Cars on a Diet: The Material and Energy Impacts of Passenger Vehicle Weight Reduction in the U.S.

by

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Submitted to the Engineering Systems Division on September 1, 2010, in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy in Engineering Systems

ABSTRACT

Vehicle weight reduction is a known strategy to address growing concerns about greenhouse gas emissions and fuel use by passenger vehicles. We find that every 10% reduction in vehicle weight can cut fuel consumption by about 7%.

In the U.S., vehicle weight reduction is essential for meeting future, more stringent fuel economy standards. New vehicles are required on average to achieve at least 34.1 miles per gallon (MPG) by year 2016, up from 28.8 MPG today. Scenarios of future vehicle characteristics and sales mix indicate that the target is aggressive. New vehicles must not only become lighter, but also forgo horsepower improvements, and progressively use advanced, more fuel-efficient powertrains, such as hybrid-electric drives.

We can reduce weight by substituting some of the iron and steel used in vehicles with lighter-weight high-strength steel or aluminum, redesigning the vehicle, and/or downsizing the vehicle. Using these approaches, it is possible to achieve up to 40% (690 kg) vehicle weight reduction. However, the cost associated with manufacturing lighter-weight vehicles is a nontrivial $3 to $4 per kilogram of total weight saved. In addition, the life-cycle energy impacts of using alternative lightweight materials, which tend to be more energy-intensive to process, must also be considered.

In this dissertation, the energy implications of pursuing this lightweighting strategy are explored on a vehicle life-cycle- and vehicle fleet system-level basis. A model of the energy and material flows through the evolving vehicle fleet system over time has been developed, which accounts for potential changes in future vehicle weight and material composition. The resultant changes in material production energy and fleet fuel savings, which are the main energy burdens for the entire product system – the vehicle fleet – are estimated.

The new 2016 fuel economy standards and more stringent standards beyond can realize significant fuel savings of 1,550 billion liters through year 2030. However, the advanced powertrains that are expected to enter the marketplace are heavier and require more energy to produce. Their production impact may be offset by efforts to use less energy-intensive high-strength steel to lightweight new vehicles, as well as efficiency gains in material processing.

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This thesis is dedicated to my husband and our beautiful daughter, Kenneth and Juniper Lim. They define my life story, in which this Ph.D. journey is but a chapter. Kenneth is my best friend, confidant, personal chef, 2009 household MVP, ukulele player, supper buddy all -in-one. Thank you for always being patient, funny, and there for us.

Looking forward to starting and ending more new chapters,

Lynette Cheah
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July 2010

TABLE OF CONTENTS

LIST OF FIGURES AND TABLES

ABBREVIATIONS AND NOMENCLATURE

Al	Aluminum
BEV	Battery electric vehicle
BOF	Steelmaking technique using a basic oxygen furnace.
CAFE	Corporate Average Fuel Economy, the sales-weighted average fuel economy of a manufacturer's vehicle fleet in a given model year.
Curb weight	Total weight of a vehicle with standard equipment, all necessary operating consumables (e.g. motor oil and coolant), and a full tank of fuel, while not loaded with either passengers or cargo.
CUV	Crossover utility vehicle. Its technical definition is unclear, because this originated as a marketing term. It is generally known as a vehicle with features of a sports utility vehicle that is built on a car platform. Examples include the Ford Escape, Honda CR-V and the Toyota RAV4.
EAF	Steelmaking technique using an electric arc furnace.
ERFC	Emphasis on Reducing Fuel Consumption, a metric to measure the tradeoff between reducing fuel consumption vs. improving acceleration performance in future vehicles. See Section 4.3.1.
EPA, or USEPA	U.S. Environmental Protection Agency
Footprint	A vehicle's footprint is the area within its four wheels, calculated by taking the product of its wheelbase and its track width.
Fuel consumption, FC	The amount of fuel consumed by a vehicle per unit distance of travel, measured in liters per 100 kilometers (L/100 km). Fuel consumption is the inverse of the more commonly used metric, fuel economy.
Fuel economy, FE	The distance traveled per unit of fuel used, measured in miles per gallon (MPG). This is the inverse of fuel consumption, and is the metric used in the U.S.
Fuel use	Total fuel used, in liters of gasoline-equivalent, by either a single vehicle or the entire vehicle fleet on the roads.
GHG	Greenhouse gas
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation model by Argonne National Laboratory.
Gross weight	Curb weight plus total passenger and cargo weight capacity of the vehicle when fully loaded. Also known as Gross Vehicle Weight Rating (GVWR).
HEV	Hybrid-electric vehicle
HSS	High-strength steel, a type of alloy steel that provides better mechanical properties or greater resistance to corrosion than carbon, or mild steel.
ICE	Internal combustion engine
Inertia weight	Curb weight plus the payload, or the weight of its passengers and cargo. The payload is typically assumed to be 136 kg (300 lb).
LCA and LCI	Life-cycle assessment and life-cycle inventory
Li-ion	Lithium-ion, a type of hybrid/electric vehicle battery chemistry

Light-duty vehicle	Passenger cars (sedans and wagons) or light trucks (sport utility vehicles, vans and pickups) weighing less than 8,500 lb (gross vehicle weight).
Light truck	Class of vehicles including sport utility vehicles, vans and pickups weighing less than 8,500 lb (gross vehicle weight).
MPG	Miles per gallon, units of vehicle fuel economy
mph	Miles per hour, units of vehicle speed
MSRP	Manufacturer's suggested retail price
MY	Model year of new vehicles
NA	Naturally aspirated (versus a turbo or supercharged) engine, which is the conventional type of spark-ignited (SI) gasoline internal combustion engine. Also abbreviated as NA SI.
NHTSA	U.S. National Highway Traffic Safety Administration
NiMH	Nickel metal hydride, a type of hybrid vehicle battery chemistry
NRC	U.S. National Research Council
OEM	Original equipment manufacturer
PHEV	Plug-in hybrid electric vehicle
SUV	Sport utility vehicle
TEDB	Transportation Energy Data Book published by Davis et al [1] of Oak Ridge National Laboratory, as contracted by the U.S. Department of Energy.
Track width	The distance between the centerline of the tire tread on one tire to the centerline of the tire tread on the opposite tire on the same end of the vehicle, i.e. front track or rear track.
VKT or VMT	Vehicle kilometers or miles traveled
Wheelbase	The distance between the centers of the front and rear wheels of a vehicle.

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1 INTRODUCTION

Chapter 1 sets the scene for exploring vehicle weight reduction in the U.S. Here, we explain the motivation behind studying this topic, review the literature, articulate the research questions, and describe the approach taken. Vehicle weight reduction is one approach to improve fuel economy, but by adopting vehicle life-cycle and vehicle fleet-level perspectives, can it ultimately reduce energy consumption? How and when can energy savings be realized?

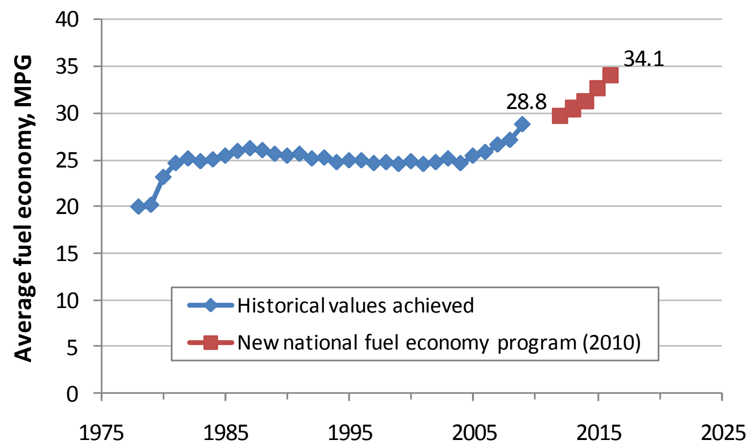
The transportation sector in the U.S. is responsible for two-thirds of total petroleum consumption and a third of the nation's carbon emissions. While the automobile has enabled remarkable mobility in the lives of Americans, it is reliant upon petroleum to fuel our transportation needs. This dependence presents a challenging energy and environmental problem. Amid growing concerns over energy security, and the impacts of global climate change, one important and effective policy option is to raise the minimum standards for light-duty passenger vehicle fuel economy.

In the U.S., such standards have been enforced under the Corporate Average Fuel Economy (CAFE) program since the late 1970s. The standard has remained mostly unchanged for the past three decades, however, until a new rule was issued in 2010. As shown in Figure 1-1, new passenger cars and light trucks, including sport utility vehicles (SUVs), pickups, and minivans, are now required on average to achieve at least 34.1 miles per gallon (MPG) by year 2016[1], up from 28.8 MPG today. Even higher standards are currently being considered for years 2017-2025. Auto manufacturers are obliged to respond by actively pursuing ways to improve the fuel efficiency of their vehicles.

Vehicle weight and size reduction is one known strategy to improve fuel economy in vehicles, and presents an opportunity to reduce fuel use from the transportation sector. By reducing the mass of the vehicle, the inertial forces that the engine has to overcome when accelerating are less, and the work or energy required to move the vehicle is thus lowered. A general rule of thumb is that for every 10% reduction in vehicle weight, the fuel consumption of vehicles is reduced by 5-7%.

