

CARBON FIBER COMPOSITES IN HIGH VOLUME GROUND TRANSPORTATION: COMPETITION BETWEEN MATERIAL ALTERNATIVES

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ABSTRACT

Vehicle lightweighting represents one of several design approaches that automotive and heavy truck manufacturers are currently evaluating to improve fuel economy, lower emissions, and improve freight efficiency (tons-miles per gallon of fuel). With changes in fuel efficiency and environmental regulations in the area of transportation, the next decade will likely see considerable vehicle lightweighting throughout the ground transportation industry. Greater use of carbon fiber composites and light metals is a key component of that strategy.

This paper examines the competition between candidate materials for lightweighting of heavy vehicles and passenger cars. A 53-component, 25 % mass reduction, body-in-white cost analysis is presented for each material class, highlighting the potential cost penalty for each kilogram of mass reduction and then comparing the various material options. Lastly, as the cost of carbon fiber is a major component of the elevated cost of carbon fiber composites, a brief look at the factors that influence that cost is presented.

1. INTRODUCTION

With high gasoline prices and new fuel economy and emission regulations for model years 2017–2025 that require car and light truck performance equivalent to 54.5 mpg and reductions in greenhouse gas emissions to 163 grams per mile in 2025, the pressure to lightweight vehicles is stronger than ever before. Vehicle lightweighting represents one of several design approaches automakers are currently evaluating to improve fuel economy. The next few years will see considerable lightweighting across the automotive industry. A maximum 20 % vehicle mass reduction has been considered in the proposed rulemaking for 2017–2025 light-duty vehicle greenhouse gas emission standards and corporate average fuel economy standards; however, some automotive executives state that a 30 % mass reduction without adding major costs will be required. [1]

The current effort by the SuperTruck Program, a collaboration between the US Department of Energy (DOE) Vehicle Technologies Office and heavy duty vehicle (HDV) manufacturers, takes a holistic approach to increasing freight efficiency through “clean sheet” design of Class 8 tractor-trailer vehicles, resulting in improved aerodynamics, engine and powertrain efficiencies, and reduced weight of the tractor and trailer. [2] Innovations in materials and design are needed to maximize flexibility while minimizing or eliminating additional weight. Opportunities for weight reduction in the drivetrain include lighter weight engines, transmissions, braking systems,

wheels, and tires. A wide variety of materials ranging from high-strength steel to glass-reinforced composites used at low production volumes in the body and chassis of modern HDVs provide an opportunity for additional weight reduction in the body and chassis while also serving as potential entry points for validating advanced lightweight material designs. A combined truck and trailer mass reduction goal of 13.2 % and 27.4 % has been suggested by the industry for the years 2025 and 2050, respectively[2].

Manufacturers generally favor lightweighting through material substitution, design optimization, and advanced manufacturing technologies while not compromising occupant or cargo space, vehicle safety, comfort, and acceleration. It is projected that the lightweight material share in the automotive sector will increase from 30 to 70 % by 2030, with high-strength steel considered as a lightweight material [3]. Several technical barriers prevent most lightweight materials from being widely commercialized. Cost, too, is a significant barrier, even after taking into account material lightweighting and part consolidation benefits. Considering cost at the complete vehicle system level is essential as it captures the cost reduction potential due to both part integration and mass de-compounding effects. Yet, original equipment manufacturers (OEMs)—because of their focus on sales—remain more focused on the vehicle’s retail price than on vehicle life-cycle cost.

The Lightweight Materials (LMs) component of the DOE Vehicle Technologies program focuses on the development and validation of advanced materials and manufacturing technologies to significantly reduce automotive passenger vehicle body and chassis weight. To achieve its long-term weight-reduction goal, the LM program has prioritized research areas in several lightweighting materials including advanced high-strength steel (AHSS), aluminum, magnesium, and carbon fiber composites. Over the past several years, the LM research and development portfolio has included assessments of various lightweight body and front-end structures, such as those constructed of AHSS or magnesium or those intensively using carbon fiber composites. Additionally, the latest LM multi-material vehicle (MMV) project aims to synthesize and demonstrate an optimized design using various lightweight material component options in a single vehicle. The specific goals of LM are to develop material and manufacturing technologies by 2015 that, if implemented in high volume, could cost-effectively reduce the weight of passenger-vehicle body and chassis systems by 50 % with safety, performance, and recyclability comparable to 2002 vehicles (Sklad 2012). This study assesses the cost-effectiveness of a 25 % total vehicle weight reduction, with substitutions occurring primarily in body and chassis systems. Considering only body and chassis components, the weight savings assessed here is greater than the DOE interim target of 25 % reduction in body and chassis weight.

A baseline cost model for an MMV has been developed to facilitate the development and validation of the cost-effectiveness of LM’s various multiyear body and chassis weight reduction goals from a system perspective. A systematic approach developed for the cost-effectiveness analysis facilitates the consideration of several lightweighting strategies such as lightweight metals, composites, and multi-materials, each of which can be optimized at the specific component level and the vehicle system level before its cost-effectiveness can be evaluated by comparison among scenarios for determining a lightweighting strategy. The baseline cost model provides not only the reference for the cost-effectiveness measure for evaluation of lightweighting strategies, but also the mass and cost breakdown at a major vehicle-component level, indicating where the most cost-effective lightweighting opportunities exist. The baseline

automotive cost model's capabilities were demonstrated using a 2002 midsize car's teardown and other industry data during FY 2011.

