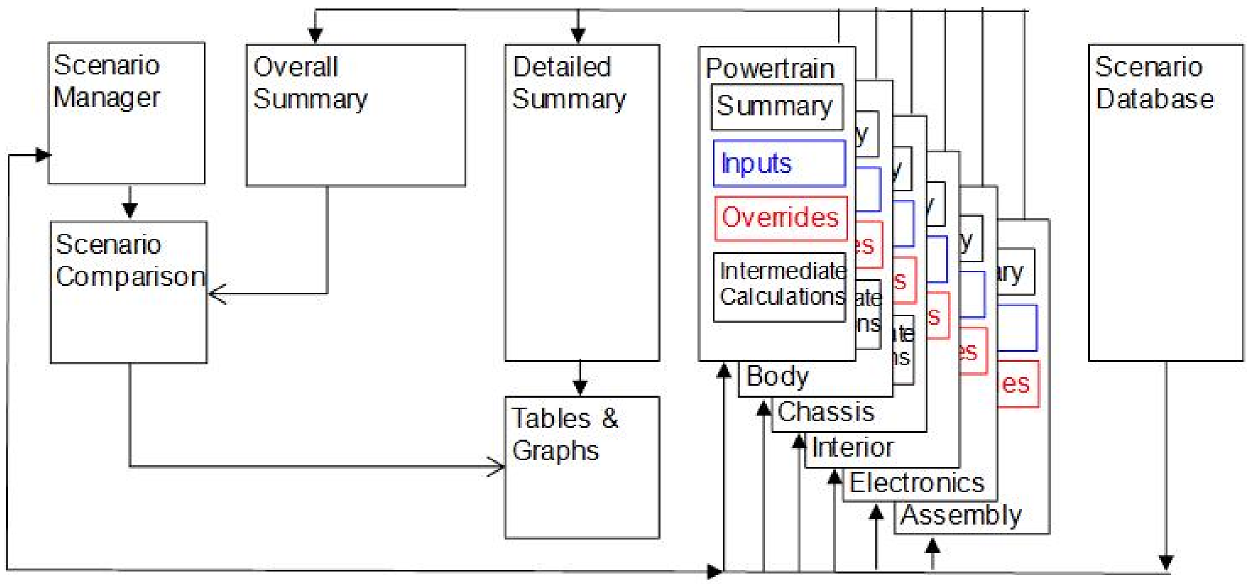


Figure E-1. Technical cost model structure schematic.

System Page Structure

Each system page includes a summary of the subsystem masses and costs at the top. Below this is a list of inputs and parameters defining functional aspects of the vehicle relevant to sizing relationships such as calculating engine horsepower required based on vehicle mass and vehicle class performance targets. The next section contains menus for selecting subsystem technologies from databases contained further below. The resulting mass and cost of the selected technology is displayed, along with input fields for user-defined overrides.

