Vehicle Materials: Material Composition of U.S. Light-duty Vehicles

by

Q. Dai, J. Kelly, and A. Elgowainy

Systems Assessment Group

Energy Systems Division

Argonne National Laboratory

September 2016

CONTENTS

FIGURES

TABLES

TABLES (CONT.)

ACRONYMS

AHSS	advanced high-strength steel
BEV	battery electric vehicle
BIW	body-in-white
CAFE	Corporate Average Fuel Economy
CFRP	carbon fiber reinforced plastic
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
FC	fuel consumption
FE	fuel economy
GFRP	glass fiber reinforced plastic
GHG	greenhouse gas
HSS	high-strength steel
ICEV	internal combustion engine vehicle
IP	instrument panel
LCA	life cycle analysis
LDV	light-duty vehicle
MMLV	Multi-Material Lightweight Vehicle
MY	model year
NHTSA	National Highway Traffic Safety Administration
ORNL	Oak Ridge National Laboratory
TEDB	Transportation Energy Data Book
VTO	Vehicle Technologies Office

This page intentionally left blank.

Vehicle Materials: Material Composition of U.S. Light-duty Vehicles

Qiang Dai, Jarod C. Kelly, and Amgad Elgowainy

Energy Systems Division
Argonne National Laboratory

September 2016

1 INTRODUCTION

The average curb weights of new U.S. light-duty vehicles (LDV) had decreased from 4,060 pounds in 1975 to 3,221 pounds in 1987, and then gradually increased back to 4,072 pounds in 2014 (EPA 2014). Aside from the increase of truck shares in the LDV fleet, which lead to the increase in average fleet weight and power, vehicle weight reduction is impacted by industry-wide deployment of technologies such as unibody construction, more efficient and/or smaller engines, and lightweight materials, while vehicle weight addition is impacted by the inclusion of new and/or better functionalities and features (Mackenzie, 2014). As different automotive components consist of different sets of materials, adding, eliminating or redesigning any single automotive component would change the makeup of the entire vehicle. Therefore, the observed changes in vehicle curb weight concurred with changes in vehicle material composition.

Vehicle lightweighting has been a focus of the automotive industry in recent years, especially after the U.S. Environmental Protection Agency (EPA) and National Highway Traffic Safety Administration (NHTSA) established the greenhouse gas (GHG) emissions and Corporate Average Fuel Economy (CAFE) standards for 2017 through 2025 model year (MY) LDVs in 2012, as lightweighting is identified as an indispensable component of possible compliance pathways (EPA 2016). Among all the commercially available lightweighting technologies, material substitution by lightweight materials has the greatest potential in reducing vehicle weight (VTO 2016). Given the historical interdependence of a fleet's average curb weight and its material composition, and the expected increasing use of lightweight materials, it can be projected that the material composition of the U.S. light-duty fleet would continue to evolve into the next few decades.

Since the total weight and the material composition of a vehicle are two determinants of the environmental footprint associated with the vehicle manufacturing cycle, in this study, historical trends of average curb weight and material composition for the U.S. LDV fleet are examined. To get a better understanding of possible curb weights and material compositions of the future U.S. LDV fleet, opportunities of vehicle lightweighting through material substitution as reported in literature, existing lightweight vehicle designs offered by the automotive industry, conceptual lightweight vehicle designs obtained from various sources, as well as automotive lightweighting targets set by DOE and the industry, are collected and analyzed. Data compiled in this study will serve to inform the life cycle analysis (LCA) of U.S. LDV fleet in Argonne's Greenhous gases, Regulated Emissions, and Energy use in Transportation (GREET®) Model while accounting for temporal variations in vehicle weights and material compositions.

2 HISTORICAL TRENDS OF VEHICLE WEIGHT AND MATREIAL COMPOSITION

The historical curb weights, material compositions, and fuel economies (FEs) of the average U.S. LDV for MY 1995-2014 are summarized in Table 1. The average FEs are obtained from EPA (EPA 2014), whereas the average automotive material weights are adopted from various editions of Transportation Energy Data Book (TEDB) published by Oak Ridge National Laboratory (ORNL). It should be noted that the vehicle weights and material compositions reported in TEDBs represent the average North American LDV, and are assumed to be representative of the average U.S. LDV. Nonetheless, the historical LDV weights extracted from TEDBs do not exactly match with those reported by EPA, which are also listed in Table 1. Therefore, the historical trend of FE is examined side by side with the curb weights reported by EPA (EPA 2014), whereas the historical trend of material composition is investigated concurrently with the weights reported by ORNL. It should be pointed out, however, that the vehicle weights reported by the two sources differ by less than 2.5% for any given MY, and the general trends of vehicle weights obtained from the two sources are in good agreement for MY 1995-2014. In the absence of more harmonized data, these two sets of historical data could be used interchangeably for the analysis of U.S. LDV fleet.

The historical trend of vehicle weights, together with that of vehicle fuel economy, is plotted in Figure 1, while Figure 2 shows the historical trends of weight percentages of select automotive materials. “Steel” in Figure 2 includes regular steel, stainless steel and other steels from Table 1 for the sake of simplicity. “Others” in Figure 2 consist of magnesium castings, copper and brass, lead, zinc castings, powder metal parts, other metals, coatings, textiles, fluids and lubricants, glass and other materials as listed in Table 1. They are grouped together for two reasons. First, for each of the categories included in “Others”, the variation of its weight percentages during 1995-2014 does not exceed 1 wt% of the total vehicle. In other words, none of these categories is a notable driver for the changes of vehicle material compositions observed during the time frame of interest. Second, categories such as magnesium castings, zinc castings, other metals and coatings each represents less than 1 wt% of the total vehicle, and are therefore deemed insignificant in impacting the vehicle-cycle environmental footprints.

2.1 Historical Vehicle Curb Weight and Fuel Economy

As can be observed from Figure 1, the average curb weight of U.S. LDVs shows a steady increase from 3,600 pounds in 1995 to 4,100 pounds in 2004, and has been fluctuating within 3% around 4,000 pounds since 2005. The average FE of U.S. LDVs, on the contrary, exhibits an average annual reduction rate of 0.7% between 1995 and 2004, and has been predominantly on the rise since 2004. The reduction of FE during 1995-2004 can be attributed to the overall weight increase at 1.4% per year during that period, but the reasons behind the continuous improvement of FE since 2004 need further analysis. To better examine the correlation between changes in vehicle weight and those in FE, the annual percentage changes for vehicle weight, FE, as well as the inverse of FE (representing fuel consumption) are plotted in Figure 3. It can be observed from Figure 3 that the annual percentage changes of vehicle weight over 1995-2014 correlate well with those of fuel consumption (FC). The overall correlation coefficient is calculated at 0.90. However, the degrees of correlation vary over time, as indicated by the shifting intervals

TABLE 1 1995-2014 U.S. light-duty fleet material content in lbs per vehicle, curb weight in lbs, and FE in mpg