This paper provides an assessment of the cost-effectiveness of a 25 % vehicle weight-reduction goal using a baseline 2002 midsize automobile cost model. The cost-effectiveness of the proposed weight reduction goal is determined based on the vehicle retail price and vehicle life-cycle costs of three lightweight material substitution scenarios involving various body and chassis components to achieve the desired weight reduction goal. The paper also presents an assessment of the cost-effectiveness of a 25 % reduction in the weight of body and chassis systems. A detailed discussion of lightweight material substitution scenarios and powertrain sizing is presented first. Cost data collected for various vehicle components considered for achieving the weight reduction goal are then addressed, as are the assumptions and methods used. A discussion of the results of the cost analysis of the lightweighting scenarios is presented and followed by conclusions.

2. COST MODEL BASELINE, ASSUMPTIONS, AND APPROACH

2.1 Baseline

A baseline vehicle is compared to alternative vehicle lightweighting scenarios to evaluate the cost-effectiveness of reducing the weight of a midsize passenger vehicle by 25 %. The model's baseline vehicle was based on a 2002 average midsize vehicle manufactured by domestic OEMs having the specific vehicle characteristics as reported by the US Environmental Protection Agency in its annual trend report of light-duty vehicles [4,5]. The 2002 midsize sedan considered as the baseline vehicle has the following characteristics.

- Curb weight of 1,477 kg
- Interior volume of 114.8 ft³
- 2.9L, 185 HP, port fuel injected, V6 aluminum, four valves per cylinder, naturally aspirated engine
- Automatic transmission
- Front-wheel drive
- 0 to 60 mph acceleration time of 9.4 s
- Top speed of 134 mph
- Adjusted city, highway, and combined fuel economy estimated to be 18.8 mpg, 26.5 mpg, and 23.3 mpg, respectively

2.2 Assumptions

The present analysis uses a conservative secondary mass savings factor estimate of 68 % based on a recent statistical and engineering analysis of the teardown data of 77 current passenger vehicles sold in North America or Europe [6]. This conservative estimate corresponds to 5th percentile, with an expected value of 95 %. Estimated secondary mass savings factors at the major component level are as follows:

- Engine (8 %),
- Suspension (20 %),
- Structure (15 %),

- Transmission (10 %),
- Fuel and exhaust (5 %),
- Tires and wheels (5 %),
- HVAC (3 %),
- Steering and brakes (1 %), and
- Exterior (1 %).

2.3 Approach

The cost-effectiveness of the target 25 % mass reduction was considered initially in terms of lightweighting body and chassis components followed by entire vehicle structure without the powertrain. The baseline body and chassis structure weighed 656 kg and a 25 % mass reduction results in reducing the mass by 164 kg. Five material systems were chosen for consideration: AHSS, aluminum alloys, magnesium alloys, carbon fiber–reinforced polymer composites (CFCs), and other material alternatives. Fifty three vehicle components were considered for lightweighting in this analysis. Based on a literature review, component level mass savings estimates from lightweight materials substitution were considered. References for each component substitution are included in the specific material system tables.

Based on the literature and for each of the material systems considered, a list of potential lighter weight components was constructed and the potential mass reduction associated with each component replacement determined along with the cost of replacing those components with the lighter weight alternative. Secondary mass savings was incorporated in the analysis. For each material system, the alternative material components were then prioritized based on the cost penalty (i.e., dollars per kilogram saved) incurred. This information was then used to construct a table leading to a 25 % mass reduction in the body and chassis structure for two vehicle options: (1) a light metals intensive solution and (2) a carbon fiber composite intensive solution. The following sections discuss the results for the metals intensive and carbon fiber intensive body and chassis substitution scenarios.

3. MATERIAL SPECIFIC OPPORTUNITIES FOR MASS REDUCTION

The cost-effectiveness of the target 25 % mass reduction was considered initially in terms of lightweighting body and chassis components, followed by entire vehicle without powertrain. Tables 1 through 5 consider lightweighting opportunities at the specific component level for AHSS, aluminum, magnesium, CFCs, and other material alternatives. Component-level mass savings estimates from lightweight material substitution were based entirely on a review of the literature on demonstration and validation of such applications. Numerous published technical cost assessments, including those provided by suppliers, in combination with limited technical cost assessments for cases where the technology is relatively more mature and already has been commercialized to a certain extent were used for lightweight material component costs. Lightweight components were prioritized on the basis of cost penalty (i.e., dollars per kilograms saved) in these tables, which were then used to develop various scenarios for achieving the 25 % mass reduction target in the least expensive way.

