

Life Cycle Analysis of 1995-2014 U.S. Light-Duty Vehicle Fleet: The Environmental Implications of Vehicle Material Composition Changes

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ABSTRACT

Vehicle lightweighting has been a focus of the automotive industry, as car manufacturers seek to comply with corporate average fuel economy (CAFE) and greenhouse gas (GHG) emissions standards for model year (MY) 2017-2025 vehicles. However, when developing a lightweight vehicle design, the automotive industry typically targets maximum vehicle weight reduction at minimal cost increase. In this paper, we consider the environmental impacts of the lightweighting technology options. The materials used for vehicle lightweighting include high-strength steel (HSS), aluminum, magnesium and carbon fiber reinforced plastic (CFRP). Except for HSS, the production of these light materials is more GHG-intensive (on a kg-to-kg basis) compared with the conventional automotive materials they substitute. Lightweighting with these materials, therefore, may partially offset the GHG emission reductions achieved through improved fuel economy. To retrospectively investigate the impact of this potential burden shifting from vehicle operation to vehicle production due to material substitution, historical weights, material compositions, fuel economies, and other characteristics of the U.S. light-duty fleet for 1995-2014 are presented and analyzed in this study. The GHG emissions from vehicle production, vehicle operation, and the entire life-cycle of the vehicle, are then estimated with Argonne's Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET®) model. Additionally, a comparison of the GHG emissions of a conventional MY 2014 and lightweighted MY 2015 Ford F150 is conducted. Finally, the effect of vehicle lightweighting, through downsizing and material substitution--as well as that of vehicle weight addition through new features and better acceleration-- on the life-cycle GHG emissions of the U.S. light-duty fleet is investigated.

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INTRODUCTION

Vehicle lightweighting has been identified as an effective means to comply with the GHG emissions and CAFE standards established by the U.S. Environmental Protection Agency (EPA) and National Highway Traffic Safety Administration (NHTSA) for 2017 through 2025 model year (MY) light-duty vehicles (LDVs) [1], and material substitution by lightweight materials, among all technology options, has the greatest potential in reducing vehicle weight [2]. Automotive material substitution is not a new concept. Mackenzie *et al* (2014) identified added emission control, safety, comfort and convenience features, increasing adoption of unibody construction and front-wheel drive, reduced engine cylinders, and changes in vehicle material compositions as primary determinants of U.S. passenger car weights between 1975 and 2010. They further noted substantial increase in HSS and aluminum contents, and decreases in conventional steel and iron contents in U.S. passenger cars during 1975-2010 [3]. Examining the historical trend of vehicle material substitution, together with its impact on the environmental footprint of a vehicle, therefore provides insights into potential trade-offs of currently available lightweighting technology options, and guides future considerations of lightweighting technologies.

To estimate the environmental impacts of a vehicle, its weight, material composition, and fuel economy (FE) are necessary. Within this study the U.S. light-duty fleet is examined for MY 1995 through 2014 due to data availability.

The curb weight of new fleet-average U.S. LDVs increased from 1,679 kg in 1995 to 1,837 kg in 2004, but remained around 1,820 kg since 2005 [4]. At the same time, the fleet average fuel economy decreased from 20.5 miles-per-gallon (mpg) in 1995 to 19.3 mpg in 2004, and then steadily increased to 24.2 mpg by 2014 [5]. Since the adoption rates of unibody construction and front-wheel drive stayed relatively constant during 1995-2014 [3], the changes in curb weight of U.S. light-duty fleet in this period could be attributed to added features, material substitution (MS), and engine down-sizing (EDS) as manifested in a reduced number of cylinders. In addition, since the engine horse power (HP) of the U.S. light-duty fleet increased substantially between 1995 and 2014 [5], presumably to provide better acceleration, HP was identified as another determinant of U.S. LDV weights. Changes in vehicle weight, material compositions, and fuel economies attributable to EDS, HP, features and MS are estimated. The 2015 version of Argonne's GREET® Model is then used to determine the resultant GHG emissions from vehicle production, fuel production, and vehicle operation.

METHODS

Dai *et al* [6] analyzed the historical trends of curb weight, material content, and fuel economy of 1995-2014 U.S. light-duty vehicle fleet, which serves as the basis for this analysis. Note that vehicle characteristics used in Dai *et al* [6] and this study are representative of the fleet-average, rather than an individual vehicle. Changes in material contents during 1996-2014 relative to the 1995 level are illustrated in Figure 1. Figure 1 shows that the same trends of increasing HSS and Al contents, and decreasing iron casting and steel contents, as pointed out by Mackenzie *et al* (2014) [3], persisted through 2014. However, those changes in material contents, could not be solely attributed to MS. Since each vehicle component consists of a distinctive set of materials, adding, redesigning or removing a single vehicle component would all change the material composition of a vehicle. EDS, HP and features also change vehicle curb weights and therefore affect material contents.