	1995 a	1996 b	1997 b	1998 b	1999 b	2000 a	2001 b	2002 b	2003 b	2004 b	2005 a	2006 a	2007 a	2008 a	2009 a	2010 a	2011 a	2012 a	2013 a	2014 b
Regular steel	1,630	1,636	1,649	1,669	1,662	1,655	1,652	1,649	1,646	1,650	1,634	1,622	1,644	1,629	1,501	1,542	1,458	1,346	1,361	1,379
High and medium strength steel	324	333	346	378	390	408	424	443	460	479	491	500	518	523	524	559	608	606	649	649
Stainless steel	51	53	55	59	60	62	63	64	65	70	71	73	75	75	69	73	73	68	74	73
Other steels	46	44	42	40	30	26	28	30	32	34	35	35	34	34	31	33	32	30	32	32
Iron castings	466	444	438	438	436	432	384	355	336	331	328	331	322	301	206	237	275	280	283	271
Aluminum	231	224	227	245	257	268	279	289	299	311	316	323	313	315	324	344	355	364	379	398
Magnesium castings	4	6	6	7	7	8	10	9	10	10	10	10	10	11	12	13	12	11	11	11
Copper and brass	50	51	53	53	52	52	66	69	70	71	59	61	53	64	63	65	67	72	73	71
Lead	33	34	35	35	35	36	37	35	35	37	37	39	42	45	45	40	41	37	36	36
Zinc castings	19	19	18	17	14	13	11	10	10	10	10	10	9	10	9	9	9	8	8	8
Powder metal parts	29	28	31	33	35	36	38	39	41	43	42	42	43	43	41	41	41	44	45	46
Other metals	4	4	4	4	4	4	4	4	4	5	4	5	5	5	5	6	5	5	5	4
Plastics and plastic composites	240	257	260	278	265	286	298	307	319	338	332	338	331	343	384	378	377	355	336	329
Rubber	149	154	158	166	159	166	163	168	169	172	173	174	189	185	212	200	222	210	203	197
Coatings	23	25	24	26	24	25	26	26	25	28	27	29	29	28	34	34	34	33	32	28
Textiles	42	41	47	43	42	44	45	45	46	51	48	48	46	48	53	54	48	49	50	49
Fluids and lubricants	192	198	199	201	204	207	208	209	210	210	210	211	215	214	219	226	223	217	222	224
Glass	97	99	100	99	101	103	104	104	105	105	104	105	106	106	93	94	98	95	96	96
Other materials	64	65	65	58	66	71	75	79	83	87	86	88	92	91	90	92	94	90	93	93
Total	3,694	3,715	3,757	3,849	3,843	3,902	3,915	3,934	3,965	4,042	4,017	4,044	4,076	4,070	3,915	4,040	4,072	3,920	3,988	3,994
EPA LDV curb weight c	3,613	3,659	3,727	3,744	3,835	3,821	3,879	3,951	3,999	4,111	4,059	4,067	4,093	4,085	3,914	4,002	4,127	3,977	4,015	4,072
EPA LDV FE (mpg) c	20.5	20.4	20.2	20.1	19.7	19.8	19.6	19.5	19.6	19.3	19.9	20.1	20.6	21	22.4	22.6	22.4	23.6	24.1	24.2

a. ORNL TEDB Editions 26-34
b. Personal communication with Ms. Stacy Davis from ORNL
c. EPA 2014

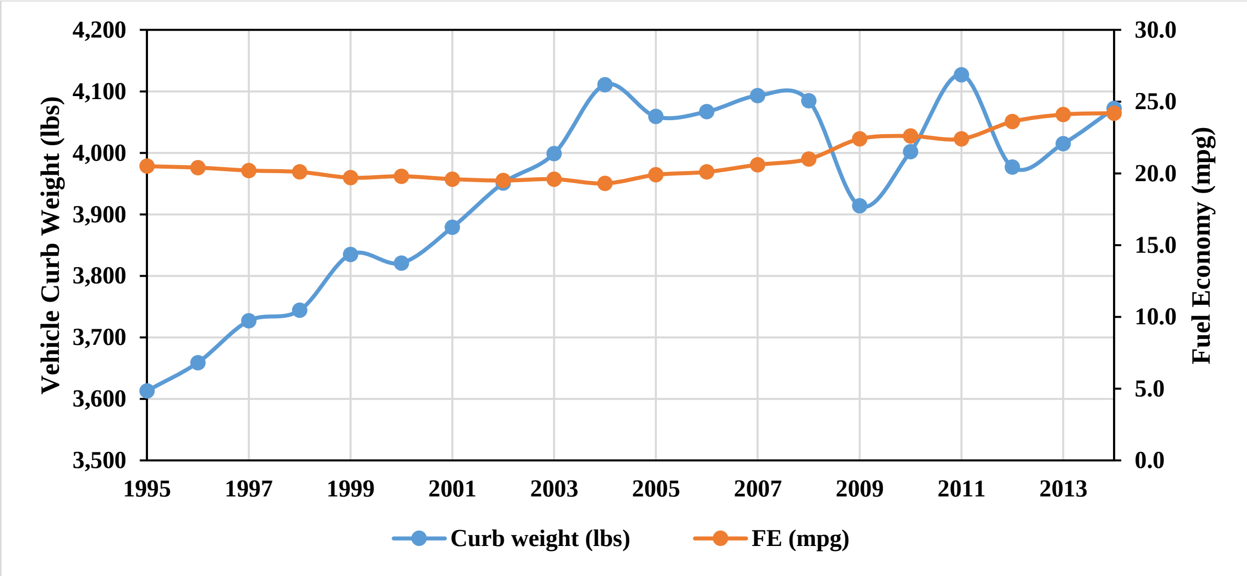

FIGURE 1 Historical trends of vehicle curb weight and FE for MY 1995-2014 U.S. LDV

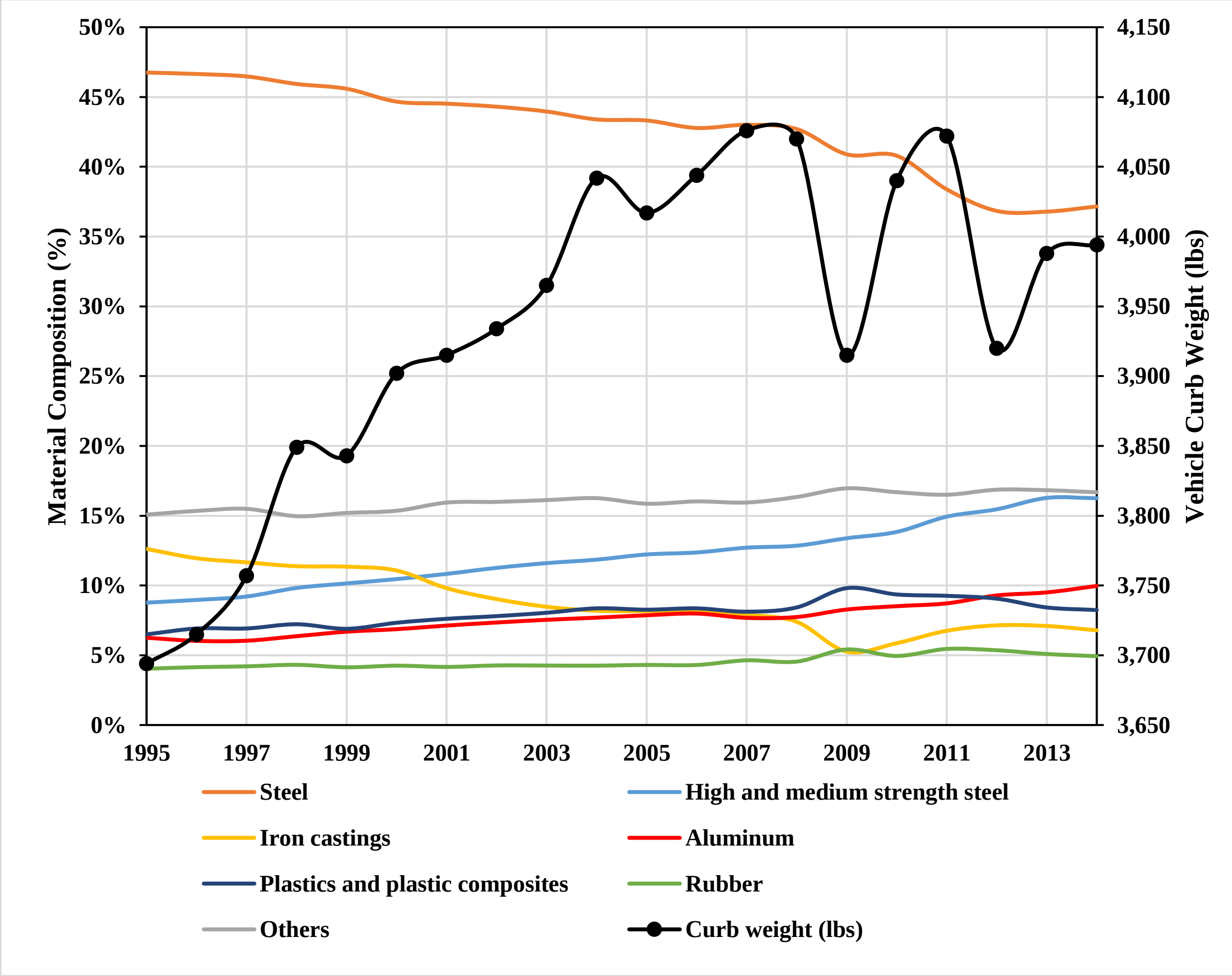

FIGURE 2 Historical trends of automotive material weight percentages for MY 1995-2014 U.S LDV

between the blue solid curve and the orange dashed curve in Figure 3. Therefore, it can be concluded that although changes in vehicle FE between 1995 and 2014 are predominantly determined by the changes in vehicle weight, there are other drivers for the variations in FE, and the efficacy of the other drivers differs in distinct MYs. These other drivers cannot be identified due to lack of data and may be subjects of future analysis. However, it can be speculated that the changes in gasoline prices, and the deployments of more efficient engines, tires of reduced rolling resistance and better aerodynamic designs are some of the notable ones.