3.1 Advanced High-Strength Steel

Table 1 shows opportunities for potential lightweight components using AHSS, which has been found to be the cheapest material for most components. Most data were taken from research by the Auto/Steel partnership. The cost penalty has been estimated to be in the range of \$0.00 to \$2.50/kg, and for body in white (BIW) AHSS is the least expensive option.

Table 1. Opportunities for potential lightweight components using advanced high-strength steel.

Part	Baseline Mass (kg)	Baseline Cost (\$/Part)	Mass Savings (%)	Mass Savings (kg)	Reduced Mass Cost (\$/Part)	Cost Penalty (\$/kg)	Reference
Panels	60	197	22	13.2	197	0.00	[7]
Cradles	32.3	78	25	8.1	85	0.87	[8]
Instrument Panel Beams	9.3	68	20	1.9	70	1.10	[9]
Seat Frames	39.3	269	50	19.7	296	1.37	[10]
BIW	321	1,025	30	96.3	1,213	1.95	[7]
Wheels	28.2	64	9	2.6	70	2.20	[9]
Suspension Control Arms	35	202	25	8.8	224	2.50	[10]

3.2 Aluminum

Twelve vehicle components were considered for lightweighting through aluminum material substitution, as shown in Table 2. Aluminum has a higher mass savings potential than AHSS, but the cost penalty is significantly higher, in the range of $-\$7.75$ to $\$11.11$ /kg. Body components belong to the higher end of the cost penalty range.

Table 2. Opportunities for potential lightweight components using aluminum.

Part	Baseline Mass (kg)	Baseline Cost (\$/Part)	Mass Savings (%)	Mass Savings (kg)	Reduced Mass Cost (\$/Part)	Cost Penalty (\$/kg)	Reference
Front/Rear Bumpers	10	91	40	4	60	$-\$7.75$	[11,12,13]
Steering Wheel Columns	3.2	5	55	1.8	5	0.00	[9]
Instrument Panel Beams	9.3	68	20	1.9	70	1.10	[9]
Steering Knuckles	6.2	32	50	3.1	71	3.42	[14]
Seat Frames	39.3	269	36	14.1	342	5.17	[9]
Suspension Control Arms	35	202	50	17.5	298	5.49	[14]
Cradles	32.3	78	40	12.9	152	5.73	[9]
Brake Actuators	7.7	12	50	3.9	36	6.16	[13]
Master Cylinders	2.7	25	50	1.4	34	6.16	[13]
BIW	321	1,025	40	128.4	2,290	9.85	[14]
Wheels	28.2	64	25	7.05	136	10.21	[9]
Panels	60	197	45	27	497	11.11	[14]

3.3 Magnesium

A total of 11 nonpowertrain components were considered for lightweighting using magnesium, as shown in Table 3. Most magnesium automotive applications today include drivetrain and interior components with a mass savings potential in the range of 40 to 60 % compared to conventional steel. A lower cost penalty is indicated for most interior components compared with chassis components such as suspension control arms and wheels, where the penalty is significantly higher.

Table 3. Opportunities for potential lightweight components using magnesium.

Part	Baseline Mass (kg)	Baseline Cost (\$/Part)	Mass Savings (%)	Mass Savings (kg)	Reduced Mass Cost (\$/Part)	Cost Penalty (\$/kg)	Reference
Instrument Panel Beams	9.3	68	50	4.7	43	-5.32	[15]
Steering Wheel Columns	3.6	5	60	2.2	9	1.82	[9]
Steering Wheels	1.4	7	35	0.5	8	2.20	[9]
Center Consoles	4.1	6	60	2.5	13	2.80	[9]
Panels	60	197	50	30	201	4.35	[14]
Seat Frames	39.3	269	45	17.7	347	4.41	[9]
Front Ends (w/Al Bumper and Rail)	82	132	38	31.2	382	8.00	[16,17]
Front/Rear Bumpers	10	91	30	3	120	9.67	[15]
Suspension Control Arms	35	202	40	14	363	11.50	[9]
Wheels	28.2	64	30	8.5	163	11.65	[7]
Cradles	32.3	78	42	13.6	571	36.25	[15]

3.4 Carbon Fiber–Reinforced Polymer Composites

Cost penalties for 11 CFC lightweighting components are found to be the maximum among the five lightweight material types considered here, as shown in Table 4. Although CFCs can offer the maximum mass savings (about 60 %) of the materials considered here compared with conventional steel, due to their higher cost their applications have been limited to niche luxury vehicles. The cost penalty has been estimated to be higher than \$30/kg in some chassis components as they have yet to be demonstrated in a production vehicle.

Table 4. Opportunities for potential lightweight components using carbon fiber–reinforced polymer composites.