[1] The U.S. Environmental Protection Agency (EPA)'s final rule is to achieve a MY2016 greenhouse gas emissions standard of 250

Figure 1-1. Sales-weighted average fuel economy of new U.S. light-duty passenger vehicles (NHTSA-reported CAFE)



Notes on vehicle fuel economy

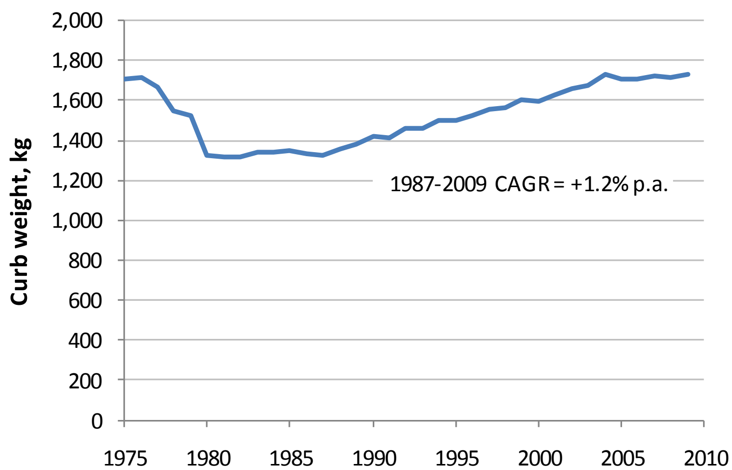
- *Fuel consumption vs. fuel economy* – Since the interest is in reducing the amount of fuel used by vehicles, the preferred metric to measure a vehicle's fuel efficiency is the fuel consumed per unit distance of travel (in liters per 100 kilometers or gallons per 100 miles), as opposed to the inverse mileage per unit of fuel (in MPG). In our assessment, fuel consumption is used in all calculations, but the more familiar metric – fuel economy – will also be documented.
- *EPA vs. NHTSA fuel economy values* – The sales-weighted average fuel economy of new U.S. passenger vehicles is reported by two different agencies each year – the U.S. Environmental Protection Agency (EPA) and National Highway Traffic Safety Administration (NHTSA). There are differences in the values reported that the reader should be aware of:
    - EPA laboratory test value – EPA compiles the fuel economy for individual vehicle models, which are measured in a laboratory using standardized test procedures on a dynamometer.
    - EPA adjusted value – EPA adjusts the laboratory values downward to better reflect real-world driving conditions, and this adjusted MPG appears on the window label of new vehicles to inform consumers. The adjusted value is around 20% lower than the test value.
    - NHTSA CAFE value – NHTSA also reports the Corporate Average Fuel Economy (CAFE) for individual manufacturers, which are used to determine compliance with the standards. These are 2-3% higher than the EPA's unadjusted laboratory values due to differences in vehicle classification, test procedure adjustment factors, and alternative fuel credits. In 2009, the CAFE value is 9% higher than the EPA laboratory values, as shown in the following table:

	EPA lab test	EPA adjusted	NHTSA CAFE
2009 average new U.S. vehicle fuel economy	26.4 MPG	21.1 MPG	28.8 MPG

- In this study, the fuel economy estimated from vehicle simulations that we ran are based on standard test drive cycles. We prefer to report this as adjusted values, which better reflect real-life driving experience. When discussing meeting the CAFE targets, however, we convert the results from our simulations and calculations to NHTSA's CAFE-equivalents, because we are interested in how the new vehicle fleet is able to meet the target. These values are kept internally consistent, and will be specified each time fuel consumption or fuel economy is mentioned.

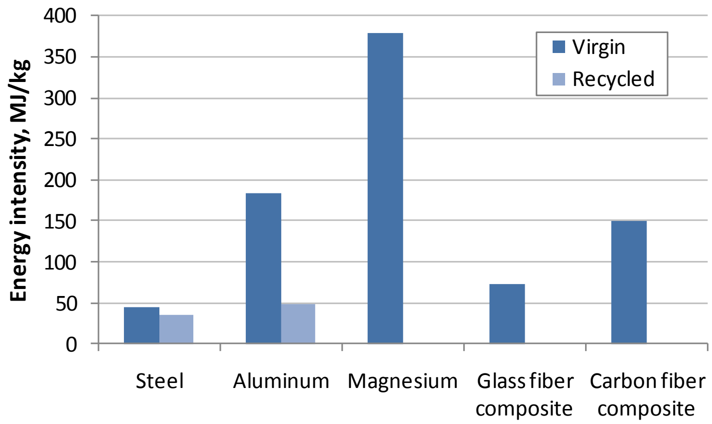
However, the opportunity to reduce energy use by vehicle weight reduction is not as straightforward as it seems on three different fronts, leading to interesting research questions. Firstly, the average new U.S. vehicle weight has been increasing steadily at a rate of 1.2% per annum over the past two decades, leveling off at around 1,730 kg in recent years (see Figure 1-2). The only occasion in the past where vehicle weight decreased significantly was in the late 1970s in a response to the oil crisis, and the introduction of the CAFE program. Now that fuel economy standards are being raised, one of unknowns regarding passenger vehicle weight in the U.S. concerns this trend: will we witness a reversal of the increasing weight trend, and by how much? How can automakers technically and economically reduce vehicle weight again?

Figure 1-2. Average new U.S. vehicle curb weight, 1975-2009, data source: [2]



Secondly, the topic of vehicle weight reduction should be studied with a life-cycle perspective. That is, one should assess the impacts of reducing vehicle weight over the entire vehicle life cycle, from “cradle to grave”. This is because alternative lightweight materials used to reduce vehicle weight tend to be more energy-intensive to produce than conventional steel used in automobiles (see Figure 1-3). An aluminum component with the same stiffness as its steel counterpart requires three times as much energy to produce. An assessment of the energy use through the vehicle’s life-cycle from material processing to its end-of-life is thus more complete than examining the use phase of the vehicle alone, and will let us evaluate the net energy benefits of pursuing this strategy. So another set of unanswered questions is: What is life-cycle energy impact, in particular the material production energy impact, of reducing vehicle weight? Could there be some impacts on material recycling associated with the increase of lightweight materials in new vehicles?

Figure 1-3. Material production energy intensity of steel vs. lighter-weight automotive materials, data source: [3]



Thirdly, while the effectiveness of weight reduction in lowering fuel use at a vehicle-level is reasonably well understood, the effectiveness at a vehicle fleet-level is less so. Studying a single vehicle alone will not allow us to make statements about the impact of weight reduction and efficiency gains on the nation's total energy use in the light-duty vehicle transportation sector. One needs to examine the entire vehicle fleet system as a whole to capture the collective impact of all 250 million vehicles on the road by considering the dynamics of lightweight vehicles entering and older, heavier vehicles exiting the fleet. Having a fleet-system perspective helps automakers and policy decision-makers evaluate the effectiveness of this weight reduction strategy in reducing the fuel used by the entire vehicle fleet in operation.

1.1 Prior work and this contribution

The objective of this dissertation is to assess the potential energy-saving benefit of vehicle lightweighting in the U.S. passenger vehicle fleet. We quantify the degree of weight reduction necessary, while considering the cost, impact on material production energy, material recycling, and the feasibility of this fuel-saving opportunity. The key research questions to be answered are:

- (i) How much weight reduction is expected in future vehicles in order to meet future fuel economy mandates?
- (ii) How can vehicle weight reduction be technically achieved?
- (iii) How much does vehicle weight reduction cost, as compared with other fuel-saving vehicle technologies?
- (iv) On a vehicle fleet system-level, what are the life-cycle energy impacts of vehicle weight changes?
- (v) What are the material recycling implications associated with vehicle weight reduction?

There are existing analyses that examine different aspects of this research topic. To assess the degree of future vehicle weight reduction, some have looked at how auto manufacturers could apply various fuel-saving technologies, including weight reduction, to comply with the 2016 CAFE standards. [4, 5] The U.S.

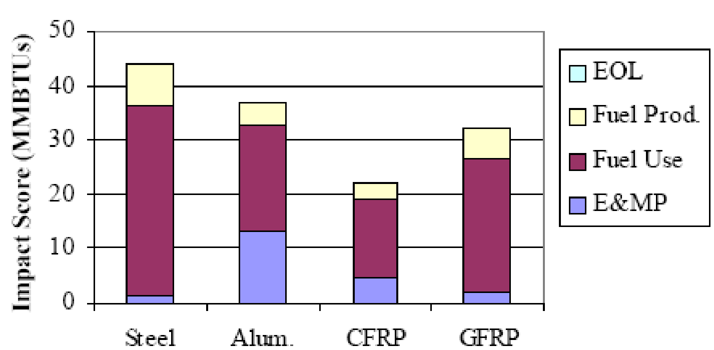
Environmental Protection Agency (EPA) and National Highway Traffic Safety Administration (NHTSA), the government agencies responsible for administering the CAFE program, estimate that the maximum reduction in vehicle weight is 5-10% by year 2014. Similarly, Frost & Sullivan reports that a weight reduction potential of 5-8% would be possible in the short- to medium-term time frame.

Others have assessed the effectiveness of the CAFE program in reducing passenger vehicle fleet fuel use, or the energy impact over the driven, use phase of vehicles. An older 2002 study from the National Research Council estimates that raising fuel economy targets by 20% by 2013 can lead to fuel savings of 10-15 billion gallons in 2015. [6] Morrow et al [7] examined the greenhouse gas (GHG) emissions reductions arising from a scenario where the fuel economy standard is raised to 43.7 MPG by year 2030. The energy and environmental impact of lighter-weight and other more fuel-efficient vehicles beyond the use phase of the vehicle, such as during the automotive material processing phase, is understandably not included in these studies, since this is not an intended effect of the vehicle fuel economy policy.

Studies that consider the life-cycle energy or environmental impact of lighter-weight vehicles usually examine this on a single vehicle level only. For example, the steel industry commissioned several life-cycle assessment studies on the use of high-strength steel in car bodies to reduce their weight. [8, 9] Gibson [10] compared the life-cycle environmental impact of using equal-sized vehicle parts made of steel versus aluminum, titanium, and polymer composites. Overly et al [11] carried out a life-cycle energy assessment (LCA) of body closure panels made of different lightweight materials, such as aluminum and carbon fiber-reinforced composites.

Figure 1-4 shows the total life-cycle energy use result reported in the latter study. Given the significant fuel savings accruing over the vehicle's long use phase, these studies generally conclude that it is beneficial to develop lighter vehicles with greater fuel economy, despite reliance on more energy-intensive materials.

Figure 1-4. Comparing life-cycle energy use in million BTUs when using different materials in a car's body panel [11]



MMBTU = million BTUs, Alum. = aluminum, CFRP/GFRP = carbon/glass fiber-reinforced polymer composites, EOL = end-of life stage of vehicle life-cycle, E&MP = extraction and materials processing stage.

There are a few vehicle fleet-based life-cycle assessments (LCA) that consider the energy impact of all vehicles within the vehicle fleet, and not just a vehicle-to-vehicle comparison. These studies arrive at the same conclusion as the vehicle-level LCAs, but the added temporal element offers insights on the timing of the expected benefit. Field et al [12] and Das [13] adopt this product system (versus single product) perspective to conclude that it takes many years for lighter-weight vehicles to penetrate hypothetical vehicle fleets and reduce fleet-level emissions and energy use. So the lightweighting benefit is dampened over time. Researchers from Argonne National Laboratory studied the energy savings potential of introducing aluminum-intensive vehicles into the actual U.S. vehicle fleet, and arrived at a similar finding – the energy savings potential exist, but will be modest. [14] The Argonne study did not look beyond the use of aluminum to include the possibility of other lightweight material candidates, however.

This study brings together these separate but connected themes into a broader system perspective, and bridges the gaps in the literature to quantify the system-wide energy impact of vehicle weight reduction in the context of the CAFE program in the U.S.

Table 1-1 shows the landscape of existing literature, and the contribution of this study. By adopting vehicle life-cycle and fleet-level perspectives, we are able to estimate the magnitude and timing of the energy-saving benefits more usefully going into the future. The material production and use-phase energy impacts are both evaluated to understand the effect of weight and material composition changes in new vehicles entering the fleet each year. Thus this analysis reveals how much, how soon, and how energy savings can be achieved via vehicle lightweighting under the new fuel economy mandate.

Table 1-1. Literature on the life-cycle energy impact of vehicle weight reduction in the U.S.