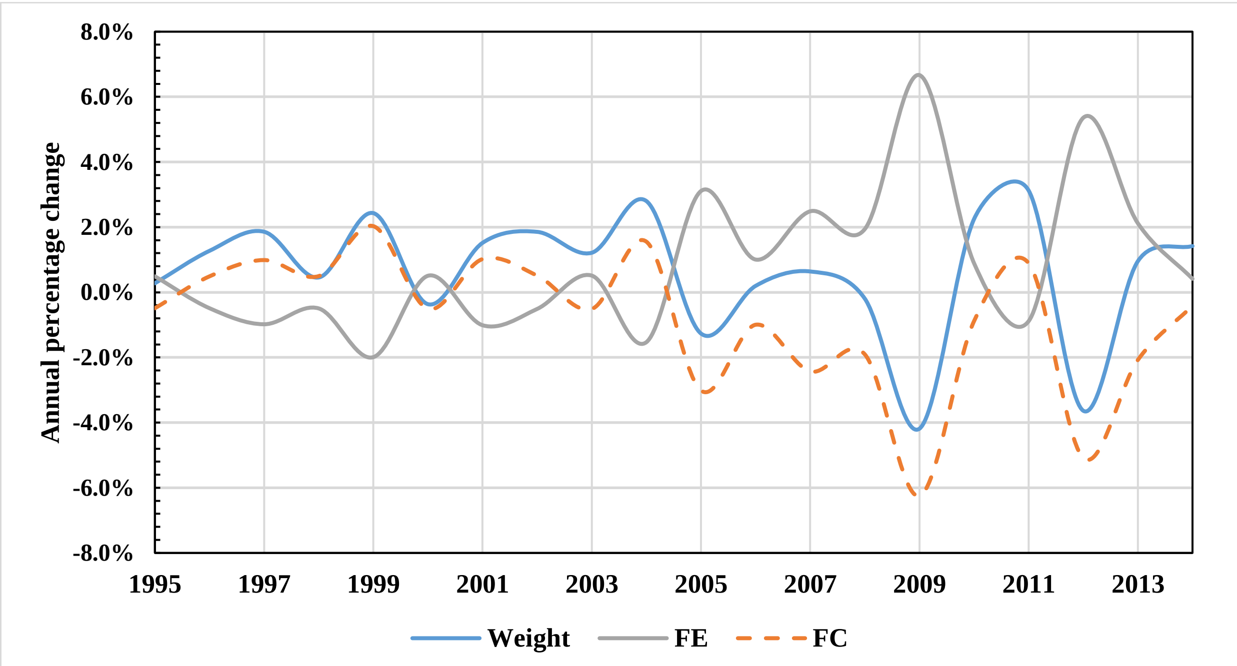

FIGURE 3 Annual percentage changes of weight, FE and FC of MY 1995-2014 U.S. LDV

2.2 Historical Vehicle Material Composition

For the variations in material composition shown in Figure 2, it is evident that the weight percentages of steel in an average U.S. LDV have decreased considerably, from 47% in 1995 to 37% in 2014, signifying an annual reduction rate of 1.2%. Meanwhile, the weight percentages of both high strength steel (HSS) and aluminum have increased almost linearly, at an average annual growth rates of 3.3% and 2.5%, respectively, whereas the weight percentages of rubber remain relatively stable between 1995 and 2014. In contrast, the weight percentages of iron castings and plastics exhibit a more complex trend, with an overall decrease at 3.2% per year for iron castings, and an overall increase at 1.3% per year for plastics, accompanied by a few deviations over the period of study. One deviation worth mentioning is the sudden decrease of cast iron content in MY2009 U.S. LDV, followed by a rebound in 2010, while the mass contents of plastics show the opposite trend for the same period. This deviation can be partially attributed to the drop of truck production share of LDVs from 40.7% in 2008 to 33.0% in 2009, together with the subsequent increase to 37.3% in 2010 as shown in Figure 4 (EPA 2014), since compared with cars, trucks contain more cast iron and less plastics on a weight percentage basis (Kelly 2015, Kelly 2014). However, another remarkable downturn in the truck shares occurs in 2012, but similar deviations are not observed for the weight percentages of cast iron and plastics.

Therefore, it is likely that some other reasons besides changes in truck shares also contribute to the variations in the contents of cast iron and plastics between 2008 and 2010.

The overall temporal variations of automotive material compositions can be explained by the automotive industry's effort to build cars out of lighter materials in the past few decades. Specifically, steel in structural parts is replaced by HSS or aluminum, while steel in non-structural parts is replaced by HSS, aluminum or plastics (EPA 2012, NHTSA 2012). Parts that were traditionally made of cast iron, such as the engine block, the cylinder head, and the gearbox housing, are now made of cast aluminum (EPA 2012, NHTSA 2012).