Part	Baseline Mass (kg)	Baseline Cost (\$/Part)	Mass Savings (%)	Mass Savings (kg)	Reduced Mass Cost (\$/Part)	Cost Penalty (\$/kg)	Reference
BIW	321	1,025	50	160.5	2,698	10.42	[18]
Panels	60	197	50	30	647	15.00	[19]
Instrument Panels	29.4	395	57	16.8	653	15.36	[20]
Wheels	28.2	64	40	11.3	282	19.29	[21]

Front/Rear Bumper Impact Modules	5.5	33	55	3	100	22.15	[22]
Seats	65.5	1075	26	17	1,484	24.06	[23]
Cradles	32.3	78	55	17.8	599	32.26	[24]
Suspension Control Arms	35	202	50	17.5	841	36.50	[20]
Steering Knuckles	6.2	32	50	3.1	145	36.50	[20]

3.5 Other Material Alternatives

Several other material alternatives, with a mass savings potential in the range of 18 to 50 %, have been demonstrated for the 11 components shown in Table 5. In some cases, such as panels, instrument panel beam assemblies, and seats, there will be net cost savings due to benefits of net shape processing. In some cases, cost penalties are estimated to be even lower than that for lightweight metals such as aluminum and magnesium.

Table 5. Opportunities for potential lightweight components using other material alternatives.

Multi	Baseline Mass (kg)	Baseline Cost (\$/Part)	Mass Savings (%)	Mass Savings (kg)	Reduced Mass Cost (\$/Part)	Cost Penalty (\$/kg)	Reference
Panels	60	197	25	15	125	-4.80	[25]
IP Beam Assemblies	9.3	68	27	2.5	60	-3.20	[26]
Seat	65.5	1,075	43.60	28.6	1,011	-2.24	[24]
Seats (Structures Cushions)	52.6	1,000	33	17.4	1,000	0.00	[27]
Trim & Insulation	41	422	18	7.2	432	1.39	[24]
Tires	29.3	231	20	5.9	253	3.73	[28]
IP	32	652	37	11.8	717	5.51	[24]
Front/Rear Bumpers	10	91	43	4.3	125	7.91	[28]
BIW	321	1,025	36	116	2,173	9.90	[24]
Exterior Lighting	18	158	23	4.2	198	9.52	[24]
Glass	21.8	1,29	50	10.9	1,190	97.33	[28]

4. BODY AND CHASSIS LIGHTWEIGHT MATERIAL SUBSTITUTION SCENARIOS

The baseline body and chassis mass is estimated to be 656 kg, and a 25 % mass reduction represents removing 164 kg from the vehicle, leaving only 492 kg as a final body and chassis mass. Total body and chassis mass savings has been estimated by taking into consideration secondary mass savings [i.e., for every kilogram of primary mass savings, an additional 0.68 kg of secondary mass savings is obtained [6]. The distribution of total secondary mass savings among various major body and chassis systems is as follows: structure, 0.15 kg; suspensions,

0.20 kg; steering and brakes, 0.01 kg; and tires and wheels, 0.05 kg. Initial lightweight component costs are estimated based on the lowest number of dollars per kilograms saved and final costs by taking into consideration that the extent of cost change will be 0.6 for every unit fraction of component mass change.

4.1 Lightweighting Metals Scenario

Table 6 shows the cost-effectiveness of the 25 % body and chassis target by choosing the least expensive way to get to the desired mass reduction target with the metals based on Tables 1 through 3, discussed previously.

Table 6. Lightweighting metals component substitutions considered for 25 % body and chassis mass reduction target scenarios (with mass decompounding).

Part	Base-line Mass (kg)	LW Mass (kg)		Mass Delta (kg)	Baseline Cost (\$)	LW Cost (\$)		\$/kg Saved		Technology
		P ^a	F ^a			P ^a	F ^a	P ^a	F ^a	
BIW	321	224.7	206.8	114.2	1,025	1,213	1,155	1.95	1.14	AHSS
Chassis										
Cradles	32.3	24.2	19.6	12.7	78	85	75	0.87	-0.22	AHSS
Corner Suspensions	134	125.2	105.9	28.1	627	649	589	2.50	-1.35	AHSS Control Arms
Braking Systems	70	68.6	67.8	2.2	294	303	301	6.16	3.08	Al Master Cylinder
Wheels and Tires	58	55.4	49.4	8.6	295	301	281	2.20	-1.60	AHSS Wheels
Steering Systems	41	38.7	38.3	2.7	350	351	349	0.43	-0.37	Al Steering Wheel Column + Mg Steering Wheel
TOTAL	656.3	536.8	487.8	168.5	2,669	2,901	2,750	1.94	0.48	

^aP = final mass based on primary mass savings only; F = final mass including secondary mass savings.

The approach illustrated in Table 6 considers only body and chassis systems and includes mass decompounding. The amount of mass decompounding that can occur in production vehicles as a result of substitution of materials with lower density materials is a subject of much debate and has a wide variation in practice. Table 7 illustrates a pathway to achieve the same mass savings without mass decompounding but by using material substitution for components not considered part of the BIW or chassis subsystems. This scenario is based on an all metals solution.

Table 7. Lightweighting metals component substitutions for a 164 kg lighter vehicle incorporating components outside the body and chassis to achieve the same mass reduction goal as other scenarios without mass decompounding.