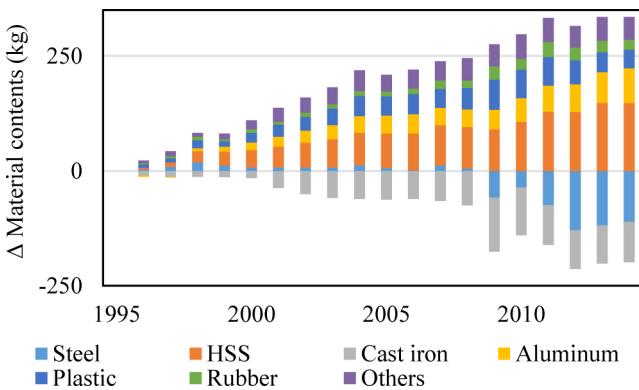


Figure 1. Changes in material contents of 1996-2014 U.S. light-duty fleet from the 1995 baseline fleet

Determining Changes in Vehicle Weights due to EDS, HP, Features and MS

Table 1 summarizes the historical trends regarding the number of cylinders and HP for the fleet-average U.S. LDV between 1995 and 2014. Note that the numbers of cylinders are not integers, because they represent the fleet-average, not an individual vehicle, of distinctive MYs. Heywood *et al* (2015) estimate that vehicle weight, on the average, would decrease by 64 kg if reducing from 8 to 6 cylinders, and by 67 kg from 6 to 4 cylinders [7]. Although moving between even and odd numbers of cylinders would entail changes in the engine design and powertrain configuration, for modeling purpose, in this study linear interpolation is applied to data reported by Heywood *et al* [7]. Therefore, the changes in vehicle weight due to EDS is calculated by multiplying 32 kg by the changes in number of cylinders for trucks, and by multiplying 33.5 kg by the changes in number of cylinders for cars. A secondary weight multiplier of 80%, the mean of reported secondary weight values [7], is used in this analysis.

Vehicle weight additions through increased HP are estimated by observing the linear fit between powertrain mass and corresponding HP developed by Sullivan *et al* (2015) based on data collected from various vehicle models from later 1990s to early 2010s [8]. The secondary weight multiplier of 80% is then applied to the calculated powertrain mass.

The increase in vehicle's weight due to added features was estimated to be 7 kg/year for U.S. passenger cars by Heywood *et al* [7]. It is scaled up to 9 kg/year for U.S. trucks in this analysis. Since the reported feature weight already accounts for secondary weight effects [7], the 80% multiplier is not applied to the added feature weights. By exclusion, the balance of vehicle's weight change is attributed to MS, as shown in equation 1.

$$MS_i = \text{Curb weight}_i - EDS_i - HP_i - \text{Features}_i \quad (1)$$

Where i represents model year.

Determining Changes in Material Contents due to EDS, HP, Features and MS

The changes in material contents are estimated by multiplying changes in subsystem weights by the material composition of the corresponding subsystem. For the secondary weights associated with EDS and HP, it is assumed that secondary weight addition/reduction would primarily occur in the chassis subsystem. Therefore, the material compositions of a typical powertrain are applied to the primary weights for EDS and HP, and typical chassis material compositions are applied to secondary weights.

Table 1. Average number of cylinders and HP for 1995-2014 U.S. light-duty fleet [5]

	Fleet-average # of Cylinders		Fleet-average HP	
	Cars	Trucks	Cars	Trucks
1995	5.23	6.22	153	168
1996	5.18	6.25	155	179
1997	5.1	6.47	156	189
1998	5.15	6.3	160	188
1999	5.21	6.5	164	199
2000	5.22	6.48	168	199
2001	5.19	6.58	169	212
2002	5.12	6.57	173	223
2003	5.13	6.56	176	224
2004	5.16	6.7	184	240
2005	5.08	6.58	183	242
2006	5.17	6.5	194	240
2007	5	6.57	191	254
2008	4.97	6.42	194	254
2009	4.7	6.23	186	252
2010	4.7	6.22	190	253
2011	4.74	6.18	200	271
2012	4.54	6.16	192	276
2013	4.51	6.05	198	277
2014	4.55	6.15	201	282

Table 2. Material composition of powertrain, chassis and feature for 1995-2014 U.S. LDV

	Powertrain		Chassis		Feature
	Car	Truck	Car	Truck	
Steel	39.5%	42.5%	84.1%	85.3%	50.0%
Cast iron	28.6%	26.9%	6.9%	7.9%	---
Cast Al	17.1%	16.1%	1.0%	0.6%	---
Cu	2.9%	2.6%	1.2%	0.7%	5.0%
Plastic	9.3%	9.5%	1.8%	1.0%	25.0%
Rubber	2.6%	2.4%	4.4%	3.8%	---
Others	---	---	0.6%	0.7%	20.0%
Total	100%	100%	100%	100%	100%

The material compositions of powertrain and chassis for car and truck in 2015 GREET are used in this analysis. For features, Zoepf estimated that safety, air conditioning, ABS and entertainment were the four features that exhibited considerable growth in adoption rates during 1995-2010 [9]. A component mass-weighted material composition of these four features is therefore estimated from weights and material compositions of corresponding feature components in a 2011 Honda Accord [10].