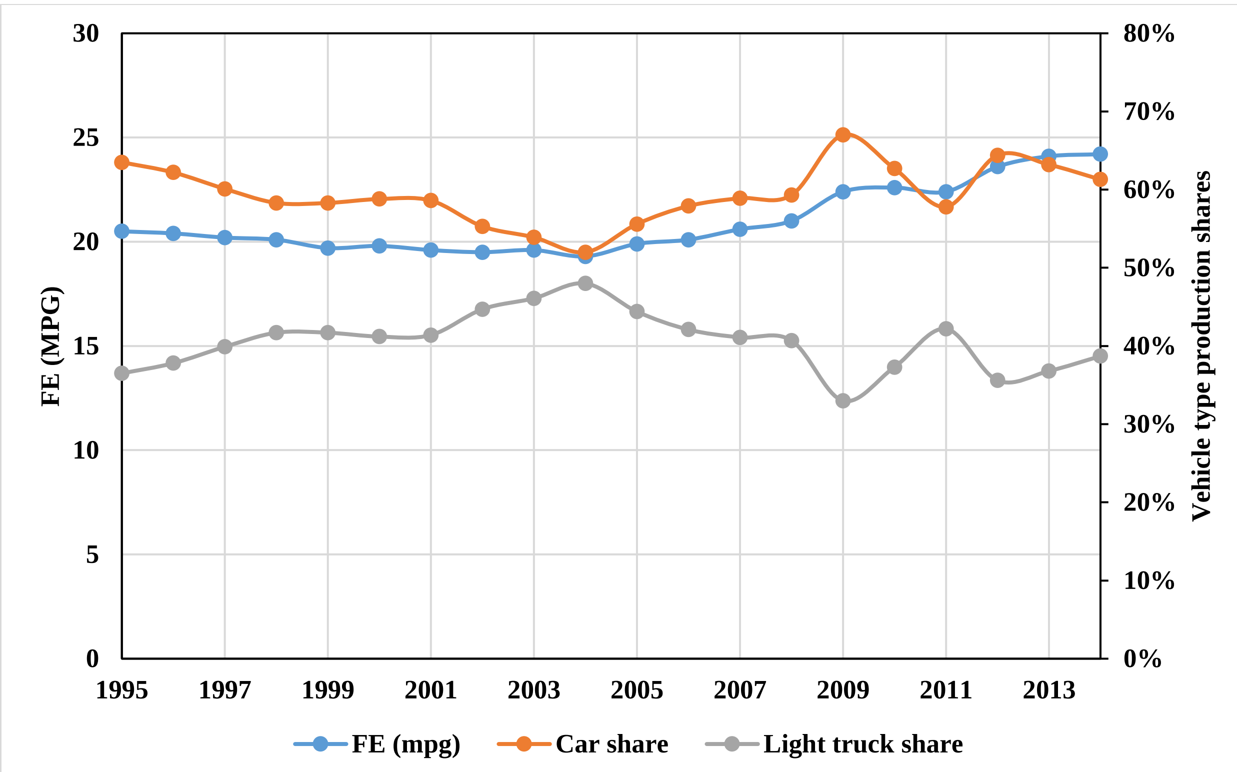

FIGURE 4 MY 1995-2014 U.S. LDV fleet vehicle type production shares

3 FUTURE TRENDS OF VEHICLE WEIGHT AND MATREIAL COMPOSITION

3.1 Future Vehicle Lightweighting Targets

As mentioned earlier, vehicle lightweighting is considered to be an effective means to meet the GHG emission and CAFE standards for MY2017-2025 LDVs. the Vehicle Technologies Office (VTO) of DOE has set targets for weight reduction for 2020-2050 light-duty internal combustion engine vehicles (ICEVs), with 2010 as the baseline year (DOE 2013). Targets for select components, subsystems and total vehicle for 2025 and 2050 ICEVs are summarized in Table 2. More recently, VTO has set a more ambitious target of 30% weight reduction from the 2012 baseline for LDVs by 2022, through the use of lightweight materials in the body, chassis and interior parts (VTO 2016).

TABLE 2 DOE Targets for Weight Reduction for 2025 and 2050 ICEVs (DOE 2013)

		2025	2050
	Closure, fenders and bumpers	50%	75%
Body	Entire subsystem	45%	65%
	Front/rear cradles	35%	50%
	Steering knuckles	25-35%	50%
	Brakes	50%	50%*
	Wheels and tires	20%	50%
	Stabilizer	50%	75%
	Ladder frames	25%	35%
	Springs	50%	50%
	Fuel/exhaust	30%*	30%*
Chassis and suspension	Entire subsystem	35%	55%
Powertrain		20%	40%
Interior		15%	35%
Entire vehicle		30%	50%

*Excluding effect of battery electric vehicle (BEV) penetration from reported values

3.2 Future Vehicle Material Compositions

Advanced high-strength steel (AHSS), aluminum (Al), carbon fiber reinforced plastic (CFRP), and magnesium are identified as four lightweight materials that offer significant weight reduction opportunities and have the potential of mass production by 2025 (VTO 2016). AHSS is categorized into HSS for simplicity in this study. HSS and aluminum use have seen steady increase in LDVs, as described in section 2. On the contrary, magnesium and CFRP are not used in notable quantities in currently available LDV models, primarily due to cost concerns. An exception is the BMW i3, which features a 330 lbs body-in-white (BIW) made of CFRP (SAE 2013).

Looking forward, predications suggest that the use of HSS and aluminum is expected to grow even faster in future generation vehicles. The automotive industry has already achieved marked success in vehicle weight reduction with these two materials, as exemplified in a few recent models listed in Table 3. Meanwhile, the content of magnesium and CFRP in the U.S. LDV is predicted to increase in the next few decades, in light of the continuous research and development (R&D) efforts supported by DOE and the automotive industry to realize the substantial lightweighting potential offered by these two materials.

TABLE 3 Available LDV Models Featuring Lightweight Designs

Model	Weight reduction (lbs)	Strategy
2014 Jaguar Land Rover[a]	880	Al-intensive body
2015 Ford F150[b]	700	Al-intensive body and HSS-intensive frame
2016 Chevy Malibu[c]	300	HSS-intensive BIW, Al hood, downsized engine
2016 Cadillac CT6[d]	200	Al BIW with HSS/AHSS reinforcement, Al exterior panels
2017 Cadillac XT5[e]	290	Optimized design by "driving out waste"

a. Altair 2016; b. Ford 2015; c. GM 2015; d. SAE 2015; e. SAE 2016.

Although the material compositions for future LDVs cannot be accurately estimated, a few conceptual lightweight designs of MY 2017-2025 LDVs provide some insight. EPA conducted a mass reduction study for LDV, and developed a conceptual vehicle offering 20% weight reduction from the baseline vehicle (a 2010 Toyota Venza) via strategic adoption of design, material, and processes that were supposed to be commercially available by 2017-2020 (EPA 2012). NHTSA carried out a similar study to design a future lightweight vehicle based on a 2011 Honda Accord. Lightweighting technologies selected in that study were assumed to be available in 2017-2025, and to satisfy a production volume at 200,000 units per year (NHTSA 2012). More recently, EPA conducted another lightweighting study on the 2011 Chevrolet Silverado. Technologies capable of mass production at 450,000 units per year during 2020-2025 were chosen to produce a future vehicle that would achieve the greatest possible weight reduction at the lowest cost (EPA 2015). The material compositions of the three conceptual lightweight vehicles, together with those of the corresponding baseline vehicles, have been incorporated into GREET (Kelly 2015, Kelly 2014).

Two additional lightweight designs are the Mach-I and Mach-II, both developed by a partnership between Vehma International and Ford Motor Company, through the Multi-Material Lightweight Vehicle (MMLV) project sponsored by VTO. The Mach-I design adopted commercially available materials and processes, and targeted a curb weight reduction of 22% from the baseline vehicle, whereas the Mach-II design aimed to achieve 50% weight reduction with materials and processes that have known potential and can be commercialized by 2025. The baseline vehicle for both Mach designs was a 2002 Ford Taurus. A 2013 Ford Fusion has been used interchangeably as the baseline vehicle, since it weighs almost the same as a 2002 Ford Taurus, both at the subsystem level and at the whole vehicle level, and serves as the donor vehicle to make prototypes of the conceptual designs (Skszek 2013). Materials and their quantities contained in the 2013 Fusion, Mach-I design, and Mach-II design are listed in Table 4. Please note that "Others" in Table 4 includes all non-metal parts excluding glazing and brake pads, and are assumed to consist of 60 wt% plastics, 25 wt% rubber, and 15wt% textile. The material contents of 2013 Fusion and Mach-I are derived from the bills of materials provided by the design team (Skszek 2015), while Mach-II composition is estimated based on disclosed attributes of the final design as explained in Appendix A.

TABLE 4 Material Contents of Mach Designs and Baseline Vehicle

	2013 Fusion[a]	Mach-I[a]	Mach-II[b]
HSS (kg)	417.5	66.9	28.9
Conventional steel (kg)	413.7	289.8	8.1
Cast iron (kg)	50.0	19.6	17.4
Paint, fluid, adhesive (kg)	72.1	60.5	38.6
Glass, ceramics (kg)	38.3	27.2	17.3
Stainless steel (kg)	19.1	9.7	0.0
Forged iron (kg)	16.0	10.0	0.0
Batteries (kg)	14.0	8.8	8.0
Copper (kg)	33.7	29.3	18.7
Cold-rolled Al (kg)	12.8	143.8	17.2
CFRP (kg)	0.0	57.6	171.5
Extruded Al (kg)	15.6	66.9	97.6
Mg (kg)	2.3	16.0	76.9
Forged Al (kg)	0.0	9.8	0.0
Titanium (kg)	0.0	3.3	3.3
Die-cast Al (kg)	146.4	147.7	114.8
Others (kg)	307.9	229.1	143.9
Total vehicle (kg)	1559	1195	762.0

a. Skszek 2015; b. Estimated.

The total weights and material compositions of all the aforementioned lightweight designs, together with those of the corresponding baseline vehicles, are shown in Figure 5.