Part	Baseline Mass (kg)	LW Mass (kg)	Mass Delta (kg)	Baseline Cost (\$)	LW Cost (\$)	\$/kg Saved	Technology
BIW	321	224.7	96.3	1,025	1,213	1.95	AHSS
Chassis							

Cradles	32.3	24.2	8.1	78	85	0.87	AHSS
Corner Suspensions	134	125.2	8.8	627	649	2.50	AHSS Control Arms
Braking Systems	70	68.6	1.4	294	303	6.16	Al Master Cylinder
Wheels and Tires	58	55.4	2.6	295	301	2.20	AHSS Wheels
Steering Systems	41	38.7	2.3	350	351	0.48	Al Steering Wheel Column + Mg Steering Wheel
Other							
Panels	60	46.8	13.2	197	197	0	AHSS
Instrument Panel Beams	9.3	4.6	4.7	68	43	-5.32	Mg
Front/Rear Bumpers	10	6.0	4.0	91	60	-7.75	Al
Seat Frames	39.3	19.3	19.7	269	296	1.37	AHSS
Center Consoles	4.1	1.6	2.5	6	13	2.80	Mg
Steering Knuckles	6.2	3.1	3.1	32	71	3.42	Al
TOTAL	785.1	618.2	166.9	3,332	3,581	1.49	

4.2 Carbon Fiber Polymer Composites Scenario

Table 8 indicates the cost-effectiveness of the 25 % body and chassis mass reduction goal achieved using CFCs coupled with mass decomposing. Note that the chassis components were maintained at the baseline technology level because BIW lightweighting was sufficient to achieve the desired total mass reduction goal.

Table 8. Carbon fiber–reinforced polymer composite component substitutions considered for 25 % body and chassis mass reduction target scenarios with and without mass decomposing.

Part	Baseline Mass (kg)	LW Mass (kg)		Mass Delta (kg)	Baseline Cost (\$)	LW Cost (\$)		Estimated \$/kg Saved		Technology
		P ^a	F ^a			P ^a	F ^a	P ^a	F ^a	
BIW	321	160.5	136.4	184.6	1,025	2,697	2,455	10.42	7.75	CFC
Chassis										
Cradles	32.3	32.3	26.1	6.2	78	78	69	NA	-1.45	Baseline
Corner Suspensions	134	134	108.1	25.9	627	627	554	NA	-2.81	Baseline
Braking Systems	70	70	69	1.0	294	294	291	NA	-2.52	Baseline
Wheels and Tires	58	58	50	8.0	295	295	271	NA	-3.05	Baseline
Steering Systems	41	41	40.4	0.6	350	350	347	NA	-5.12	Baseline
TOTAL	656.3	495.8	430	226.3	2,669	4,341	3,987	7.75	5.82	

^aP = final mass based on primary mass savings only; F = final mass savings including secondary mass savings.

The approach taken in Table 8 considers only body and chassis systems and includes mass decomposing. The amount of mass decomposing that can occur in production vehicles as a result of substitution of materials with lower density materials is a subject of much debate and has a wide variation in practice. Table 9 is a pathway to achieve the same mass savings without mass decomposing but by using material substitution for components not considered part of the BIW or chassis subsystems. It is the **all CFC solution** to save 164 kg from a vehicle, which

is equivalent to 25 % of the BIW **at the lowest cost**. This is accomplished simply by substituting conventional bumper systems with CFC bumper systems.

Table 9. Carbon fiber–reinforced polymer composite component substitutions considered for 25 % body and chassis mass reduction target scenarios including parts not considered part of the body in white or chassis subsystems (without mass decompounding).

Part	Baseline Mass (kg)	LW Mass (kg)	Mass Delta (kg)	Baseline Cost (\$)	LW Cost (\$)	\$/kg Saved	Technology
BIW	321	160.5	160.5	1,025	2,698	10.42	CFC
Front/Rear Bumper Impact Modules	5.5	2.5	3.0	33	100	22.33	CFC
TOTAL	326.5	163	163.5	1058	2,798	10.67	

For information purposes an “all composite” solution, which gives the best balance of mass reduction and cost efficiency and includes glass fiber composites, is provided below (Table 10). This approach provides a mass reduction greater than the target of 164 kg at the lowest cost per kilogram saved.

Table 10. All composite solution considered for 25 % body and chassis mass reduction target scenarios (without mass decompounding).

Part	Baseline Mass (kg)	LW Mass (kg)	Mass Delta (kg)	Baseline Cost (\$)	LW Cost (\$)	Estimated \$/kg Saved	Technology
BIW	321	160.5	160.5	1,025	2,698	10.42	CFC
Panels	60	45	15	197	125	-4.80	Glass FRP
IP Beam Assembly	9.3	6.8	2.5	68	60	-3.20	Hybrid Glass-mat TP Composite /Steel
Seat	65.5	26.9	38.6	1,075	1,011	-1.66	Lotus
TOTAL	455.8	239.2	216.6	2,365	3,894	7.06	

4.3 Multi-Material Vehicle Scenario

Tables 11 and 12 show the cost-effectiveness of the 25 % body and chassis mass reduction target achieved by choosing the least expensive way to get to the desired mass reduction target with the metals and the material alternatives described in Tables 1 through 5, discussed previously, with and without mass decompounding.