The material compositions of powertrain, chassis, and features are summarized in Table 2. Once changes in material contents due to EDS, HP and features are estimated, the changes in material contents due to MS are then calculated by equation 2.

$$MS_{i,j} = Material_{i,j} - EDS_{i,j} - HP_{i,j} - Features_{i,j} \quad (2)$$

Where i represents model year, and j represents material.

The changes in material contents due to MS are shown in Figure 2.

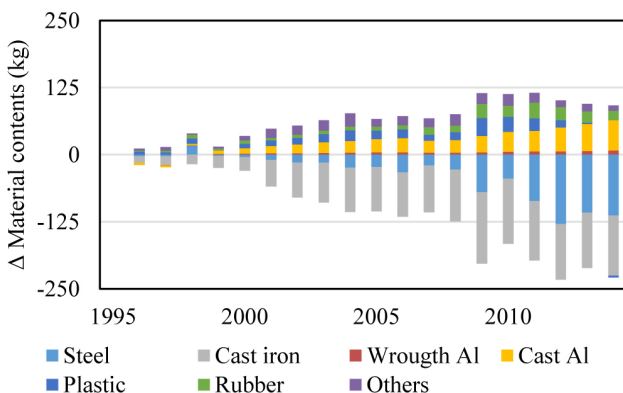


Figure 2. Changes of material contents due to MS for 1996-2014 U.S. light-duty fleet relative to 1995 baseline

Determining Changes in Fuel Economy due to Changes in Vehicle Weight

Changes in fuel economy due to vehicle weight addition/reduction are estimated using the fuel reduction value (FRV) approach described in [11]. Since the vehicle weight changes estimated in this study already account for secondary weight effects, a FRV value of

0.25 L gasoline/100 kg/100 km is adopted for life cycle analysis. Note that the FRV used is representative of cars. In the absence of truck FRV studies, it is also applied to trucks as a proxy.

Evaluating Life-Cycle GHG Emissions

Once the material contents and the fuel economies of the LDVs are obtained, they are incorporated in the GREET model. The GREET model then calculates the GHG emissions associated with vehicle production, assembly and disposal, which is often referred to as vehicle cycle, in addition to the GHG emissions associated with vehicle fuel production and consumption, which is often referred to as fuel cycle or well-to-wheels (WTW). WTW impacts can be further divided into two subcategories, the well-to-pump (WTP) impacts, and the pump-to-wheels (PTW) impacts. WTP impacts account for environmental burdens associated with upstream fuel extraction, production, transportation and distribution, whereas PTW impacts account for environmental impacts of fuel consumption during vehicle operation [15].

Note that GREET assumes a vehicle miles traveled (VMT) of 160,000 for cars, and 180,000 for trucks. Also, GREET reports GHG emissions in the unit of carbon dioxide equivalent (CO_2e), which converts all GHG emissions into CO_2 emissions based on equivalent global warming impacts [15].

RESULTS AND DISCUSSION

1995-2014 U.S. LDV Life-Cycle GHG Emissions

The life-cycle GHG emissions for a LDV representative of the average 1995 U.S. fleet is estimated to be 566 g $\text{CO}_2\text{e}/\text{mile}$, of which 46 g $\text{CO}_2\text{e}/\text{mile}$ is from the vehicle cycle, 98 g $\text{CO}_2\text{e}/\text{mile}$ from WTP, and 422 g $\text{CO}_2\text{e}/\text{mile}$ from vehicle operation. Figure 3 illustrates the changes in life-cycle GHG emissions relative to the 1995 baseline for LDVs representative of 1996-2014 U.S. light-duty fleets, along with changes in fuel consumptions of the corresponding fleets.

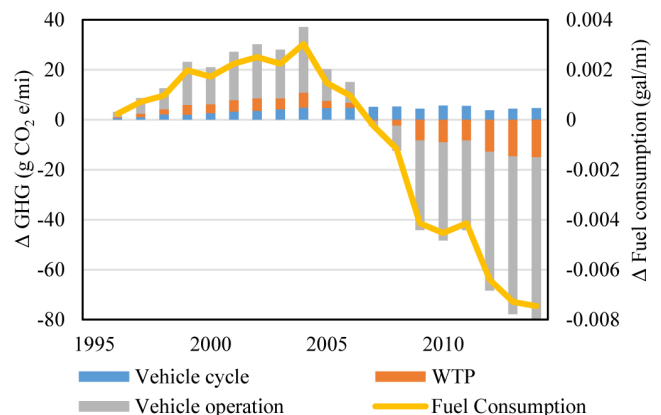


Figure 3. Changes of life-cycle GHG emissions and fuel consumptions of 1996-2014 U.S. light-duty fleet from the 1995 baseline fleet

Figure 3 shows that the GHG emissions from the vehicle cycle increased by around 5 g $\text{CO}_2\text{e}/\text{mi}$ over the past twenty years. Changes in fleet-average curb weight and material content drive this result. However, the vehicle cycle accounts for less than 10% of the total life-cycle GHG emissions of the U.S. light-duty fleet for any given