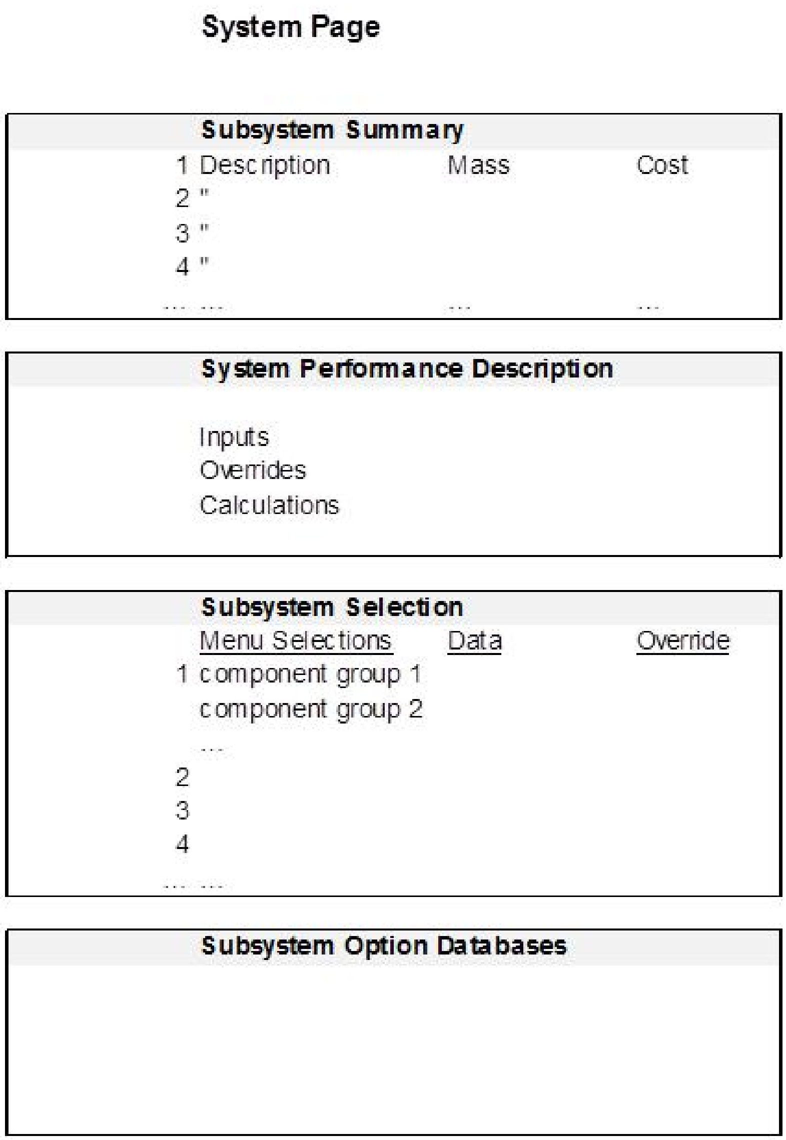


Figure E-2. Technical cost model system page layout.

Sizing Relationships

Data can be entered directly through the override fields to reflect specific known data points from a component description or results of a vehicle tear down. In many cases, it may be desirable to modify the values for a system as implemented on one vehicle to reflect the cost and mass if it were to be implemented on a different vehicle. To address this, sizing relationships that allow the downsizing or upsizing of a system to match the current scenario are incorporated. In the databases where subsystem descriptions are entered, a “vehicle basis” mass is recorded for the sake of making these calculations.

Engine Power Requirement

The power requirement is calculated as a function of frontal area, aerodynamics, rolling resistance, acceleration target, load capacity, and grade climbing of the selected vehicle class, along with the selected engine power density and glider mass from the overall vehicle definition.

Engine Mass and Cost

From the engine power requirement calculation or a defined power (horsepower or kilowatt) direct input, the engine mass and cost is then calculated from the engine type selection on the powertrain page, according to the values of the power density and cost equation for the selection. If no overrides are entered, the engine power, mass, and cost will continue to scale with the overall vehicle mass.