Table 11. Multi-material component substitutions considered for 25 % body and chassis mass reduction target scenarios (with mass decompounding).

Part	Baseline Mass (kg)	LW Mass (kg)		Baseline Cost (\$)	LW Cost (\$)		\$/kg Saved		Technology
		P ^a	F ^a		P ^a	F ^a	P ^a	F ^a	
BIW	321	224.7	214.6	1,025	1,213	1,145	1.95	1.12	AHSS
Chassis									
Cradles	32.3	24.2	19.7	78	85	76	0.87	-0.20	AHSS
Corner	134	125.2	106.5	627	649	591	2.50	-1.32	AHSS Control

Suspensions									Arms
Braking Systems	70	70	69.3	294	294	292	NA	-2.52	Baseline
Wheels and Tires	58	49.5	43.7	295	323	300	3.26	0.35	AHSS Wheels + Tires
Steering Systems	41	39.2	38.8	350	350	348	0.00	-1.03	Al Steering Wheel Column
TOTAL	656	532.8	492.6	2,669	2,913	2,751	1.98	0.50	

^aP = based on primary mass savings only; F = total mass savings including secondary mass savings.

Table 12. Multi-material component substitutions considered for 25 % body and chassis mass reduction target scenarios (without mass decompounding).

Part	Baseline Mass (kg)	LW Mass (kg)	Baseline Cost (\$)	LW Cost (\$)	\$/kg Saved	Technology
BIW	321	224.7	1,025	1,213	1.95	AHSS
Chassis						
Cradles	32.3	24.2	78	85	0.87	AHSS
Corner Suspensions	134	94	627	899	6.79	AHSS Control Arms+ Front End (w/ Al Bumper and Rail)
Braking Systems	70	64.7	294	327	6.16	Al Master Cylinder + Mg Brake Actuators
Wheels and Tires	58	45.05	295	323	2.14	Al Wheels + Tires
Steering Systems	41	38.8	350	354	1.82	Mg Steering Wheel Column
TOTAL	656	492	2,669	3,201	3.24	

5. TOTAL VEHICLE 25 % MASS REDUCTION SCENARIO

The baseline vehicle curb mass is estimated to be 1,477 kg, of which powertrain mass is estimated to be 448 kg. A 25 % vehicle mass reduction, that doesn't include the powertrain, represents removing 257 kg from the vehicle, leaving only 772 kg as a final vehicle mass without the powertrain. Tables 13 and 14 show the cost-effectiveness of the 25 % vehicle mass reduction target achieved by choosing the least expensive way to get to the desired mass reduction target with the metals and materials alternatives in Tables 1 through 5, discussed previously, both with and without mass decompounding.

Table 13. Multi-material component substitutions considered for 25 % vehicle mass reduction target scenarios (with mass decompounding).

Part	Baseline Mass (kg)	LW Mass (kg)		Baseline Cost (\$)	LW Cost (\$)		Estimated \$/kg Saved		Technology
		P ^a	F ^a		P ^a	F ^a	P ^a	F ^a	
Body									
BIW	321	224.7	197.3	1,025	1,213	1,124	1.95	0.80	AHSS
Panels	60	45	45	197	125	125	-4.80	-4.80	Glass Fiber Reinforced Polymer Composites
Front/Rear Bumpers	10	6	6	91	60	60	-7.75	-7.75	Al

Glass	22	22	22	129	129	129	NA	NA	Baseline
Paint	12	12	12	450	450	450	NA	NA	Baseline
Exterior Trim	11	11	11	104	104	104	NA	NA	Baseline
Body Hardware	12	12	12	250	250	250	NA	NA	Baseline
Chassis									
Cradles	32.3	24.2	17.1	78	85	70	0.87	-0.52	AHSS
Corner Suspensions	134	125.2	95.8	627	649	557	2.50	-1.82	AHSS Control Arms
Braking Systems	70	70	68.8	294	294	291	NA	-2.52	Baseline
Wheels and Tires	58	49.5	40.4	295	323	287	3.26	-0.45	Al Wheels + Tires
Steering Systems	41	39.2	38.5	350	350	346	0.00	-1.46	Al Steering Wheel Column
Interior									
Instrument Panels	32	27	27	652	651	651	-0.20	-0.20	Hybrid Glass-mat Thermoplastic I-Beam Assembly + Mg Center Console
Trim and Insulation	41	33.8	33.8	422	432	432	1.39	1.39	Soft Foam MuCell Trim
Door Modules	30	30	30	211	211	211	NA	NA	Baseline
Seating and Restraints	88	59.4	59.4	1,349	1,285	1,285	-2.24	-2.24	Composite Lotus Seat
HVAC	21	21	21	327	327	327	NA	NA	Baseline
Electrical	24	24	24	404	404	404	NA	NA	Baseline
Final Assembly	10	10	10	605	605	605	NA	NA	Baseline
TOTAL	1,029	846	771	7,860	7,342	7,103	-2.83	-2.93	

^aP = final mass based on primary mass savings only; F = final mass including secondary mass savings.

Table 14. Multi-material component substitutions considered for 25 % vehicle mass reduction target scenarios (without mass decompounding).