"Others" in Figure 5 include glass fiber reinforced plastic (GFRP), zinc, nickel, platinum and all other materials in the vehicles that have not been accounted for. It can be observed that in general, the lightweight designs achieve substantial weight savings through replacing steel and cast iron with HSS, wrought Al, Mg, and CFRP. HSS and Al are the preferred lightweight materials for MY2017-2025 LDVs when cost and mass-production capability are of concern. However, weight reduction beyond 20-30% would require significant increase in the contents of CFRP and Mg, but probably at higher costs.

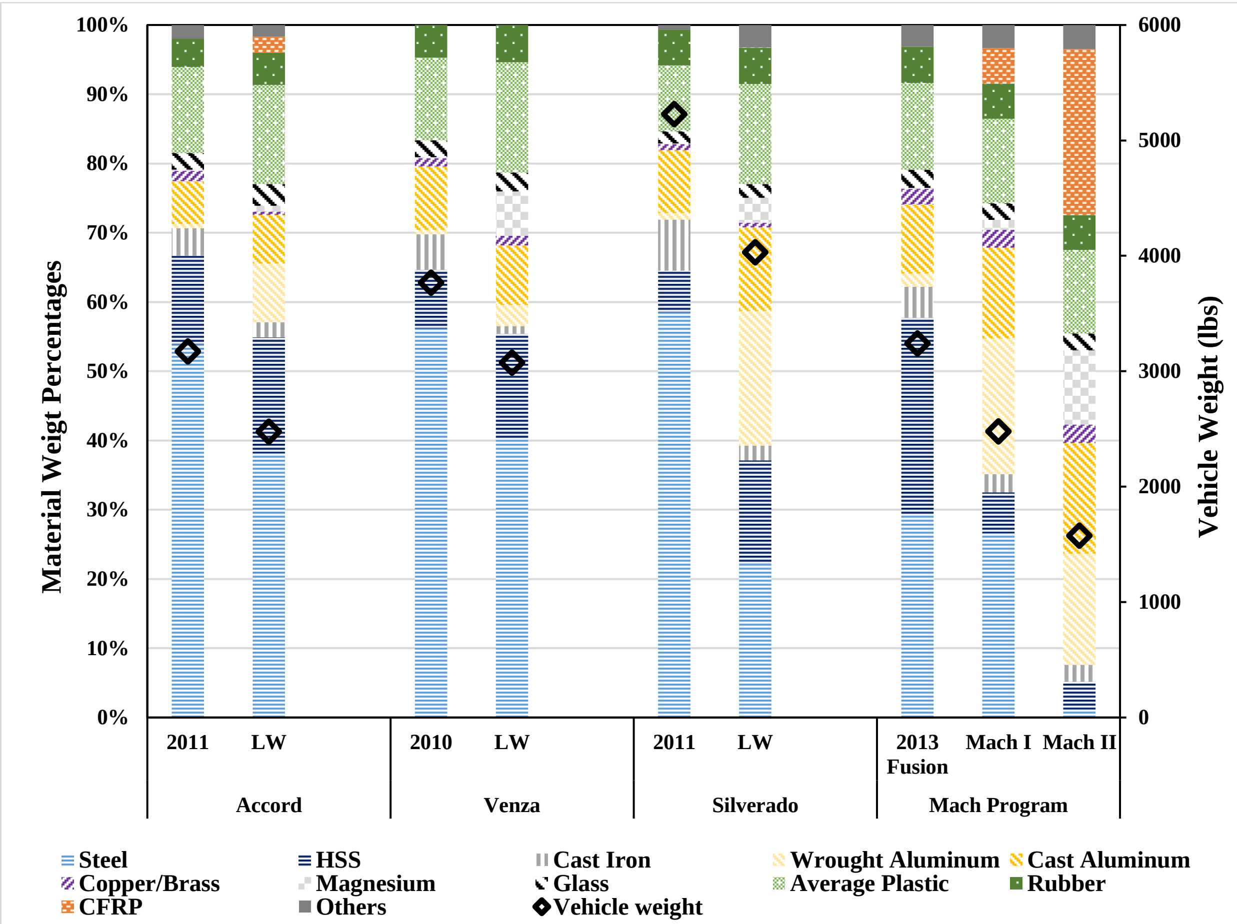

FIGURE 5 Weights and material compositions of lightweight designs and their baseline vehicles

The conceptual lightweight designs provide information regarding the material matrices and their mass percentages at the vehicle level. To make more educated estimates of the weights and material compositions of future LDVs, the material matrices and their mass percentages of future component and/or subsystem designs will be required. Existing literature on automotive component lightweighting are reviewed for possible lightweight material options and corresponding weight reduction potentials. Data compiled are categorized by component as shown in Appendix B. The material substitution strategies proposed for distinct components, the arithmetic average of the weight reduction potentials of each material substitution strategy for each examined component, and the overall weight reduction potentials for each material substitution strategy across all components are charted in Figure 6. It is clear that Al, Mg and

CFRP can be the lightweighting solutions for various vehicle components. Moreover, Mg and CFRP offer greater potential of weight reduction than HSS and Al.

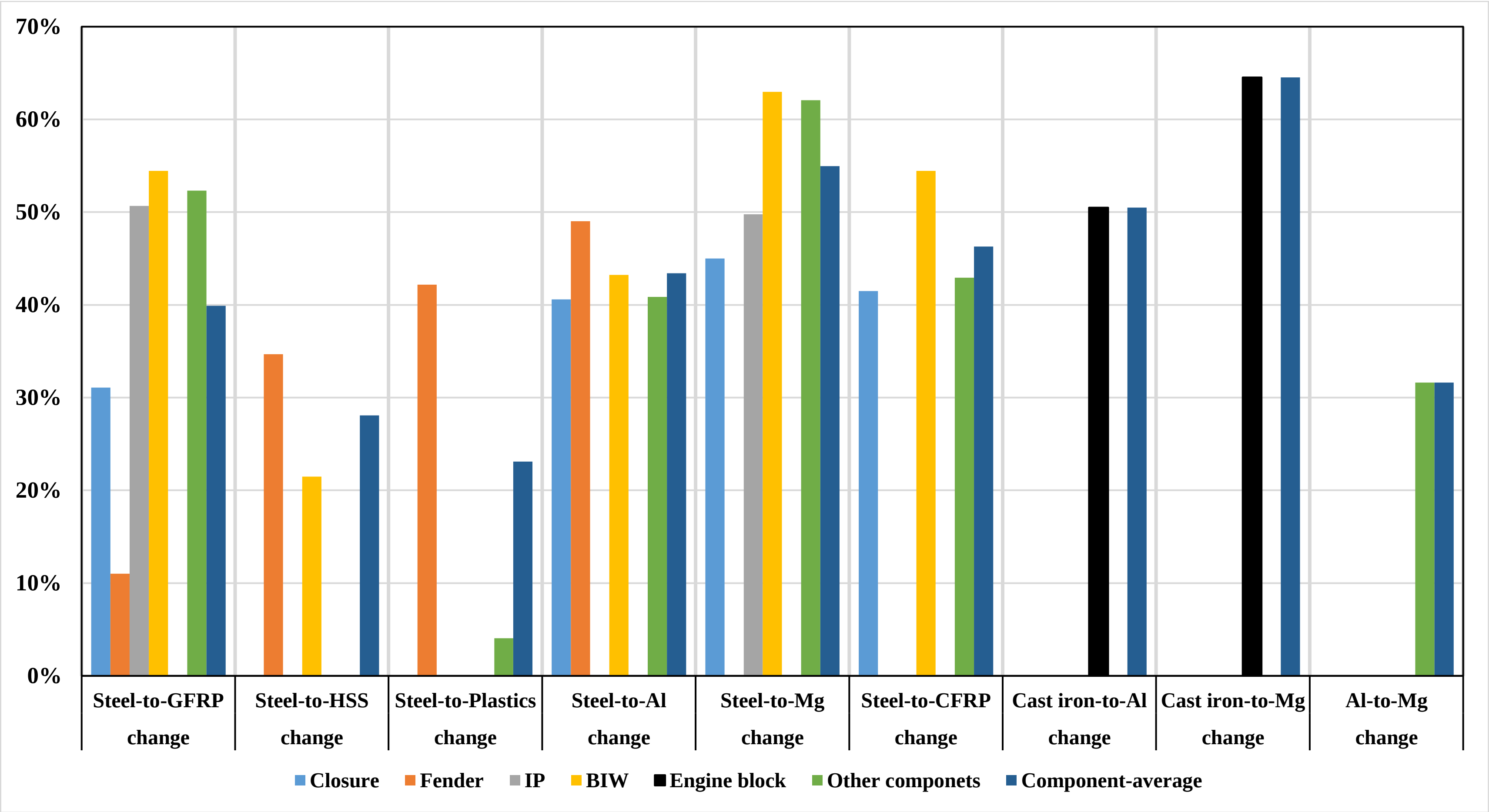

FIGURE 6 Mass reduction potentials of material substitution strategies for various vehicle components