Chassis Components

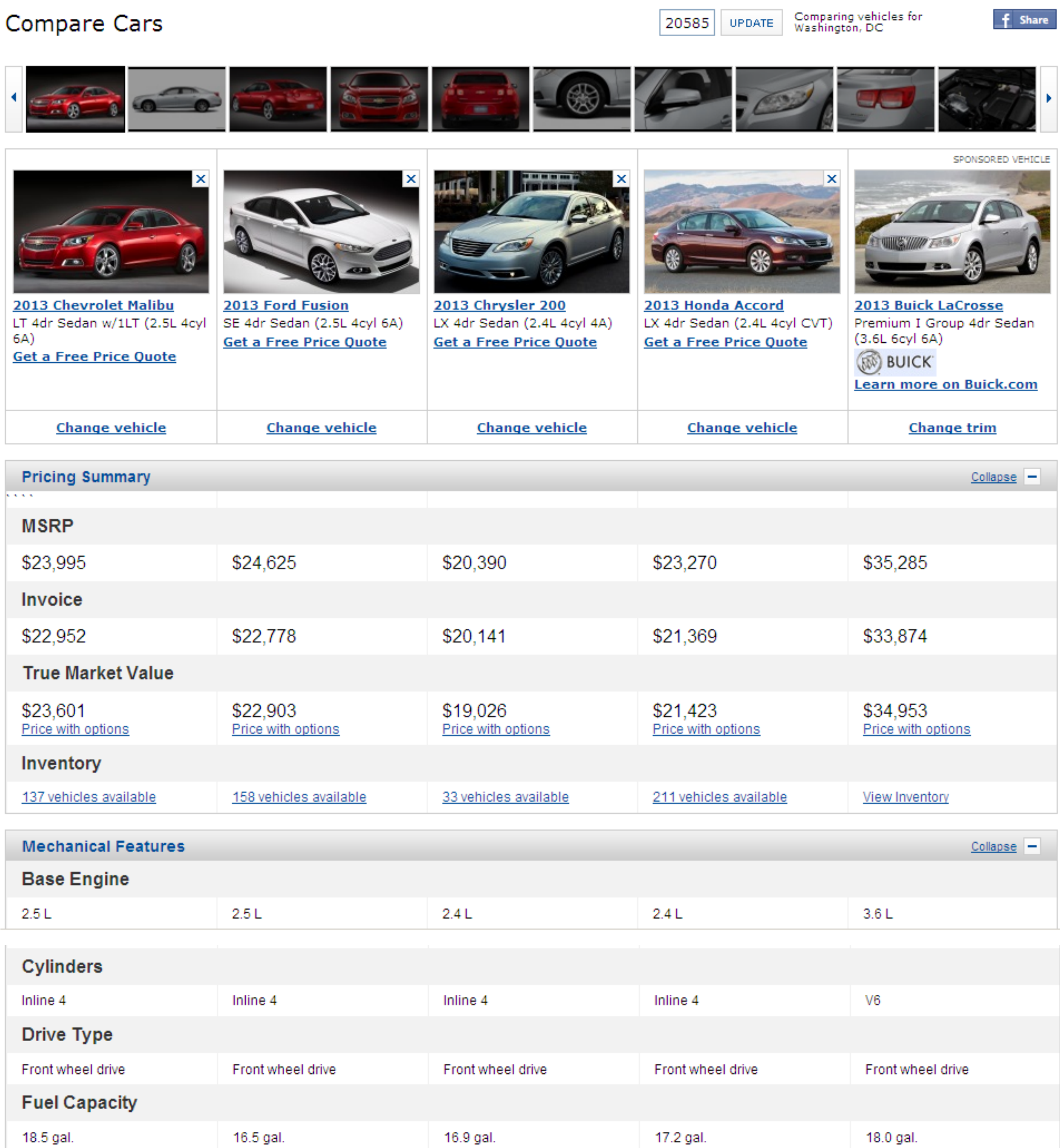
The suspension, brakes, steering, wheels, engine cradle, and driveline systems were scaled with the overall vehicle mass and costs are adjusted according to the added or saved material required.

Data Capture and Scenario Analysis

The model has been developed for the evaluation and comparison of multiple vehicle concepts. As such, it has been designed with databases for each subsystem to allow the user to select from different options contained. Each time an analysis is conducted, the user has the opportunity to enter new data into these databases from known data points and thereby capture data for use in future analyses. Furthermore, the model contains a "scenario database" in which all component selections, as well as overrides and other vehicle scenario descriptions, can be saved and recalled for comparison to other concepts or be edited at the start of a new scenario. In these two ways, the model is designed to grow and become more robust with time and use.

Appendix F
Target Vehicle Published Data

Midsize vehicle example specifications from Edmunds.com provided by Energetics.



Compare Cars

20585 UPDATE Comparing vehicles for Washington, DC Share

2013 Chevrolet Malibu	2013 Ford Fusion	2013 Chrysler 200	2013 Honda Accord	2013 Buick LaCrosse
LT 4dr Sedan w/1LT (2.5L 4cyl 6A)	SE 4dr Sedan (2.5L 4cyl 6A)	LX 4dr Sedan (2.4L 4cyl 4A)	LX 4dr Sedan (2.4L 4cyl CVT)	SPONSORED VEHICLE Premium I Group 4dr Sedan (3.6L 6cyl 6A) BUICK
Get a Free Price Quote	Get a Free Price Quote	Get a Free Price Quote	Get a Free Price Quote	Learn more on Buick.com
Change vehicle	Change vehicle	Change vehicle	Change vehicle	Change trim