Part	Baseline Mass (kg)	LW Mass (kg)	Mass Delta (kg)	Baseline Cost (\$)	Estimated \$/kg Saved	Technology
Body						
BIW	321	193	1,025	2,290	9.85	Al
Panels	60	45	197	125	-4.80	Glass Fiber Reinforced Polymer Composites
Front/Rear Bumpers	10	6	91	60	-7.75	Al
Glass	22	22	129	129	NA	Baseline
Paint	12	12	450	450	NA	Baseline
Exterior Trim	11	11	104	104	NA	Baseline
Body Hardware	12	12	250	250	NA	Baseline
Chassis						
Cradles	32.3	24.2	78	85	0.87	AHSS
Corner Suspensions	134	94	627	899	6.79	AHSS Control Arms+ Front End (w/Al Bumper and Rail)
Braking Systems	70	64.7	294	327	6.16	Al Master Cylinder + Mg Brake Actuators

Wheels and Tires	58	45.05	295	323	2.14	Al Wheels + Tires
Steering Systems	41	38.3	350	355	1.89	Mg Steering Wheel Column+ Steering Wheel
Interior						
Instrument Panels	32	20.2	652	810	5.51	IMPAMO
Trim and Insulation	41	33.8	422	432	1.39	Soft Foam MuCell Trim
Door Modules	30	30	211	211		Baseline
Seating and Restraints	88	59.4	1,349	1,285	-2.24	Composite Lotus Seat
HVAC	21	21	327	327	NA	Baseline
Electrical	24	24	404	404	NA	Baseline
Final Assembly	10	10	605	605	NA	Baseline
TOTAL	1,029	765	7,860	9,471	6.10	

Note: An aluminum BIW was chosen to achieve the target mass reduction; however, if an AHSS BIW is chosen, vehicle mass reduction would be 22.5 %, but the cost penalty would be reduced to \$2.16/kg saved. An AHSS BIW is 32.1 kg heavier than aluminum but costs \$1,077 less.

6. CONCLUSIONS

Based on the literature, for each of the material systems considered, a list of potential lighter weight components was constructed, the potential mass reduction associated with each component replacement determined along with the cost of replacing those components with the lighter weight alternative. Secondary mass savings was incorporated in the analysis. For each material system, the alternative material components were then prioritized based on the cost penalty (i.e., dollars per kilogram saved) incurred. This information was then used to construct a table leading to a 25 % mass reduction in the body and chassis structure (164 kg) for two vehicle options: (1) a light metals intensive solution and (2) a carbon fiber composite intensive solution. Finally scenarios were considered for reducing the mass using all of the material options previously mentioned. This was done for a 25 % mass reduction in the body and chassis both with and without mass decompounding and also for a 25 % mass reduction in the entire vehicle (excluding the powertrain) with and without mass decompounding (Table 15).

Table 15. Multi-material component substitutions considered for 25 % body and chassis and 25 % total vehicle (without powertrain) mass reduction target scenarios with and without mass decompounding.

System	Baseline Mass (kg)	LW Mass (kg)		Baseline Cost (\$)	LW Cost (\$)		\$/kg Saved	
		P ^a	F ^a		P ^a	F ^a	P ^a	F ^a
Optimized Composite Body and Chassis with Mass Decompounding	656	495.8	430	2,669	4,341	3,987	7.75	5.82
Optimized Composite Body and Chassis without Mass Decompounding	656	492.5		2669	4409		10.65	
Optimized Metal Body and	656	536.8	487.8	2,669	2,901	2750	1.94	0.48

Chassis with Mass Decomponding								
Optimized Metal Body and Chassis without Mass Decomponding	656	492		2,669	3,201		3.24	
All Material Entire Vehicle (except powertrain) with Mass Decomponding	1,029	846	771	7,860	7,342	7103	-2.83	-2.92
All Material Entire Vehicle (except powertrain) without Mass Decomponding ^b	1,029	765		7,860	9,471		6.10 ^b	

^aP = final mass based on primary mass savings only; F = final mass including secondary mass savings.

^bAn aluminum BIW was chosen to achieve the target mass reduction; however, if an AHSS BIW is chosen, vehicle mass reduction would be 22.5 %, but the cost penalty would be reduced to \$2.16/kg saved. An AHSS BIW is 32.1 kg heavier than aluminum but costs \$1,077 less and would yield a cost increase of only \$534 per vehicle.

By comparison, the all composite solution seems expensive but at a cost of \$5.82/kg to save 164 kg of mass, the total increase in vehicle cost would only be \$954.48. That is less than the price of leather seats!

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8. REFERENCES

1. Ashley, S., "Lightweight Materials Compete for Automakers Attention", in SAE International, 24 June (2013).
2. US Department of Energy (DOE). Trucks and Heavy-Duty Vehicles Technical Requirements and Gaps for Lightweight and Propulsion Materials, Final Report, Vehicle Technologies Office, Feb. (2013)
3. McKinsey & Company. "Lightweight, heavy impact." McKinsey Advanced Industries Sector. Accessed via McKinsey Automotive and Assembly Extranet. (2012).
4. EPA (US Environmental Protection Agency). Light-duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 through 2010, Report EPA420-R-10-023. Nov (2010).