Study	Life-cycle energy impact assessment…		…of vehicle weight reduction…		…on a vehicle fleet system level		Study description
	Fuel savings only	Impacts from other life-cycle phases	Vehicle lightweighting only	Within CAFE program	Vehicle level	Fleet level	
NRC 2002	X			X		X	Estimates cost and fuel-saving benefit of individual technologies and of meeting CAFE
Morrow 2010	X			X		X	Examines fuel use and GHG impact of various policy options, including CAFE
EPA 2010	X			X	X		Model to facilitate CAFE rulemaking
Knittel 2009				X			Assesses changes in vehicles necessary to meet the 2016 CAFE targets
Gibson 2000 Overly 2002 Smith 2002 Geyer 2007	X	X	X		X		Vehicle-level LCA of lightweight vehicles
Stodolsky 1995 Das 2000 Field 2001	X	X	X			X	Fleet-level LCA of lightweight vehicles
This research	**X**	**X**	**X**	**X**		**X**	**Fleet-level LCA of lightweight vehicles in context of CAFE program**

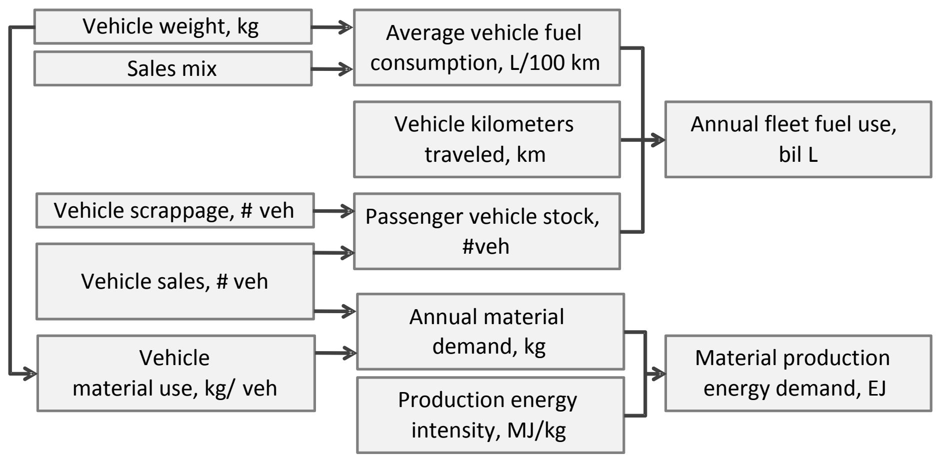
1.2 Research approach

We focus on the light-duty passenger vehicle fleet in the U.S., which consist of 250 million vehicles. The timeframe of analysis is from 1975-2030, with particular interest in exploring ways to reduce energy impact over the next 20 years. A dynamic model of energy and material flows through this fleet is developed, using the following approach:

- *Scenario analysis* is first used to evaluate the technologies adopted, plausible changes in vehicle characteristics including weight, and the sales mix necessary to meet mandated fuel economy targets in 2016, as well as a doubling of the fuel economy by 2030.
- *Dynamic material flow analysis* is carried out to track the flow and accumulation of automotive material stocks over time, under the various future vehicle weight and material use scenarios. This is done by modeling the vehicle fleet, accounting for the stock of in-use vehicles and the corresponding material stocks. This analysis can be used to explore the generation of scrap material from this system and implications on metal recycling.
- *Temporal life-cycle energy assessment* is done to capture the effects of evolving material and fuel use in the vehicle fleet, while accounting for efficiency improvements in materials processing, and declining vehicle fuel consumption over time.

The key outputs of the model are the material production energy demands and annual fleet fuel use in each scenario, which are the main energy burdens in the vehicle's life cycle. These vehicle production and use-phase energy impacts are both evaluated to better understand the larger system-wide impact of weight and material composition changes in the roughly 15 million new vehicles which enter the fleet each year. The energy associated with producing and distributing the fuel, or "well-to-tank" impacts are not included. So the energy burden of charging plug-in hybrids is not within the scope of this study.[2] Figure 1-5 depicts an overview of the model.

Figure 1-5. Model overview



This research is relevant in today's carbon-conscious and energy-constrained context. By examining vehicle weight and size reduction in the U.S. over the next two decades, the model developed enables one to (i) compare vehicle weight reduction with other approaches to meet future fuel economy mandates on a common energy-basis, and (ii) explore ways to reduce material production energy consumption by altering material selection or vehicle design choices. It is intended to inform automakers and policymakers and aid decision-making.

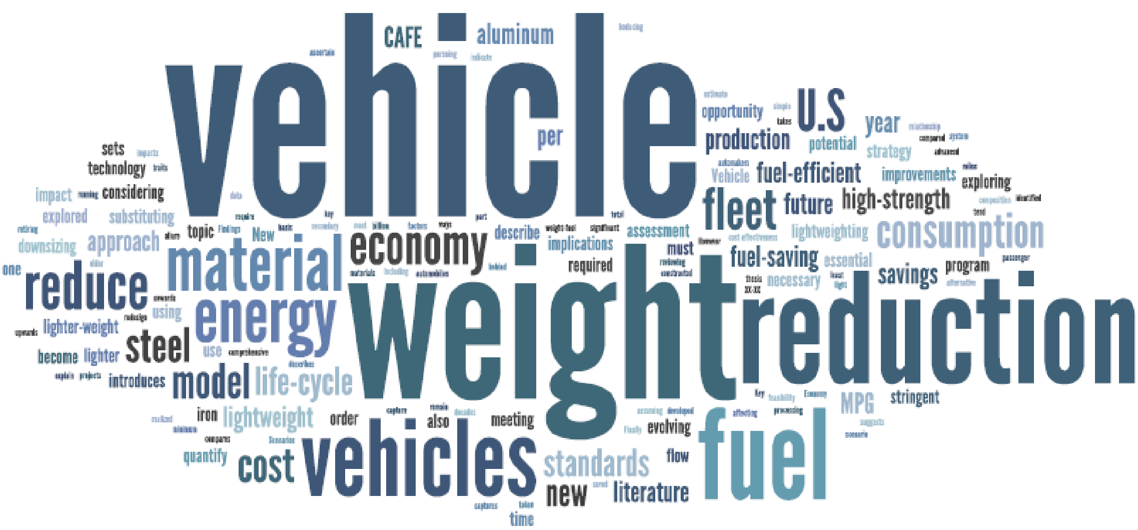
The rest of this thesis is organized to take the reader step by step through the intricacies and potential impacts of vehicle weight reduction. Chapter 2 first explains and quantifies the relationship between vehicle weight and fuel consumption. Chapter 3 provides the technical details of how vehicle lightweighting can be achieved, and considers various lightweight material candidates. In Chapter 4, we explore scenarios of the future U.S. vehicle fleet to understand the role of vehicle weight reduction in the context of more stringent fuel economy standards. Chapter 5 describes a vehicle fleet model to help quantify the fuel savings that can result from the CAFE program, part of which is credited to vehicle

[2] These "well-to-tank" impacts have been investigated in two recent studies carried out by our research group at the Sloan Automotive Laboratory. Interested readers should refer to Bandivadekar et al (2008) *On the Road in 2035: Reducing Transportation's Petroleum Consumption and GHG Emissions*; and Kromer and Heywood (2007) *Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet*.

weight reduction. Chapter 6 assesses the cost of vehicle lightweighting, in comparison with other fuel-saving strategies. Chapter 7 looks into the material production energy impact of producing lighter-weight vehicles, and the implications of the changing vehicle's material composition on material recycling. Finally, Chapter 8 summarizes and discusses the findings, and concludes the thesis.

Figure 1-6 is a word cloud of this thesis – a visual depiction of the word content, where the size of the font indicates the frequency and importance of the word. The word cloud illustrates the overall theme of this study, emphasizing weight reduction on the basis of the evolving in-use vehicle fleet system.

Figure 1-6. Word cloud of this thesis, created using Wordle™



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2 THE RELATIONSHIP BETWEEN VEHICLE WEIGHT AND FUEL CONSUMPTION

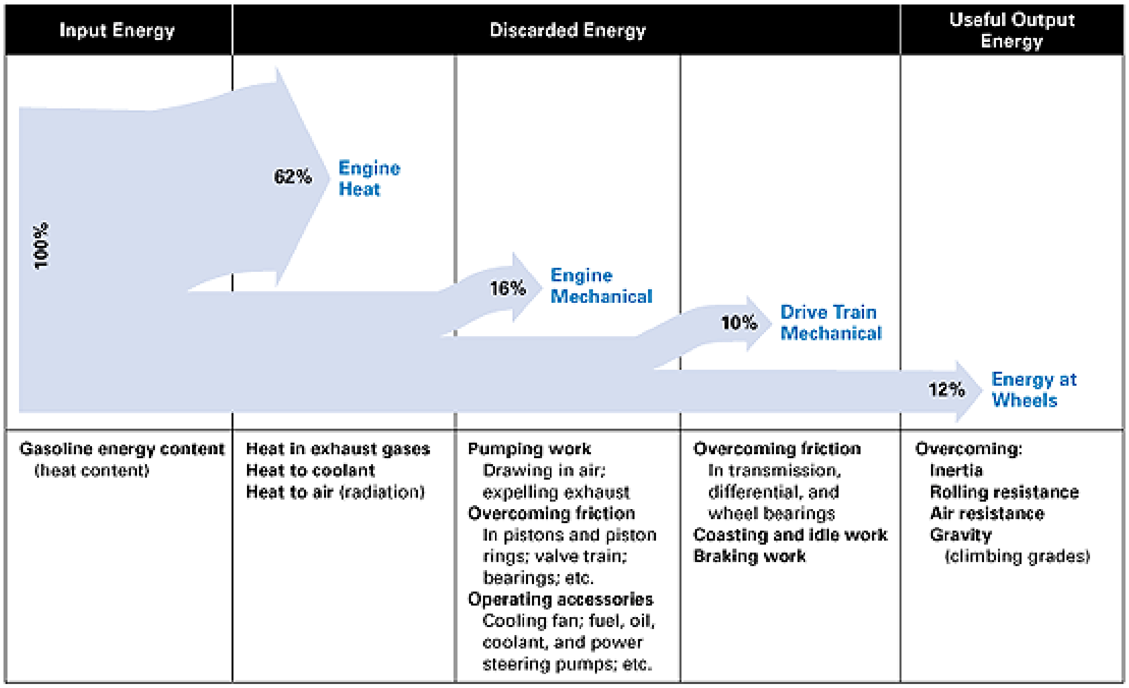
Chapter 2 describes the allure of vehicle weight reduction – its potential to reduce fuel consumption. We quantify the vehicle weight-fuel consumption relationship by exploring the physics of vehicle weight and size reduction, examining empirical data, reviewing the literature, and running vehicle simulations.