Pricing Summary Collapse

MSRP				
$23,995	$24,625	$20,390	$23,270	$35,285
Invoice				
$22,952	$22,778	$20,141	$21,369	$33,874
True Market Value				
$23,601 Price with options	$22,903 Price with options	$19,026 Price with options	$21,423 Price with options	$34,953 Price with options
Inventory				
137 vehicles available	158 vehicles available	33 vehicles available	211 vehicles available	View Inventory

Mechanical Features Collapse

Base Engine				
2.5 L	2.5 L	2.4 L	2.4 L	3.6 L
Cylinders				
Inline 4	Inline 4	Inline 4	Inline 4	V6
Drive Type				
Front wheel drive	Front wheel drive	Front wheel drive	Front wheel drive	Front wheel drive
Fuel Capacity				
18.5 gal.	16.5 gal.	16.9 gal.	17.2 gal.	18.0 gal.

Fuel Economy (city/hwy)				
22/34 mpg	22/34 mpg	21/29 mpg	27/36 mpg	17/27 mpg
Fuel Type				
Regular unleaded	Regular unleaded	Regular unleaded	Regular unleaded	Flex-fuel (unleaded/E85)
Horsepower				
197 hp @ 6300 rpm	175 hp @ 6000 rpm	173 hp @ 6000 rpm	185 hp @ 6400 rpm	303 hp @ 6800 rpm
Monthly Fuel Cost				
$180	$180	$195	$156	$223
Torque				
191 ft-lbs. @ 4400 rpm	175 ft-lbs. @ 4500 rpm	166 ft-lbs. @ 4400 rpm	181 ft-lbs. @ 3900 rpm	264 ft-lbs. @ 5300 rpm
Transmission				
6-speed shiftable automatic	6-speed automatic	4-speed automatic	Continuously variable-speed automatic	6-speed shiftable automatic

Interior Features Collapse

A/C with climate control				
Available on other styles	Optional	Available on other styles	Standard	Standard
Bluetooth				
Standard	Standard	Optional	Standard	Standard
Built-in hard drive				
N/A	N/A	Available on other styles	Available on other styles	Optional
Concierge Service*				
OnStar	N/A	N/A	N/A	OnStar
Destination Download*				
OnStar	SYNC	N/A	N/A	OnStar
Destination Guidance (also Turn-by-Turn Navigation)*				
OnStar	SYNC	N/A	N/A	OnStar
HD radio				
N/A	Available on other styles	N/A	N/A	N/A
Hand-Free Calling*				
OnStar	N/A	N/A	N/A	OnStar
Heated/Cooled seats				
Available on other styles	Optional	Optional	Available on other styles	Standard
Keyless ignition				
Available on other styles	N/A	N/A	Available on other styles	Standard
Navigation				
Available on other styles	Standard	Available on other styles	Available on other styles	Optional
Parking assistance				
Available on other styles	Optional	N/A	N/A	Standard
Power seats				
Standard	Standard	Optional	Available on other styles	Standard

Premium sound system				
N/A	N/A	N/A	N/A	N/A
Rear seat DVD				
N/A	N/A	N/A	N/A	Optional
Roadside Assistance*				
OnStar	N/A	N/A	N/A	OnStar
Satellite radio				
Standard	Standard	Optional	Available on other styles	Standard
Seating capacity				
5	5	5	5	5
Upholstery				
Premium cloth	Cloth	Premium cloth	Cloth	Premium leather
iPod				
Standard	Standard	Available on other styles	Standard	Standard

Exterior Features				Collapse −
All season tires				
Standard	Optional	Standard	Standard	Standard
Power glass sunroof				
Optional	Optional	Available on other styles	Available on other styles	Optional
Run-flat tires				
N/A	N/A	N/A	N/A	N/A
Tire size				
P215/60R16 tires	235/50R17 tires	225/55R17 tires	205/65R16 95H tires	P235/50R18 97V tires
Wheel tire size				
N/A	N/A	N/A	N/A	N/A
Wheels				
Alloy wheels	Alloy wheels	Steel wheels	Alloy wheels	Painted alloy wheels