4 CONCLUSIONS

This study investigates historical trends of weights and material compositions for U.S. LDVs, and also examines possible lightweighting strategies of future LDVs. Two findings from this study are particularly instructive for the modeling of vehicle lightweighting in GREET model, as well as for LCA of LDVs in general. First, although decreases in vehicle weight generally lead to improvements in FE, and vice versa, the historical trends reveal that FE does not increase linearly with reductions of vehicle weight, because other technologies can also affect the FE without changing the weight of a vehicle. Therefore, when estimating FE based on vehicle weight changes, especially for a fleet, it is better to make the estimates in the context of weight and FE changes of previous years if such information is available, to account for the effects of the non-lightweighting technologies as they gradually penetrate the automotive industry, rather than use the "rule-of-thumb" of 7% reduction in fuel consumption with 10% reduction in weight. Second, future lightweight vehicle designs can be developed based on a weight reduction target and a set of available technologies. It should be noted, however, that material substitution strategies are subject to cost considerations, and their weight reduction potentials are component specific. As a result, future vehicle weights and material compositions should be built upon component-level material substitution and the corresponding weight reduction.

APPENDIX A MACH-II MATERIAL CONTENT CALCULATION

The weights for each component in a 2013 Ford Fusion, the final Mach-I design, and the final Mach-II design are disclosed by the design team (Skszek 2015), so are the material composition of select components for the Mach-I and Mach-II designs (Skszek 2015, Skszek 2014, Skszek 2013). These information are summarized in Table 5. Material contents of the final Mach-II design are estimated based on assumptions listed in Table 6.

TABLE 5 Weights and Material Compositions of Components in 2013 Fusion, Mach-I and Mach-II

	Baseline (2013 Fusion)		Mach I (final)		Mach II (final)	
Component	Material	Weight (kg)	Material	Weight (kg)	Material	Weight (kg)
BIW		326	37% sheet Al, 14% extruded Al, 13% cast Al, 29% HSS, 7% AHSS	250	20% extruded Al, 15% cast Al, 13% HSS, 6% Mg, 46% CFRP	171
Closures	Al hood	98	65% wrought Al, 4% Mg, 12% HSS, 19% AHSS for door; 100% Al for the rest	69	25% sheet Al, 13% HSS, 2% cast Mg, 51% sheet Mg, 9% extruded Mg	51
Bumpers		37	Al (6xxx roll formed)	25	24% sheet Al, 76% extruded Al	21
Glazing		37	PC for rear windows	25		18
Remainder (trim, paint, seals, etc.)		96		87		47
Seating		70	CFRP seat structure	42	CFRP	34
IP		22	CFRP	14	CFRP	11
Climate control		27		25		10
Remainder (trim, restraint, console, etc.)		88		80		45
Suspension		96	Hollow steel F/R stabilizer; composite front spring, Ti or hollow steel rear spring	81	Assumed to be 60% extruded Al, 20% cast Al, 3.3 kg (6%) Ti, and 14% CFRP	55
Subframes		57	C. Al F/R subframe	30	97% C. Mg, 3% E. Mg	17
Wheels and tires		103	CFRP wheel, tire downsizing	64	Assumed to be 42% wheels, 58% tires	42
Brakes		61	C. Al rotor	49	Assumed to be 100% cast Al	34
Remainder (steering, jack, etc.)		33		29		18
Engine		101	Al cylinder block (-48%) and connecting rod (-38%); CFRP front cover (-41%), oil pan (-26%) and cam carrier (-15%)	71	Assumed to be 70% cast Al, 30% CFRP	63

TABLE 5 (CONT.)

	Baseline (2013 Fusion)		Mach-I (final)		Mach-II (final)	
Component	Material	Weight (kg)	Material	Weight (kg)	Material	Weight (kg)
Transmission and driveline	Steel pump support, side cover, clutch hub and bolts; Al valve body;	106	Al pump support, side cover, clutch hub and bolts; Mg transmission case and valve body; CFRP driveshafts	92	Assumed to be 40% extruded Al, 50% Mg and 10% CFRP	36
Remainder (fuel, cooling, mounts, etc.)		133		104		61
Wiring		28		25		14
Battery		14	12V DC LIB	8		5
Remainder (alternator, starter, speakers)		27		26		9
Remainder total		377		326		
Total vehicle		1560		1196		762

TABLE 6 Assumptions Made to Calculate Mach-II Material Contents

Materials	Assumptions
HSS	Summing up HSS in BIW and closure
Conventional steel	Only in tires (33.3 wt%)
Cast iron	Assumed in engine; scaled down from Mach I based on engine weight
Paint, fluid, adhesive	Scaled down from Mach I based on total weight
Glass, ceramics	Scaled down from Mach I based on total weight; ceramic assumed to be the friction material for brakes
Stainless steel	Not used
Forged iron	Not used
Batteries	Same as Mach I
Copper	Assumed in all the wiring and part of all electronics; Scaled down from Mach I based on total weight
Cold-rolled Al	Summing up sheet Al in closure and bumper
CFRP	Summing up sheet CFRP in BIW, seating, IP, suspension, wheels, transmission, and engine
Extruded Al	Summing up extruded Al in BIW, bumper, suspension, and transmission
Mg	Summing up all kinds of Mg in BIW, closure, subframe and engine
Forged Al	Rolled up in extruded Al
Ti	Same amount as Mach I; used in rear springs
Die-cast Al	Summing up cast Al in BIW, suspension, brake, and engine
Balance	Subtracting the sum of all the materials listed above from the total vehicle weight; Assumed to contain all non-metal parts excluding glazing and brake pads; Assume to be 60% plastic, 25% rubber and 15% textile
Total vehicle	Mass percentages shown in Figure 5 are based on the vehicles sans paint, adhesives, fluids and batteries

APPENDIX B COMPONENT LIGHTWEIGHTING LITERATURE

TABLE 7 Lightweighting Studies on Fender

Fender			
Vehicle	Material	Weight (kg)	Source
1994 German generic compact	Steel	5.6	Saur 1995
	SMC	4.97	
	PPO/PA	3.35	
	Al	2.8	
1997 German generic Midsize	Steel	5.6 (11.16 for 2)	Saur 2000
	Al	2.77 (5.63 for 2)	
	PP/EPEM T10	3.21 (3.37 for 2)	
	PPO/PA	3.35 (3.52 for 2)	
	PC/PBT	3.72 (3.9 for 2)	
Unknown year EU generic	Mild steel	3.46	Ribeiro 2008
	AHSS 600DP	2.66	
	AHSS 1000DP	1.86	
	Al 6010 T4	1.84	
	Al 2036 T4	1.68	
	GZ45/30-30	1.86	
Unknown year EU generic	Steel	5.9	Baroth 2012
	Noryl GTX resin	2.7	