There are many ways to approach improving vehicle fuel economy. We can define general fuel-saving strategies by examining how the fuel energy is distributed during the vehicle's operation (see Figure 2-1). Vehicle technologies tend to fall into one of following categories:

(i) *Improvements in the engine* to increase the brake work or usable work output per unit of fuel energy input. Reducing engine friction, or variable valve timing control are examples of these;
(ii) *Transmission improvements* to increase the efficiency with which power from the engine is transmitted to the driveshaft and to the wheels;
(iii) *Minimizing parasitic losses* in accessories like the cooling fan, alternator, and water pump. Technologies include regenerative battery charging, exhaust heat recovery, and HVAC control;
(iv) Use of *alternative, more fuel-efficient powertrains* like hybrid electric drives; and finally,
(v) *Reducing the driving load* by reducing the inertial forces (weight) and resistances (aerodynamic drag, tire rolling resistance) encountered by the vehicle. This reduces the propulsion requirement on the engine and reduces the fuel energy needed to move the vehicle over a given distance.

Vehicle weight and size reduction fall in the final category. To better understand the effect of pursuing a lightweighting strategy on vehicle fuel consumption, let us first understand the physics of weight and size reduction.

Figure 2-1. Distribution of fuel energy in a vehicle [15]



2.1 The physics of vehicle weight reduction[3]

It is well known that vehicle weight reduction has the potential to reduce fuel consumption. By reducing the mass of the vehicle, the inertial forces that the engine has to overcome as the vehicle is accelerated are reduced, so the work required to move the vehicle is thus lessened. To understand the physical impact of vehicle weight on fuel consumption, we examine the key parameters that contribute to a vehicle's fuel consumption from the following relation [16]:

$$FC = \frac{\int b_e \cdot P dt}{\int v dt} = \frac{\int b_e \cdot \left(\frac{F_t \cdot v}{\eta} \right) dt}{\int v dt}$$

Where	FC	=	Vehicle's fuel consumption	[L/km]
	b_e	=	Engine's specific fuel consumption	[L/kWh]
	P	=	Engine power output	[kW]
	t	=	Time	[s or hr]
	v	=	Instantaneous vehicle speed	[m/s or km/hr]
	F_t	=	Tractive force	[kN]
	η	=	Drivetrain efficiency	

[3] I am using the terms weight and mass interchangeably here. Although technically, I should be refering to vehicle mass, as measured in kilograms, throughout this thesis.

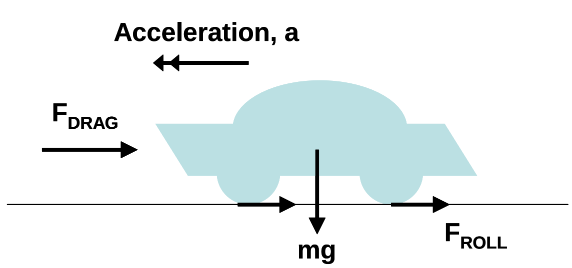
For a vehicle's given speed-time trace, or drive cycle, assuming that the engine's specific fuel consumption and efficiency as a function of load and speed are known, the key parameter that affects the amount of energy output needed from the engine is the amount of tractive or resistive forces the vehicle has to overcome. The tractive force is the sum of tire rolling resistance, acceleration or braking resistance, aerodynamic drag and climbing resistance. For an accelerating vehicle on a level road (with zero climbing resistance), as shown in Figure 2-2, the total tractive force is:

$$F_t = F_{ROLL} + F_{ACC} + F_{DRAG} = (f \cdot mg) + (ma) + \left(\frac{1}{2} C_D \cdot \rho_{AIR} \cdot v^2 \cdot A\right)$$

Where	F_{ROLL}	=	Rolling resistance	[N]
	F_{ACC}	=	Acceleration resistance	[N]
	F_{DRAG}	=	Aerodynamic drag	[N]
	f	=	Rolling resistance coefficient	
	m	=	Vehicle plus payload mass	[kg]
	g	=	Gravitational acceleration	[m/s^2]
	a	=	Vehicle acceleration	[m/s^2]
	C_D	=	Drag coefficient	
	ρ_{AIR}	=	Air density	[kg/m^3]
	A	=	Vehicle frontal area	[m^2]
	v	=	Instantaneous vehicle speed	[m/s]

From this equation, we see how reducing vehicle's mass has a direct impact on reducing the total tractive force and thus the fuel consumption, since mass appears in both the rolling and acceleration components of the total resistive force.

Figure 2-2. Forces on an accelerating vehicle on a level road



2.2 The physics of vehicle size reduction

Vehicle downsizing impacts fuel consumption by (i) reducing the frontal area, which lowers aerodynamic drag; and by (ii) reducing vehicle mass. The National Research Council reports that a 5-10% reduction in the coefficient of drag (C_D) can reduce fuel consumption by 1-2%. A 10% weight reduction is expected to improve it by 6-7%. [17] However, the two effects are interrelated since frontal area reduction could result in some weight reduction as well. To understand the relative and combined contribution of these two effects, it helps to interpret the effect of frontal area reduction in the form of mass reduction.

First, let us assume a constant effective vehicle "density" (ρ_{veh}), and that the vehicle's mass decreases proportionately with its size or volume (V). The vehicle's frontal area scales approximately as L^2, where L is a characteristic vehicle length, and its volume can be characterized by L^3. The frontal area can then be expressed as being proportional to the volume to the ⅔ power. Since mass and volume are proportional, the frontal area is hence proportional to the mass to the ⅔ power. This simplification is summarized by the following symbolic relations:

$$\begin{aligned} &\overline{\rho_{veh}} \Rightarrow m \propto V \\ &A \approx L^2 \\ &V \approx L^3 = A^{3/2} \Rightarrow A \approx V^{2/3} \\ &\Rightarrow A \propto m^{2/3} \end{aligned}$$

Substituting this into the tractive force equation above, the total tractive force then becomes:

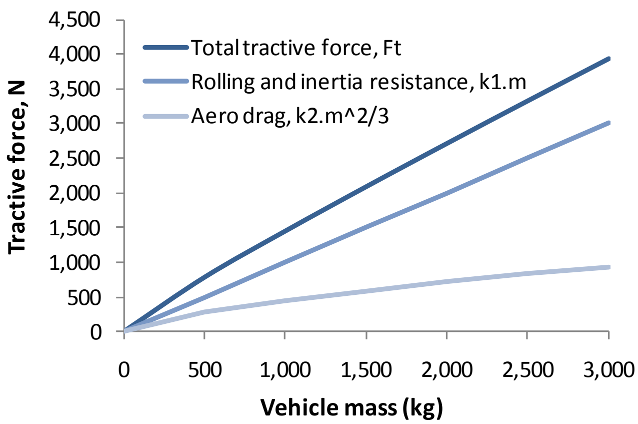
$$F_t = (fg + a)m + \left(\frac{1}{2} C_D \cdot \rho_{AIR} \cdot v^2\right) k \cdot m^{2/3} = k_1 \cdot m + k_2 \cdot m^{2/3}$$

where k, k_1 and k_2 are constants at constant acceleration and velocity. The first term (k_1.m) is the sum of the rolling and acceleration resistance, while the second term (k_2.$m^{2/3}$) is the aerodynamic drag. Substituting typical values for k_1 and k_2, the relationship between the tractive force and vehicle mass is illustrated in Figure 2-3. For these conditions, we see from this figure that the contribution of frontal area reduction on total tractive force, when expressed as a mass factor, is about 25-35% of the total tractive force. Since tractive force is the key parameter that affects vehicle fuel consumption, the impact of frontal area reduction on fuel consumption would be similar. Most of the fuel consumption benefit from downsizing can therefore be attributed to mass reduction that accompanies it.

The earlier tractive force equation hinted at this result as well. Reducing vehicle mass will have a more direct impact on fuel consumption, since mass appears in both the rolling and acceleration components of the total resistive force. Aerodynamic drag does not dominate the vehicle's work requirements, except when the vehicle is traveling at high speeds, since drag varies with the square of the vehicle's velocity. However, even when one traces the resistive work distribution over the U.S highway driving cycle, where the vehicle is traveling at high average speed (48 mph), drag still accounts for less than half of the work (Figure 2-4). So, reducing aerodynamic drag will have relatively less impact on reducing fuel consumption than reducing weight.

In sum, vehicle size reduction improves fuel consumption mainly by reducing its mass. By examining the key factors that affect the work performed by a vehicle, it is observed that the impact of frontal area reduction is smaller, compared to the accompanying mass reduction that results from vehicle downsizing. It is hence more important to use weight reduction to justify the benefits of downsizing.

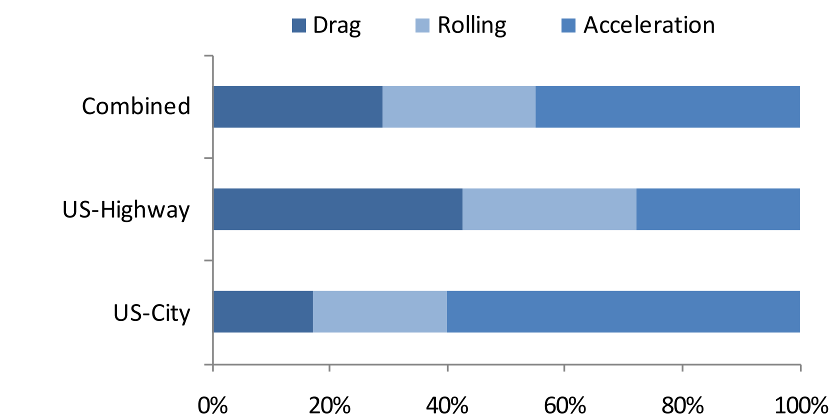
Figure 2-3. The relationship between vehicle mass and tractive force



Assumed values used:

f =	0.012	C_D =	0.25
g =	9.81 m/s^2	ρ_{AIR} =	1.1 kg/m^3
a =	0.89 m/s^2	v =	60mph = 27m/s
k_1 =	**1**	k =	$\rho_{VEH}^{-2/3}$ = 0.05
		k_2 =	**4.5**

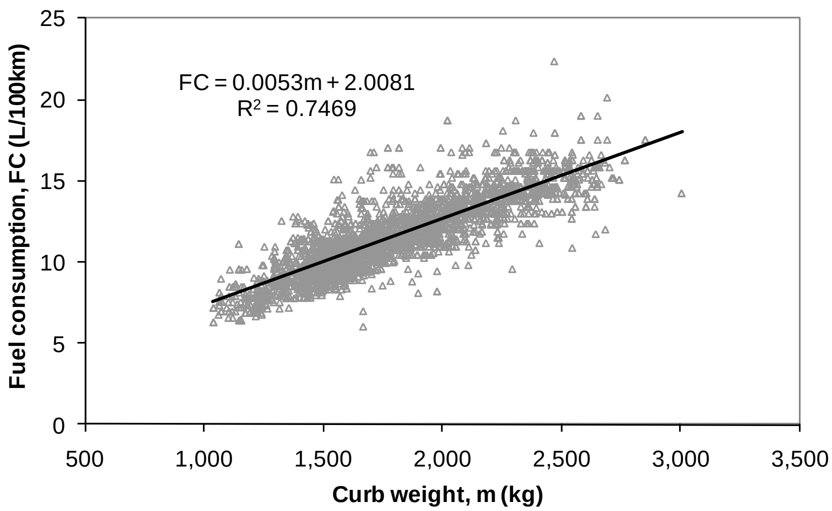
Figure 2-4. Work distribution for a compact car in different drive cycles, data source: [18]



2.3 Empirical data

To explore the effect of vehicle weight reduction on its fuel consumption for new vehicles being sold and driven in the U.S., one can also analyze empirical data. Figure 2-5 shows a plot of the (EPA adjusted) fuel consumption[4] and corresponding curb weights of all model year 2006-2008 light-duty vehicles offered in the U.S., revealing a linear positive correlation among these two variables. This data is obtained from Ward's Automotive [19]. On average across all vehicle models, every 100 kg weight reduction will achieve a reduction of 0.53 L/100 km in fuel consumption. While this figure is useful to detect a general trend, such data is not normalized for performance, size, or other vehicle attributes.