5. EPA (US Environmental Protection Agency). Light Duty Technology Cost Analysis—Report on Additional Case Studies, Report No. EPA-420-R-10-010 prepared by FEV Inc., Apr (2010).
6. Alonso, E., Lee, T.M., Bjelkengren, C., Roth, R., and Kirchain, R.E. “Evaluating the Potential for Secondary Mass Savings in Vehicle Lightweighting,” *Environmental Science & Technology*, 46(5) (2012) 2893–2901.
7. ACC-USAMP (2012). http://www1.eere.energy.gov/vehiclesandfuels/pdfs/lm_11/4_usamp_cooperative_research.pdf; accessed on June 7, 2012.
8. US Department of Energy (DOE). 2010 Annual Progress Report – Lightweighting Material. http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/2010_lightweighting_materials.pdf, 4-33–4-35; accessed on June 8 (2012).
9. Energy and Environmental Analysis, (EEA) Inc. Analysis of Light Duty Vehicle Weight Reduction Potential, Draft Final Report, prepared for the US Department of Energy, Office of Policy, July (2007).
10. Carney, D. “Thin On The Side,” *Automotive Engineering International*, 33–35, Mar. 6 (2012).
11. Ducker Worldwide. “American Iron and Steel Institute—SMDI Light Vehicle Steel Content,” presentation prepared for the Steel Market Development Institute, Mar. (2011).
12. Sedgwick, D. “Automakers Snap Up Aluminum: Body-in-White Coming to North America,” *Automotive News*, June 18 (2012) p. 26.
13. Automotive Engineering International (AEI) Online 2011. “JCI Joins Steel, Aluminum for Seat Structures,” Apr. 19; accessed at <http://www.sae.org/mags/aei/mater/9690> on July 20, 2012.
14. Ducker Worldwide. “Aluminum in 2012 North American Light Vehicles: Executive Summary,” presentation at Aluminum in Transportation, The Aluminum Association, Inc. Sept. 7 (2011).
15. Greer, D. Meridian Lightweight Technologies, Inc., Detroit, MI. Personal communication with Sujit Das, Oak Ridge National Laboratory, Oak Ridge, TN, Apr. 2 (2010).
16. Luo, A.A. Li, M., and Logan, S.D. “Magnesium Front End Design and Development (Phase II—AMD 904),” 2011 Annual Progress Report (Lightweighting Materials); http://www1.eere.energy.gov/vehiclesandfuels/pdfs/lm_11/4_usamp_cooperative_research.pdf, 4-22–4-26; accessed on June 8 (2012).
17. Luo, A.A., Wagner, D.A., and Logan, S.D. “Magnesium Front End Design and Development (AMD 603),” 2010 Annual Progress Report (Lightweighting Materials). (2011)

18. Iobst, S., Berger, L., Fernholz, K., Dahl, J., and Smith G “Fabrication of the Automotive Composites Consortium Carbon Fiber B-Pillar,” International SAMPE Symposium and Exhibition (Proceedings), v 52, SAMPE’07: M and P—From Coast to Coast and Around the World, Conference Proceedings, (2007) 11p.
19. Marsh, G. “Composites Conquer with Carbon Supercars,” Reinforced Plastics, Jan., 20–24 (2006).
20. Rehkopf, J. Personal communication with Sujit Das, Oak Ridge National Laboratory, Oak Ridge, TN. Plasman Carbon Composites, Oak Ridge, TN, Apr. 16 (2012).
21. Composites Manufacturing. “Carbon Revolution Invents First One-Piece Carbon Fiber Wheel,” June 29 (2012). Also available at: <http://www.compositesmanufacturingblog.com/2012/06/one-piece-wheel/>.
22. Aachen, University of . Stiffness Relevance and Strength Relevance in the Crash of Car Body Components, Report No. 83440, May.
23. Koeber, A., and Riedel, U. “CAMISMA—Carbon/Amid/Metal based Interior Structure with Multi-Material System Approach,” CFK-Valley Convention, June 12 (2012).
24. Lotus Engineering, Inc. “An Assessment of Mass Reduction Opportunities for a 2007-2020 Model Year Vehicle Program,” Apr (2010).
25. US Department of Energy (DOE). “Automotive Composites Consortium Focal Project 4,” Automotive Lightweighting Materials: FY2007 Progress Report, Washington, DC (2008).
26. Sklad, P.S. et al, Vehicle Technologies Program Workshop Report: Light-Duty Vehicles Material Technical Requirements and Gaps, October (2012).
27. Thryft, A. R. “Performance Car Seat Eliminates Steel,” (2012). http://www.designnews.com/document.asp?doc_id=237504; accessed on 1/30/2012.
28. Hollowell, W. T. “Opportunities for Lightweighting Vehicles Using Advanced Plastics and Composites,” paper presented at SAE 2011 Annual Congress, Apr. 12–14, (2011) Detroit, Michigan.