TABLE 8 Lightweighting Studies on Instrument Panel

Instrument panel (IP)				
Vehicle	Design	Material	Weight (kg)	Source
Unknown EU cross bar beam	Steel	steel (drawn)	6.18	Kiefer 1998
	Mg	AM60 (die cast)	3.65	
Unknown US instrument panel	Steel	Steel	10.9	Tharumarajah 2010
		PP-GF30	4.5	
	Mg	Steel	1	
		AZ91D	4.1	
		PP-GF30	3.4	
	Plastic	Steel	3.4	
		PP-GF30	8.2	

TABLE 9 Lightweighting Studies on BIW

BIW				
Vehicle	Design	Material	Weight (kg)	Source
Passenger car	Steel	steel	271	Das 2000
	ULSAB	HSS	203	
	Al	Al	135	
Fullsize	Steel	steel	366	Kojima 2003
	ULSAB	AHSS	275	
	Al	Al	238	
Midsize	Steel	steel	317	
	Al	Al	206	
Luxury car	steel	steel	475	Bertram 2009
	Al	Al	195	
Midsize (est.)	Steel	AISI 3140	270	Mayyas 2012
	HSS	HSLA 456/524	240	
	AHSS	Mart 950/1200	203	
	Al	AA 6060	135	
	Mg	AZ61	100	
	CFRP	CF+epoxy	123	
	GFRP	GF 40-60% + matrix	123	
Fullsize (est.)	Steel	steel	430	Stasinopoulos 2012
	Al	Al	300	

TABLE 10 Lightweighting Studies on Air Intake Manifold

Air intake manifold				
Vehicle	Design	Material	Weight (kg)	Source
1995 Contour	Nylon composite	PA 6.6 FG33	2.07	Keoleian 2003
		Stainless steel	0.41	
		Brass 360	0.26	
	Sand cast	Secondary Al	6.5	
	Brazed Al tubular	Secondary Al	2.73	
		Primary Al	0.89	
2012 EU generic	Polyamide composite	polyamide 6	1.246	Delogu 2015
		glass fiber	0.534	
	Polypropylene composite	PP	0.983	
		glass fiber	0.530	

TABLE 11 Lightweighting Studies on Closure Parts

Closure					
Vehicle	Component(s)	Design	Material	Weight (kg)	Source
1994 Taurus	4 door panels, the hood, and the deck lid	Steel	100% virgin steel	100	Overly 2002
		Al	Al (89%/11%)	55	
		CFRP	CFRP (30%/70% epoxy)	40	
		GFRP	GFRP (15%/85% PET)	69	
Midsize car	Body panels	Steel	Steel	149.7	Khanna 2009
		CNF composite	CNF(3.4v%) + UPR	85	
2007 Cadillac CTS	Front end	Steel	hot-dip galvanized coil	74	Dubreuil 2012
			finished cold-rolled coil	8.2	
		Mg	AM60B (die cast)	30.3	
			AZ31 (stamping)	4.1	
			AM30 (extruded)	10.8	
		Al	AA 5754 (stamping)	29.8	
			A 356 (casting)	16.1	
			AA 6061 (extruded)	13.4	
			AA 6061 (hydroforming)	1.7	
Generic Australian car	4 door skins	Steel	steel	17	Puri 2009
		Al	Al	9.35	
		GFRP	GFRP (60%/40%PP)	11.7	
Dodge Caravan	Liftgate inner	Steel	Steel (stamping)	15	Das 2005
		Al	F356 (perm mold)	11.8	
Audi A3	Side panel inner lining	ABS	ABS copolymer (die cast)	1.125	Wotzel 1999
		Hemp fiber composite	66 v% fiber, 34% epoxy	0.82	
05-06 compact	Bumper beam	HSS	HSS	5.8	Bertram 2009
		Al	Al	3.2	
NA family car	Front hood	HSS	HSS	17.5	
		Al	Al (stamping?)	10.1	
West EU passenger car	Bulkhead	Steel	Steel (stamping)	5.8	Witik 2011
		SMC	GF+UPR+filler (press molding)	2.5	
		GMT	GF+polyamide 6 (press molding)	2.4	
		GFRP	GF+PUR (reaction IM)	2.3	
		Mg	AZ91 (die cast)	2.2	
		CFRP	CF+PUR (reaction IM)	1.8	

TABLE 12 Lightweighting Studies on Other Components

Other components					
Vehicle	Component(s)	Design	Material	Weight (kg)	Source
Cadillac CTS	Floor pan	Steel	steel (stamping)	30.8	Das 2011
		CFRP	29% CF +11% PP + 60% matrix	25.6	
Midsize (est.)	Fuel tank	steel	mild steel	13.05	Dlamini 2011
			paint	1.75	
		HDPE	HDPE	12.73	
			ethylene vinyl alcohol	0.49	
			resin adhesive	0.98	
Passenger car	Brake system	Steel	steel spring (rolling)	2	Ribeiro 2007
			steel washer (cutting)	5.2	
			rubber poppet (IM)	5.5	
			plastic poppet-retainer (IM)	3.75	
		Composite	steel spring (rolling)	3.18	
			GFRP washer (30% GF+PA6.6)	0.94	
			thermoplastic poppet	3.48	
			GFRP poppet-retainer	3.36	
Unknown year Opel Corsa	Front bumper carriers	Steel	steel (drawn)	4.65	Thiel 2000
		Al	Al (extruded)	2.75	
Unknown US LDT	Unspecified powertrain structural component	Al	A380	1.85	Shen 1999
		Mg	AZ91D	1.25	
1995 Contour	Transmission case	Al	2nd cast Al	9.76	Reppe 1998
		Mg	AZ91HP	6.75	

REFERENCES

Altair. 2016. Jaguar Land Rover Switches to Aluminum Bodies and Saves Some Green. http://www.altair.com/c2r/ws2016/jlr-switches-to-aluminum-bodies-saves-some-green.aspx (accessed 8.22.16).

Baroth, A., karanam, S., and McKay, R., 2012. Life Cycle Assessment of Lightweight Noryl* GTX* Resin Fender and Its Comparison with Steel Fender, SAE Technical Paper 2012-01-0650, doi:10.4271/2012-01-0650.

Bertram, M., Buxmann, K., Furrer, P., 2009. Analysis of greenhouse gas emissions related to aluminium transport applications. Int J Life Cycle Assess 14, 62–69. doi:10.1007/s11367-008-0058-0

Das, S., 2011. Life cycle assessment of carbon fiber-reinforced polymer composites. Int J Life Cycle Assess 16, 268–282. doi:10.1007/s11367-011-0264-z

Das, S., 2005. Life cycle energy impacts of automotive liftgate inner. Resources, Conservation and Recycling 43, 375–390. doi:10.1016/j.resconrec.2004.07.003

Das, S., 2000. The life-cycle impacts of aluminum body-in-white automotive material. JOM 52, 41–44. doi:10.1007/s11837-000-0173-2

Davis, S. 2016. Personal communication (September 02, 2016)

Delogu, M., Pero, F.D., Romoli, F., Pierini, M., 2015. Life cycle assessment of a plastic air intake manifold. Int J Life Cycle Assess 20, 1429–1443. doi:10.1007/s11367-015-0946-z

Dlamini, N.G., Fujimura, K., Yamasue, E., Okumura, H., Ishihara, K.N., 2011. The environmental LCA of steel vs HDPE car fuel tanks with varied pollution control. Int J Life Cycle Assess 16, 410–419. doi:10.1007/s11367-011-0277-7

DOE. 2013. Workshop report: light-duty vehicles technical requirements and gaps for lightweight and propulsion materials. https://www1.eere.energy.gov/vehiclesandfuels/pdfs/wr_ldvehicles.pdf

Dubreuil, A., Bushi, L., Das, S., Tharumarajah, A. et al., 2012. A Comparative Life Cycle Assessment of Magnesium Front End Autoparts: A Revision to 2010-01-0275, SAE Technical Paper 2012-01-2325, doi:10.4271/2012-01-2325.