Figure 2-5. Curb weight and fuel consumption of U.S. MY2006-2008 vehicles, data source: [19]



To segment the data by powertrain, vehicle type and performance, a subset of the data is plotted – only gasoline cars that accelerate from zero to 60 miles per hour (mph) in around 9.5 seconds. This is the time the average new car sold in 2008 takes to accelerate from zero to 60 mph. The vehicle's acceleration time is estimated from their reported horsepower, using the following relationship [2]:

$t = 0.892*(hp/lb)^{-0.805}$ for vehicles with automatic transmission

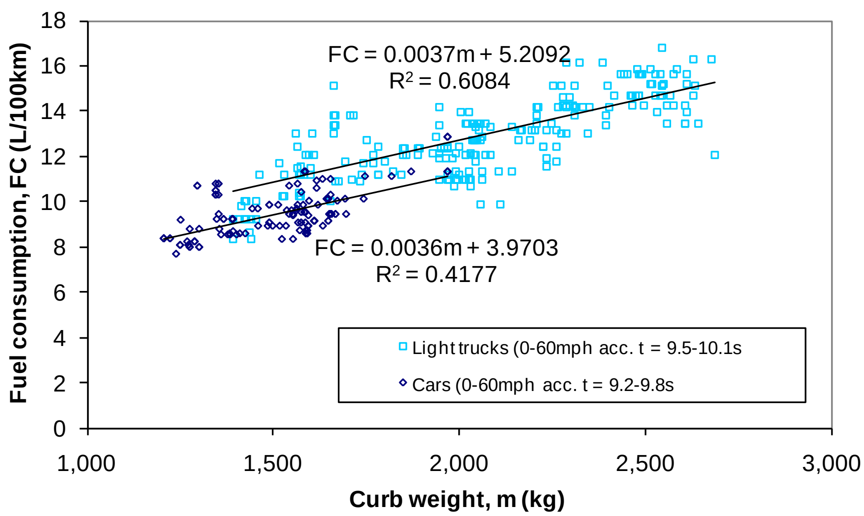
$t = 0.967*(hp/lb)^{-0.775}$ for vehicles with manual transmission

Where	t	=	Time taken to accelerate from 0-60mph	[sec]
	hp	=	The vehicle's maximum horsepower	[hp]
	lb	=	The vehicle's inertia weight in pounds	[lb]

[4] See detailed notes on page 14.

In 2006-2008, there were 146 car models that fit in this specific category, i.e. accelerate from zero to 60 mph in 9.5±0.3 seconds. Doing the same for light trucks, we stratify the data and identify gasoline light trucks that have the current sales-weighted average 0-60 mph time of around 9.8 seconds, and find 382 data points in this light truck category. The plots of (EPA adjusted) fuel consumption versus curb weight of these representative gasoline cars and light truck are shown in Figure 2-6 below. For both cars and light trucks of similar acceleration performance, every 100 kg vehicle weight reduction will yield a 0.4 L/100 km decrease in fuel consumption. In percentage terms, every 10% reduction in vehicle weight, cars will consume 5.6% less fuel, and light trucks will consume 6.3% less fuel.

Figure 2-6. Curb weight and fuel consumption of select MY2006-2008 U.S. gasoline cars and pickups



2.4 Results from the literature

There are several studies that attempt to quantify the vehicle fuel consumption reduction benefit associated with lightweighting. For vehicles using conventional gasoline-fueled internal combustion engines (ICE), a summary of the results from literature is shown in Table 2-1. The reported improvement in fuel consumption varies widely from 1.9-8.2% for every 10% reduction in vehicle weight. The average of these numbers, which has no inherent validity, gives 4.9%. Factors that affect this relationship include the size and type of vehicle, the drive cycle used to evaluate the vehicle (e.g. city, highway, or combined) and whether or not the powertrains were resized to maintain vehicle performance (i.e., secondary weight savings included or excluded, see Section 3.3).

Table 2-1. Mass-fuel consumption relationship for gasoline vehicles from literature

Size/type	Fuel consumption reduction per 10% mass reduction	Includes secondary weight savings?	Drive cycle[5]	Source
Small car	2.6%	No	NEDC	[20]
Small car	3.5%	No	43/57 city/hwy	[21]
Small car	4.7%	No	55/45 city/hwy	[22]
Small car	5.3%	Yes	43/57 city/hwy	[21]
Small car	6.8%	Yes	NEDC	[20]
Midsize car	1.9%	No	NEDC	[20]
Midsize car	2.5%	No	43/57 city/hwy	[21]
Midsize car	4.1%	No	55/45 city/hwy	[22]
Midsize car	5.6%	Yes	43/57 city/hwy	[21]
Midsize car	7.0%	Yes	55/45 city/hwy	[22]
Midsize car	6 to 8%	(not specified)	(not specified)	[6]
Midsize car	8.0%	Yes	55/45 city/hwy	[23]
Midsize car	8.2%	Yes	NEDC	[20]
Small SUV	3.1%	No	43/57 city/hwy	[21]
Small SUV	5.2%	Yes	43/57 city/hwy	[21]
Small SUV	7.9%	Yes	55/45 city/hwy	[23]
Midsize SUV	2.4%	No	NEDC	[20]
Midsize SUV	7.4%	Yes	NEDC	[20]
Large SUV	2.5%	No	43/57 city/hwy	[21]
Large SUV	5.2%	Yes	43/57 city/hwy	[21]
Large pickup	2.7%	No	43/57 city/hwy	[21]
Large pickup	3.7%	Yes	43/57 city/hwy	[21]

[5] NEDC is the New European Driving Cycle, which is supposed to represent the typical usage of a car in Europe. 43/57 and 55/45 city/hwy drive cycles are used by the U.S. EPA that combine city and highway drive cycles. These cycles are based on the standardized Federal Test Procedure (FTP) and Highway Fuel Economy Driving Schedule (HWFET). They are calculated using an updated weighting of 43%/57%, or the previous 55%/45% city/highway weighting.

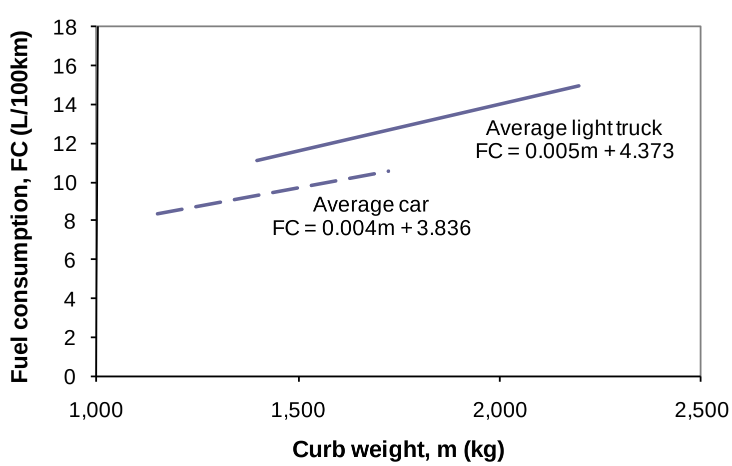
2.5 Vehicle simulation

We now compare the results reported in the literature and from the regression analysis with that from vehicle simulations using AVL© ADVISOR vehicle simulation software. For any predefined vehicle model, ADVISOR calculates the torque, speed, and power passing through different vehicle components, and predicts the vehicle's fuel consumption and acceleration performance over a prescribed speed-time trace. To simplify, we use the best-selling midsize sedan and pickup models in the U.S. – the model year 2005 gasoline Toyota Camry and the gasoline Ford F-150 – to represent a current average car and an average light truck. The drive cycles used are the standard U.S. Federal Test Procedure (FTP) and Highway Fuel Economy Driving Schedule (HWFET) to represent city and highway driving.

The simulations reveal that while leaving vehicle acceleration performance and size unchanged, for every 100 kg weight reduction, the adjusted (or "real world"), combined city/highway fuel consumption can decrease by 0.39 L/100 km for cars, and 0.48 L/100 km for light trucks in the U.S. (see Figure 2-7). In other words, for every 10% weight reduction from the average new car or light truck's weight, the vehicle's fuel consumption reduces by 6.9% and 7.6% respectively.

Simulations were likewise carried out on representative vehicle models of the future, which embody expected improvements in engine efficiency and reductions in aerodynamic drag and rolling resistance that may be achieved within the next two decades. For the "future" Camry and F-150, their fuel consumption decreases by 0.30 L/100 km and 0.35 L/100 km for every 100 kg weight reduction respectively.

Figure 2-7. Simulation results – Curb weight-fuel consumption relationship for today's vehicles



2.6 Chapter summary

To determine the effect of vehicle weight reduction on its fuel consumption, results from a literature review, empirical data, and engineering simulation have been reviewed and reported. The results are summarized in Table 2-2 below for a conventional gasoline-fueled midsize car only, assuming that the engine is resized to maintain vehicle performance. The relationship is observed to be fairly consistent across all three approaches. Results from literature sources and empirical data analysis appear to validate the "10-7" results from the engineering simulation carried out. That is, a 10% reduction in vehicle weight will reduce fuel consumption by about 7%. In absolute terms, every 100 kg weight reduction will yield a 0.39 L/100 km reduction in (EPA adjusted) fuel consumption for the current average gasoline car in the U.S. This simulation results will be used to quantify the sensitivity between vehicle weight and its fuel consumption in our model. The assumed relationship for current and future vehicles, including cars and light trucks, used in the models subsequently described in this thesis are shown in Table 2-3 below.