Safety Features				Collapse −
Airbag Deployment Notification*				
OnStar	SYNC	N/A	N/A	OnStar
Anti-lock brakes (ABS)				
Standard	Standard	Standard	Standard	Standard
Anti-theft system				
Standard	Standard	Standard	Available on other styles	Standard
Child seat anchors				
Standard	Standard	Standard	Standard	Standard
Emergency Service*				
OnStar	N/A	N/A	N/A	OnStar
Side/Curtain airbags				
Standard	Standard	Standard	Standard	Standard

Stability Control				
Standard	Standard	Standard	Standard	Standard
Stolen Vehicle Tracking/Assistance*				
OnStar	N/A	N/A	N/A	OnStar
Traction Control				
Standard	Standard	Standard	Standard	Standard
Vehicle Alarm Notification*				
N/A	N/A	N/A	N/A	N/A

Warranty Features				Collapse
Basic				
3 yr./ 36000 mi.	3 yr./ 36000 mi.	3 yr./ 36000 mi.	3 yr./ 36000 mi.	4 yr./ 50000 mi.
Drivetrain				
5 yr./ 100000 mi.	5 yr./ 60000 mi.	5 yr./ 100000 mi.	5 yr./ 60000 mi.	6 yr./ 70000 mi.

Measurements				Collapse
Front head room				
39.0 in.	39.2 in.	40.1 in.	39.1 in.	38.0 in.
Front hip room				
55.0 in.	55.0 in.	52.6 in.	55.6 in.	55.2 in.
Front leg room				
42.1 in.	44.3 in.	42.4 in.	42.5 in.	41.7 in.
Front shoulder room				
57.5 in.	57.8 in.	56.3 in.	58.6 in.	57.4 in.
Rear hip Room				
54.3 in.	54.4 in.	52.8 in.	54.7 in.	53.9 in.
Rear head room				
37.5 in.	37.8 in.	38.4 in.	37.5 in.	37.3 in.
Rear leg room				
36.8 in.	38.3 in.	36.2 in.	38.5 in.	40.5 in.
Rear shoulder room				
57.1 in.	56.9 in.	56.0 in.	56.5 in.	56.0 in.
Width				
73.0 in.	72.9 in.	72.5 in.	72.8 in.	73.1 in.
Height				
57.6 in.	58.1 in.	54.9 in.	57.7 in.	59.2 in.
Length				
191.5 in.	191.7 in.	191.7 in.	191.4 in.	196.9 in.
Front track				
62.2 in.	62.7 in.	61.7 in.	62.8 in.	61.7 in.

Rear track				
62.0 in.	62.4 in.	62.7 in.	62.7 in.	62.0 in.
Wheel base				
107.8 in.	112.2 in.	108.9 in.	109.3 in.	111.7 in.
Cargo capacity, all seats in place				
16.3 cu.ft.	16.0 cu.ft.	13.6 cu.ft.	15.8 cu.ft.	13.3 cu.ft.
Maximum cargo capacity				
16.3 cu.ft.	N/A	N/A	N/A	N/A
EPA interior volume				
116.5 cu.ft.	118.8 cu.ft.	113.9 cu.ft.	119.0 cu.ft.	116.0 cu.ft.
Drag Coefficient				
0.29 Cd	N/A	0.34 Cd	N/A	N/A
Curb weight				
3439 lbs.	3615 lbs.	3402 lbs.	N/A	4032 lbs.
Ground clearance				
N/A	N/A	6.1 in.	N/A	N/A
Maximum towing capacity				
N/A	N/A	1000 lbs.	N/A	1000 lbs.
Gross weight				
N/A	N/A	4600 lbs.	N/A	N/A

5-Year Ownership Costs Collapse

Average Cost Per Mile				
$0.63	$0.66	$0.68	$0.57	
True Cost to Own®				
$47,606	$49,701	$50,917	$42,802	
Depreciation				
$12,373	$13,539	$11,477	$11,340	
Taxes & Fees				
$1,891	$2,221	$1,542	$1,685	
Financing				
$2,153	$2,508	$1,823	$2,052	
Fuel				
$11,426	$11,426	$12,376	$9,902	
Insurance				
$15,239	$14,704	$19,322	$13,787	
Maintenance				
$3,782	$4,532	$3,597	$3,365	
Repairs				
$742	$771	$780	$671	