EPA. 2016. Midterm evaluation of light-duty vehicle greenhouse gas emission standards and corporate average fuel economy standards for model years 2022-2025 (draft). https://www3.epa.gov/otaq/climate/documents/mte/420d16900.pdf

EPA. 2015. Mass Reduction and Cost Analysis— Light-Duty Pickup Truck Model Years 2020-2025. EPA-420-R-15-006.

https://www3.epa.gov/otaq/climate/documents/mte/420r15006.pdf

EPA. 2014. Light-duty automotive technology, carbon dioxide emissions, and fuel economy trends: 1975 through 2014.
https://www3.epa.gov/fueleconomy/fetrends/1975-2014/420r14023a.pdf

EPA. 2012. Mass Reduction and Cost Analysis— Midsize Crossover Utility Vehicle. EPA-420-R-12-026.
https://www3.epa.gov/otaq/climate/documents/420r12026.pdf

Ford. 2015. Spotlight: Reinventing the Ford F150.
https://corporate.ford.com/microsites/sustainability-report-2014-15/environment-spotlight-f150.html (accessed 8.22.16).

GM. 2015. 5 Ways Chevrolet Made 2016 Malibu Segment's Lightest.
https://media.gm.com/media/us/en/chevrolet/news.detail.html/content/Pages/news/us/en/2015/jun/0617-malibu.html (accessed 8.25.16).

Kelly, J., Dai, Q., Elgowainy, A. 2015. Addition of New Conventional and Lightweight Pickup Truck Models in the GREET Model.
https://greet.es.anl.gov/publication-pickup-truck-update

Kelly, J., Burnham, A., Sullivan, J., Elgowainy, A., Wang, M. 2014. Addition of New Conventional and Lightweight Vehicle Models in the GREET Model.
https://greet.es.anl.gov/publication-vehicle-additions-2014

Keoleian, G.A., Kar, K., 2003. Elucidating complex design and management tradeoffs through life cycle design: air intake manifold demonstration project. Journal of Cleaner Production 11, 61–77. doi:10.1016/S0959-6526(02)00004-5

Khanna, V., Bakshi, B.R., 2009. Carbon Nanofiber Polymer Composites: Evaluation of Life Cycle Energy Use. Environ. Sci. Technol. 43, 2078–2084. doi:10.1021/es802101x

Kiefer, B., Deinzer, G., Haagensen, J., and Saur, K., 1998. Life Cycle Engineering Study of Automotive Structural Parts Made of Steel and Magnesium, SAE Technical Paper 982225, doi:10.4271/982225

Kojima, S., Ohmi, Y., Nakanishi, E., and Mori, T., 2003. A Study of Car Body Structure to Reduce Environmental Burdens, SAE Technical Paper 2003-01-2833, doi:10.4271/2003-01-2833.

MacKenzie, D., Zoepf, S., Heywood, J., 2014. Determinants of US passenger car weight. International Journal of Vehicle Design 65, 73. doi:10.1504/IJVD.2014.060066

Mayyas, A.T., Qattawi, A., Mayyas, A.R., Omar, M.A., 2012. Life cycle assessment-based selection for a sustainable lightweight body-in-white design. Energy, Sustainable Energy and Environmental Protection 2010 39, 412–425. doi:10.1016/j.energy.2011.12.033

NHTSA. 2012. Mass reduction for light-duty vehicles for Model Years 2017-2025. DOT-HS-811-666.
ftp://ftp.nhtsa.dot.gov/CAFE/2017-25_Final/811666.pdf

Overly, J., Dhingra, R., Davis, G., and Das, S., 2002. Environmental Evaluation of Lightweight Exterior Body Panels in New Generation Vehicles, SAE Technical Paper 2002-01-1965, doi:10.4271/2002-01-1965.

Puri, P., Compston, P., Pantano, V., 2009. Life cycle assessment of Australian automotive door skins. Int J Life Cycle Assess 14, 420–428. doi:10.1007/s11367-009-0103-7

Reppe, P., Keoleian, G., Messick, R., and Costic, M., 1998. Life Cycle Assessment of a Transmission Case: Magnesium vs. Aluminum, SAE Technical Paper 980470, doi:10.4271/980470.

Ribeiro, I., Peças, P., Silva, A., Henriques, E., 2008. Life cycle engineering methodology applied to material selection, a fender case study. Journal of Cleaner Production 16, 1887–1899. doi:10.1016/j.jclepro.2008.01.002

Ribeiro, C., Ferreira, J.V., Partidário, P., 2006. Life cycle assessment of a multi-material car component. Int J Life Cycle Assess 12, 336. doi:10.1065/lca2006.12.304

SAE. 2016. Cadillac XT5's new platform cuts weight—at less cost.
http://articles.sae.org/14679/ (accessed 8.25.16).

SAE. 2015. Cadillac's 2016 CT6 is a body-engineering benchmark
http://articles.sae.org/14020/ (accessed 8.25.16).

SAE. 2013. BMW i3, the inside story: what it's made of, how it's made.
http://articles.sae.org/12056/ (accessed 9.2.16).

Saur, K., Fava, J.A., Spatari, S., 2000. Life cycle engineering case study: Automobile fender designs. Environ. Prog. 19, 72–82. doi:10.1002/ep.670190205

Saur, K., Schuckert, M., Beddies, H., and Eyerer, P., 1995. Foundations for Life Cycle Analysis of Automotive Structures - The Potential of Steel, Aluminium and Composites, SAE Technical Paper 951844, doi:10.4271/951844.

Shen, D., Phipps, A., Keoleian, G., and Messick, R., 1999. Life-Cycle Assessment of a Powertrain Structural Component: Diecast Aluminum vs. Hypothetical Thixomolded® Magnesium, SAE Technical Paper 1999-01-0016, doi:10.4271/1999-01-0016.

Skszek, T., Conklin, J., Wagner, D., Zaluzec, M. 2015. Multi-material lightweight vehicles.
http://energy.gov/sites/prod/files/2015/06/f24/lm072_skszek_2015_o.pdf

Skszek, T., Conklin, J., Wagner, D., Zaluzec, M. 2014. Multi-material lightweight vehicles: Mach-II design.
http://energy.gov/sites/prod/files/2014/07/f17/lm088_skszek_2014_o.pdf

Skszek, T., Zaluzec, M., Schutte, C. 2013. Demonstration project for multi-material lightweight prototype vehicle as part of the clean energy dialogue with Canada – Vehma International of America, Inc. and Ford Motor Company, in FY 2013 Annual Progress Report of VTO.
http://energy.gov/sites/prod/files/2014/04/f15/2013_lightweight_materials_apr.pdf

Stasinopoulos, P., Compston, P., Newell, B., Jones, H.M., 2011. A system dynamics approach in LCA to account for temporal effects—a consequential energy LCI of car body-in-whites. Int J Life Cycle Assess 17, 199–207. doi:10.1007/s11367-011-0344-0
Tharumarajah, A., Koltun, P., 2010. Improving environmental performance of magnesium instrument panels. Resources, Conservation and Recycling 54, 1189–1195. doi:10.1016/j.resconrec.2010.03.014

Thiel, C. and Jenssen, G., 2000. Comparative Life Cycle Assessment of Aluminium and Steel Bumper Carriers, SAE Technical Paper 2000-01-1495, doi:10.4271/2000-01-1495.
ORNL. Transportation Energy Data Book.
http://cta.ornl.gov/data/index.shtml (accessed 9.9.16)

VTO. 2016. Materials technology – overview.
http://energy.gov/sites/prod/files/2016/06/f32/lm000_wu_2016_o_web.pdf

Witik, R.A., Payet, J., Michaud, V., Ludwig, C., Månson, J.-A.E., 2011. Assessing the life cycle costs and environmental performance of lightweight materials in automobile applications. Composites Part A: Applied Science and Manufacturing 42, 1694–1709. doi:10.1016/j.compositesa.2011.07.024

Wötzel, K., Wirth, R., Flake, M., 1999. Life cycle studies on hemp fibre reinforced components and ABS for automotive parts. Angew. Makromol. Chem. 272, 121–127. doi:10.1002/(SICI)1522-9505