Table 2-2. Fuel consumption (FC)-curb weight relationship for a current conventional gasoline midsize car

Approach	FC reduction per 10% mass reduction	FC reduction per 100 kg mass reduction
Literature review	5.6-8.2%	0.36-0.58 L/100 km
Empirical data (MY2006-08)	5.6%	0.36 L/100 km
Engineering simulation (ADVISOR)	6.9%	0.39 L/100 km

Table 2-3. Assumed vehicle fuel consumption sensitivities to weight reduction for various vehicles

Gasoline vehicle	Fuel consumption reduction per 100 kg mass reduction (L/100 km)	
	Current	Future (2030)
Average car	0.39	0.30
Average light truck	0.48	0.35

3 HOW TO REDUCE VEHICLE WEIGHT, AND ITS COST

Chapter 3 provides a technical assessment of the vehicle weight reduction opportunity, as well as a review of how much it will cost. How can vehicle weight reduction be achieved? Through substituting iron and steel with lightweight alternatives like aluminum and high-strength steel, redesigning the vehicle, and vehicle downsizing. Findings from various lightweight concept vehicle projects, as well as cost estimates in the literature, are summarized.

Reductions in vehicle weight can be achieved by a combination of (i) material substitution; (ii) vehicle redesign; and (iii) vehicle downsizing. Material substitution involves replacing heavier iron and steel used in vehicles with weight-saving materials like aluminum, magnesium, high-strength steel, and plastics and polymer composites. Vehicles can be redesigned to optimize the size of the engine and other components as vehicle weight decreases, or to improve the vehicle's packaging and reduce exterior vehicle dimensions while maintaining the same passenger and cargo space. Finally, downsizing can provide further weight reduction by shifting sales away from larger and heavier to smaller and lighter vehicle categories. The following sections will first describe weight and material breakdown of the current average U.S. vehicle to provide context, explain each of these three approaches in detail, and finally review the cost associated with vehicle weight reduction.

3.1 Current U.S. vehicle weight characteristics

The average new light-duty passenger vehicle sold in the U.S. weighs 1,730 kg in 2009. 80% of this weight is incorporated in its powertrain, chassis, and body (see Figure 3-1). The bulk of which are made of ferrous metals. Other major materials found in an average automobile in the United States include aluminum and plastics or composites, as shown in Figure 3-2. This figure also shows how the use of aluminum and high-strength steel (HSS) as a percentage of total vehicle mass has been increasing over the past two decades, while the use of iron and other types of steel has been declining. Despite greater use of these lightweight materials, however, the average new vehicle weight has in fact increased over time. So use of these materials has helped to curb further increase in vehicle weights due to the introduction of various weight-adding features and a stronger preference for larger-sized vehicles.

Figure 3-1. Vehicle mass distribution by subsystem, data source: [24]

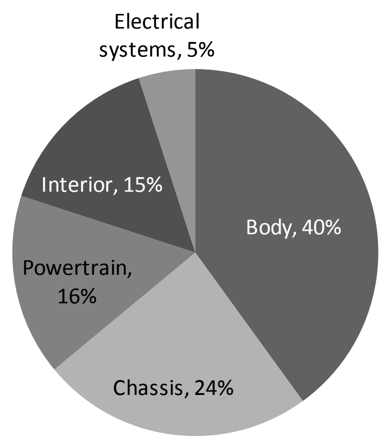
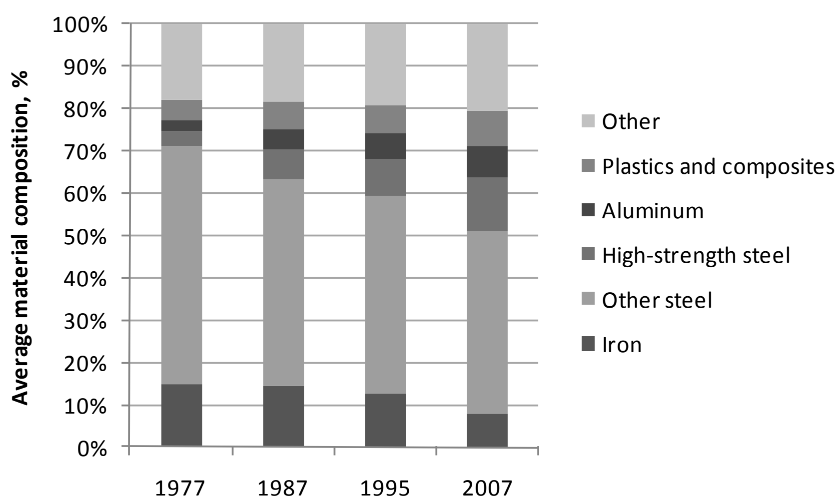


Figure 3-2. Material composition of the average automobile in the U.S., data source: Ward's via [1]



3.2 Material substitution

Aluminum and high-strength steel are two of several alternative lightweight materials that can be used to replace substantial amounts of heavier steel and iron in the vehicle. Other lightweight material candidates which are less dense still, or higher-strength, include magnesium and polymer composites such as glass- and carbon-fiber-reinforced thermosets and thermoplastics. Comparative properties of these materials are summarized in Table 3-1 below, and the prospects of each will be discussed in turn. Less common lightweight materials like metal matrix composites and titanium have been omitted due to their high costs, which limit their application within the vehicle. The cost of weight reduction will be reviewed later in this chapter.

Table 3-1. Relevant properties of automotive materials

Material	Density, g/cm[3] (relative)	Yield strength, MPa	Tensile strength, MPa	Elastic modulus, GPa	Equal stiffness thickness ratio[6]	Equal strength thickness ratio[7]	Relative cost per part [25]
Mild steel	7.86 (1.00)	200	300	200	1.00	1.00	1.0
High strength steel (A606)	7.87 (1.00)	345	483	205	0.99	0.64	1.0-1.5
Iron (D4018)	7.10 (0.90)	276	414	166	-	-	-
Aluminum (AA6111)	2.71 (0.34)	275	295	70	1.42	0.85	1.3-2.0
Magnesium (AM50)	1.77 (0.23)	124	228	45	1.64	1.27	1.5-2.5
Composites - Carbon fiber - Glass fiber	1.57 (0.20)	Flexural: 200	810	190	1.01	-	2.0-10.0

Table 3-2. Summarized evaluation of lightweight automotive materials

Material	Current use	Advantages	Challenges
High-strength steel	230 kg/vehicle, in structural components e.g. pillars, rails, rail reinforcements	Makes use of existing vehicle manufacturing infrastructure, there is OEM support for near-term use	- More expensive at higher volume scale - Lower strength-to-weight ratio compared to other lightweight materials
Aluminum	140 kg/vehicle, 80% are cast parts e.g. engine block, wheels	- Can be recycled - Manufacturers familiar with metal forming	- High cost of aluminum - Stamped sheet is harder to form than steel - Softer and more vulnerable to scratches - Harder to spot weld, uses more labor-intensive adhesive bonding
Magnesium	5 kg/vehicle, mostly thin-walled cast parts e.g. instrument panels and cross car beams, knee bolsters, seat frames, intake manifolds, valve covers	- Low density - Good strength-to-weight ratio - Ability to consolidate parts and functions, so less assembly is required	- Higher cost of magnesium components - Production of magnesium in sheet and extruded forms
Glass-fiber reinforced polymer composite	Rear hatches, roofs, door inner structures, door surrounds and brackets for the instrument panel	- Ability to consolidate parts and functions, so less assembly is required - Corrosion resistance - Good damping and NVH control	- Long production cycle time, more expensive at higher volume scale - Not easily recycled - Lack of design know-how and familiarity
Carbon-fiber reinforced polymer composite	Drive shaft	Highest strength-to-weight ratio, offering significant weight-saving benefit	- As above - High price volatility and cost of fibers ($13-22/kg)

[6] The equal bending stiffness thickness ratio is calculated using the following formula: $t_1/t_0 = \sqrt[3]{(E_0/E_1)}$, where t is thickness, and E is the elastic modulus.
[7] The equal bending strength thickness ratio is calculated using the following formula: $t_1/t_0 = \sqrt{(\sigma_0/\sigma_1)}$, where t is thickness, and σ is the yield strength.

3.2.1 High-strength steel

High-strength steels (HSS) are manufactured using a combination of alloy compositions and processing methods to achieve high strength with almost the same formability as mild steel. HSS are a popular alternative automotive material because they make use of existing vehicle manufacturing infrastructure, and there is OEM support for near-term use. The challenge is to develop manufacturing technologies to make the production and use of these new materials economically viable on a high-volume scale, such as using tailored blanks and tube hydroforming. Today, one-fifth of the steel used in the average automobile is HSS, and this fraction has been increasing steadily. Using mostly dual-phase steel, the International Iron and Steel Institute's Ultralight steel Auto Body (ULSAB) Program demonstrated mass savings of 68 kg or 25% for a C-class (compact) car's body structure. [26] HSS is an attractive nearer-term option, due to its relatively low cost and its accessibility.

3.2.2 Aluminum

8% of the mass of the average automobile in the United States is aluminum, and this aluminum content has been growing at an annual rate of 4% since 1975. Most (81%) of the aluminum is cast, and used in the engine, wheels, transmission, and driveline. It is more difficult to form stamped-sheet body components with aluminum than with steel, and the material has to be handled with care to prevent scratches, because it is softer. Aluminum is also a better conductor than steel, making it more difficult to spot weld, so it is likely to require more laborious adhesive bonding. Despite these challenges, Ducker Research [27] projects aluminum use in automotive applications to increase from 142 kg in 2007 to 170 kg per vehicle by 2020.

3.2.3 Magnesium

Magnesium designs with equal stiffness offer around 60% weight reduction over steel, and 20% weight reduction over aluminum. Promising automotive applications include structural components in which thin-walled magnesium die castings may be used. About 40% of magnesium in vehicles today is cast into instrument panels and cross car beams. Other applications include knee bolsters, seat frames, intake manifolds, and valve covers. The U.S. Automotive Materials Partnership [28] sees the potential of magnesium content per vehicle increasing from 5 kg today, to an ambitious 160 kg by 2020. However, factors limiting the growth of magnesium in the automotive industry include the need to develop creep-resistant alloys for high-temperature applications, improvements in the die casting quality and yield, corrosion issues, and the production of magnesium in sheet and extruded forms. High and volatile magnesium price has also been an inhibitor. See Appendix B for further discussion on the potential limits/constraints for magnesium in automotive applications.

3.2.4 Polymer composites

Plastics and polymer composites currently make up about 8% of a vehicle by weight and 50% by volume, and these numbers are expected to increase slowly. The main factors restricting the growth of polymer composites in vehicles today are the long production cycle times and the cost of the fibers. The most common type of automotive composites is glass fiber reinforced thermoplastic polypropylene, which is applied to rear hatches, roofs, door inner structures, door surrounds, and brackets for the instrument panel. Other types include glass mat thermoplastics, sheet molding compounds made of glass fiber reinforced thermoset polyester, and bulk molding compounds or glass fiber reinforced thermoset vinyl ester. Carbon fiber reinforced polymer (CFRP) composites are more expensive and less popular, although they offer significant strength and weight-saving benefit. The Rocky Mountain Institute's concept Hypercar® used CFRP to achieve a body-in-white weight that is 60% lighter than a conventional steel one. [29] However, carbon fibers cost an inhibiting $13–$22 per kilogram, compared to $1–$11 per kilogram of glass fibers. [30] Use is typically restricted to low-volume applications in high-end luxury vehicles. One successful application in production vehicles is the carbon fiber drive shaft. Other technical challenges of using CFRP include the infrastructure to deliver large quantities of materials and the recycling of composites at the vehicle's end of life.

3.2.5 Other materials

Beyond the materials discussed that may replace ferrous metals, there are also alternative materials that may be used to replace other materials within the vehicle, reducing weight to a smaller degree. For example, using copper-clad aluminum instead of copper in cables can slash weight from wiring. Lighter polycarbonate materials can replace conventional glass for glazing, and lighter-weight foams can be used for seats. The potential weight savings that may be obtained by reducing the weight of glazing, lighting, instrument panel display, and seating is around 42 kg. [31]

3.2.6 Weight saving potential of material substitution

On the component-level, the amount of weight savings resulting from using alternative materials in any vehicle component depends on the application and design intent. For instance, for a body panel designed for strength and resistance to plastic deformation, 1 kg of aluminum can replace 3–4 kg of steel. For a structural component designed for stiffness in order to restrict deflection, 1 kg of aluminum replaces only 2 kg of steel. The equal-stiffness and -strength thickness ratios for different materials, as compared to a steel component, are included in the same Table 3-1. In general, the amount of weight reduction obtained by replacing steel tends to be greater for polymer composites and magnesium, followed by aluminum. To illustrate this, the degree of weight savings obtained by using different materials to make a rear floor of a car is shown in Table 3-3. All materials fulfill the technical specifications for the body part.

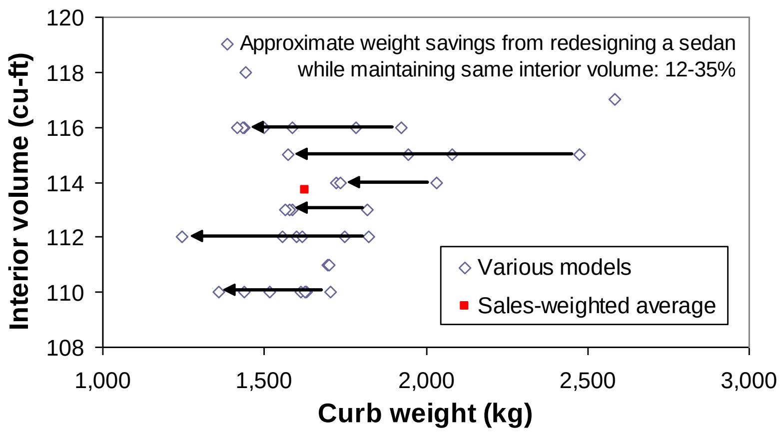
Table 3-3. Weight of rear floor part using different material alternatives [24]

Material	Mass, kg	Weight savings, %
Steel sheet	6.54	-- (reference)
Aluminum sheet (5182)	3.38	48%
Polyamide glass fiber (PA 6.6 GF30)	2.87	56%
Polypropylene glass fiber (PP GF30)	2.35	64%
Magnesium sheet (AZ31)	2.18	67%

3.3 Vehicle redesign

Redesigning or reconfiguring the vehicle is another strategy to achieve weight savings. Creative design and packaging can be employed to minimize the exterior dimensions of the vehicle while maintaining the same interior space. Figure 3-3 plots the interior volume of various midsize sedans offered in model years 2007 and 2008 with their curb weights. The arrows illustrate the range of possible weights across similarly-sized vehicles.

Figure 3-3. Potential weight savings from redesigning MY2007-08 midsize sedans while maintaining same interior volume



Another weight minimizing approach is to consolidate, eliminate, or downsize parts, and/or to remove some content from the vehicle. Vehicles on the lower end of the weight range are likely to have a smaller powertrains, and fewer optional features like powered seats or entertainment systems. For example, removing optional entertainment systems can save 3-14 kg. Not opting for a sunroof can also save 25 kg from the vehicle. Weight reduced using this "de-featuring" approach would require sacrificing some utility of the vehicle, in terms of comfort, safety, or other. This may be hindered by the need for safety features, either by regulation or consumer demand. For instance, the National Highway Traffic Safety Administration (NHTSA) anticipates average vehicle weight gain of 8-9 kg by 2016 due to safety standards, including electronic stability control, side air bags, and roof crush protection. [32]

To further illustrate the possibility of "de-featuring" and downweighting while preserving vehicle size and performance, let us look at a case of two cars offered in the U.S. market. Vehicle models from MY2006-2008 were scanned to find pairs of similarly-sized vehicles with similar acceleration performance. One pair of compact cars, the 2008 Audi A4 and the 2006 Mazda3, was observed to have similar exterior dimensions and both cars are estimated to accelerate from 0 to 60 mph in 9.6 seconds.[8] However, the Audi A4 weighs 345 kg or a nontrivial 22% more than the Mazda3. The Audi is a premium model and offers more utility with luxury features and better safety and quietness, which partly explains

[8] See Section 2.3 on how acceleration time is estimated.

why it is denser. As expected, it has a poorer fuel economy than the Mazda. The specifications of these two sedans are shown in Table 3-4.

Table 3-4. Audi A4 vs. Mazda3 – Illustrating weight reduction potential while maintaining vehicle size and performance

Year, Model	**2008 Audi A4 2.0T Quattro**	**2006 Mazda3 s Touring**
		
Body style	4-dr sedan (seats 5)	4-dr sedan (seats 5)
Wheelbase	104.3 in	103.9 in
length x width x height	180.6 x 69.8 x 56.2 in^3	178.7 x 69.1 x 57.7 in^3
Overall volume (l*w*h)	11.61 m^3	11.68 m^3
Horsepower	200 hp	160 hp
Power-to-weight ratio	0.057 hp/lb	0.058 hp/lb
0-60mph acceleration time (est.)	9.58 sec	9.59 sec
Engine displacement	2.0L I4	2.3L I4
Front head, leg room	37.9 in, 41.3 in	39.1 in, 41.9 in
Luggage capacity	13.4 ft^3	11.4 ft^3
City/hwy (adj.) fuel economy	22/31 MPG	26/32 MPG
Features	16" wheels, AWD, power seat adjustment, sunroof, heated mirrors, dual zone climate controls, 10 speakers + subwoofer, traction and stability control	17" wheels, FWD, manual seat adjustment, sunroof optional
NHTSA crash test ratings – driver, passenger, side impact front, rear, rollover	4, 4, 5, 4, 4 stars	4, 4, 3, 3, 4 stars
MSRP	$28,900	$17,600
Curb weight	**1,595 kg (3,516 lb)**	**1,251 kg (2,758 lb)**

Another aspect of redesigning vehicles for minimal weight is to realize secondary weight savings by downsizing subsystems that depend on the total vehicle weight. As the vehicle weight decreases, the performance requirements of the engine, suspension, brake subsystems and others are lowered, and these can be resized accordingly. Malen and Reddy [33] report secondary weight savings to range from 0.8 to 1.5 kg per kg of primary weight savings. Similarly, Bjelkengren [34] reports an average mass decompounding coefficient of 1.0, with the most savings derived from downsizing body closures and the vehicle structure. The variation depends on the extent of redesign and resizing that takes place. Including the secondary weight savings will naturally increase the total vehicle weight reduction and increase its effectiveness in reducing fuel consumption. However, it is acknowledged in these studies that their approach does not normalize the data for other parameters, such as vehicle size or acceleration performance, which could lead to less optimistic weight savings.

It is not easy to generalize the amount of weight savings that can result from using lightweight materials and redesigning a vehicle, as the weight savings depends on the final designs of subsystems and of the entire vehicle. Examining concept vehicles that have been designed with minimal weight as their primary objective can provide a further sense of this. Table 3-5 lists various concept lightweight vehicles and their corresponding weight savings. These vehicles have demonstrated a wide range of weight savings, as compared to similarly-sized reference vehicles, with generally greater savings obtained when employing more aluminum or polymer composites.

Three of the more comprehensive demonstration projects suggest that total vehicle weight savings of 20-38% are possible. Firstly, steel companies reported 20% (215 kg) weight reduction for a compact car in the UltraLight Steel Auto Body's-Advanced Vehicle Concept (ULSAB-AVC) program. [26] In the more recent European SuperLIGHT concept car project, a consortium of automakers and research organizations demonstrated cost-effective reduction of a mass-produced compact car by a similar amount. This was achieved by using alternative lightweight materials, primarily extensive use of stamped aluminum, in the body. [24] Finally, Lotus Engineering suggested weight saving potential of 21-38% in a crossover utility vehicle by using high-strength steel, aluminum, magnesium, and composites, and by eliminating parts. [35]

Table 3-5. Concept lightweight vehicles

Concept	Year	Segment	Reference vehicle	Reference curb weight, kg	Concept curb weight, kg	Weight savings, %	Source
Steel-intensive							
ULSAB-AVC	2002	Compact car	Ford Focus	1,147	933	19%	[26]
ULSAB-AVC	2002	Midsize car	--	1,470	998	32%	[26]
NewSteelBody	2003	Minivan	Opel Zafira	1,393	1,295	7%	[36]
Arcelor Body Concept	2004	Midsize car	--	--	--	(40kg)	[37]
Future Steel Vehicle	2009	Compact car	--	1,199	1,044	13%	[31]
Future Steel Vehicle	2009	Midsize car	--	1,483	1,260	15%	[31]
Lotus study	2010	CUV	Toyota Venza	1,290	800-1,019	21-38%	[35]
Aluminum-intensive							
Ford P2000	1998	Midsize car	Ford Taurus	1,505	907	40%	[38]
fka Aluminum-intensive vehicle	2002	Compact car	--	1,229	836	32%	[39]
Lotus APX	2006	SUV	Porsche Cayenne	2,170	1,567	28%	[40]
SuperLIGHT-CAR	2009	Compact car	VW Golf V	--	--	(201kg)	[24]
Polymer/composite-intensive							
Chrysler ESX2	1998	Midsize car	Dodge Intrepid	1,570	1,021	35%	[41]
Hypercar Revolution	2000	CUV	--	1,800	857	52%	[42]

3.4 Vehicle downsizing

Vehicle size reduction is considered independently from the other approaches to vehicle weight reduction mentioned earlier. We are interested in how reducing passenger vehicle size can reduce its weight and thus lower its fuel consumption. As reviewed in Chapter 2, smaller vehicles consume less fuel because they weigh less, and also because they have smaller frontal area and thus less aerodynamic drag. To consumers, vehicle size is a more tangible attribute than weight and it is important to examine the fuel-saving potential of this strategy.

To begin, one has to develop a clear definition of vehicle size, as there are a variety of size metrics:

- Vehicle segment – cars, light trucks (SUVs, pickups, minivans)
- Engine displacement volume, in cubic centimeters or liters
- Volume (L^3) – interior (passenger + cargo space), or overall volume (length x width x height)
- Area (L^2) – footprint (wheelbase x track width[9]), or shadow (length x width), or frontal area (≈ 0.8 x width x height)
- Length (L) – wheelbase (distance between the centers of the front and rear wheels), or vehicle length

In the U.S., the Environmental Protection Agency (EPA) classifies cars and wagons by interior volume, and light trucks by their wheelbase (see Table 3-6). The National Highway Traffic Safety Administration (NHTSA) uses a vehicle's footprint, or the area bounded within the four wheels, as a measure of its size to impose attribute- or size-based minimum Corporate Average Fuel Economy (CAFE) standards.

Table 3-6. U.S. EPA vehicle size classification

Vehicle type	Definition base	Small	Midsize	Large
Cars	Interior volume (cu-ft)	< 110	110 - 120	120+
Wagons	Interior volume (cu-ft)	< 130	130 - 160	160+
Sport utility vehicles	Wheelbase (in)	< 100	100 - 110	110+
Vans	Wheelbase (in)	< 109	109 - 124	124+
Pickups	Wheelbase (in)	< 105	105 - 115	115+

To determine which vehicle size metric correlates well with weight, we plotted various size metrics of all vehicle models offered in the U.S. from MY2006-2008 against their curb weights. It turns out that the vehicle's footprint and overall volume are two size metrics that scale reasonably well with weight, with higher coefficient of determination (R^2) values. The footprint vs. curb weight chart is shown below in Figure 3-4, which shows the positive correlation. Reducing the footprint of a vehicle by one square meter can reduce that vehicle's weight by 625 kg, if it is a car, or 385 kg, if it is a truck. The next Figure 3-5 shows the curb weight of various segment-sizes of current (MY2009) vehicles using the EPA size classification. On average, downsizing from a truck to a car results in weight savings 535 kg, or 27%.

[9] Track width is the distance between the centerline of two wheels on the same axle.

Figure 3-4. How vehicle weight scales with vehicle size (footprint)

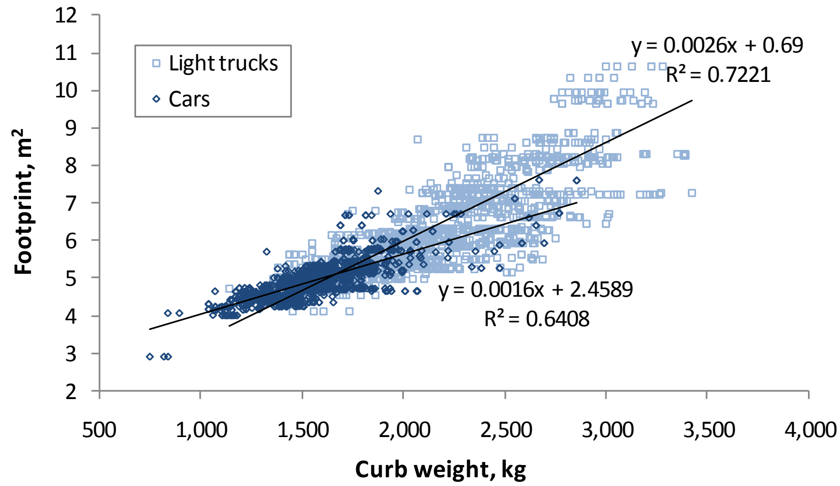
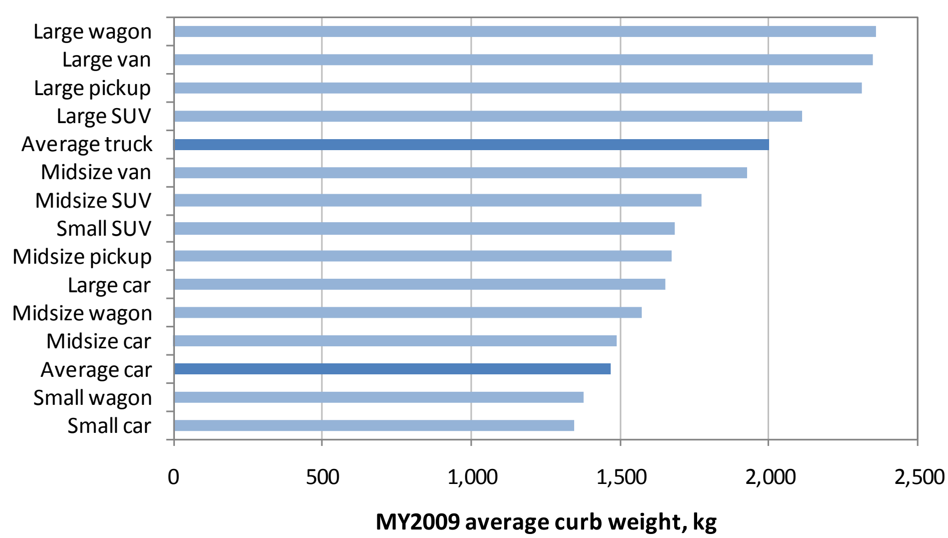
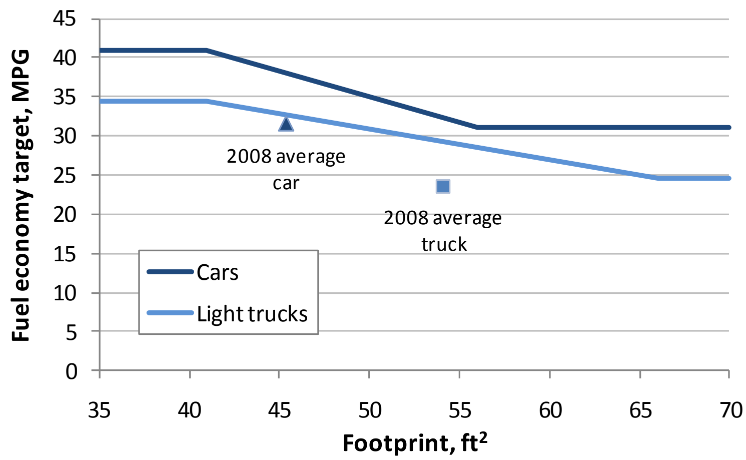


Figure 3-5. How vehicle weight scales with vehicle size (segment)



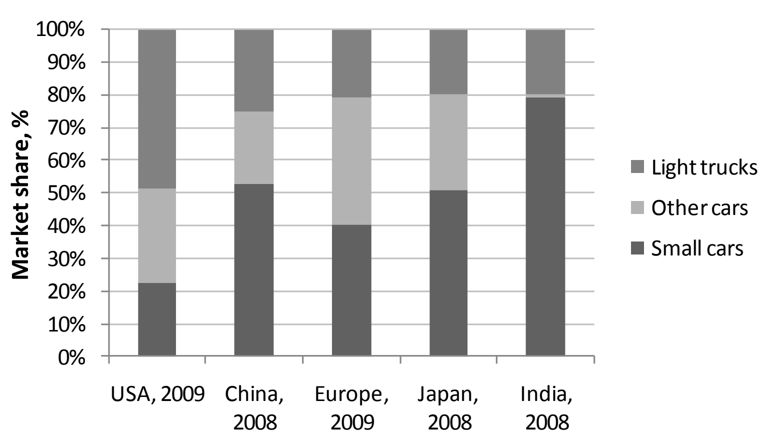
Regarding the potential of vehicle downsizing in the U.S., it is noted that under the CAFE ruling, each vehicle will have a target fuel economy based on its footprint. The minimum fuel economy target as a function of vehicle footprint is shown in Figure 3-6, with the 2008 average car and light truck plotted for reference. Each manufacturer's average fuel economy requirements will thus vary according to the size mix of the vehicles sold. A manufacturer that sells vehicles with larger footprints will be required to meet a lower CAFE standard than another who sells vehicles with smaller footprints. This attribute-based feature of the rule is intended in part to not penalize manufacturers whose vehicle mix include many big pickups and SUVs, and effectively discourages vehicle downsizing.

Figure 3-6. Vehicle footprint-based fuel economy (CAFE) targets for MY2016



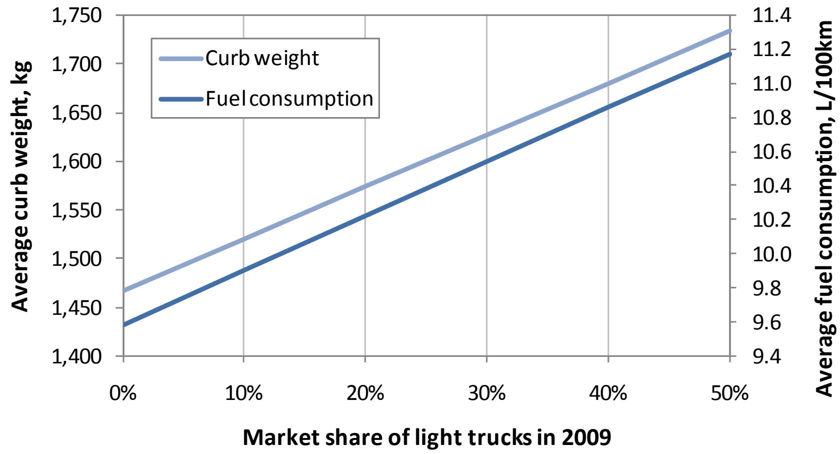
Despite this feature, we choose to not exclude downsizing as part of our analysis, because there is strong potential to downsize vehicles in the U.S. American vehicles are generally larger than compared with other markets. Figure 3-7 contrasts the breakdown of new vehicles sold by three vehicle segments – small cars, other cars, and light trucks – in the U.S. with other vehicle markets. The market share of light trucks is the highest in the U.S. at 49%, while the share of small cars[10] is only 22%. Reversing the order of these ratios can cut the sales-weighted average vehicle weight, and improve fuel economy. If the 2009 market share of light trucks had been 30% instead of 49%, the average new vehicle curb weight will be lower by 100 kg, and the average (adjusted) fuel consumption will decrease by 0.6 L/100 km. The general effect of shifting vehicle sales away from light trucks is shown in Figure 3-8.

Figure 3-7. Current passenger vehicle sales by segment in different markets [2, 43-46]



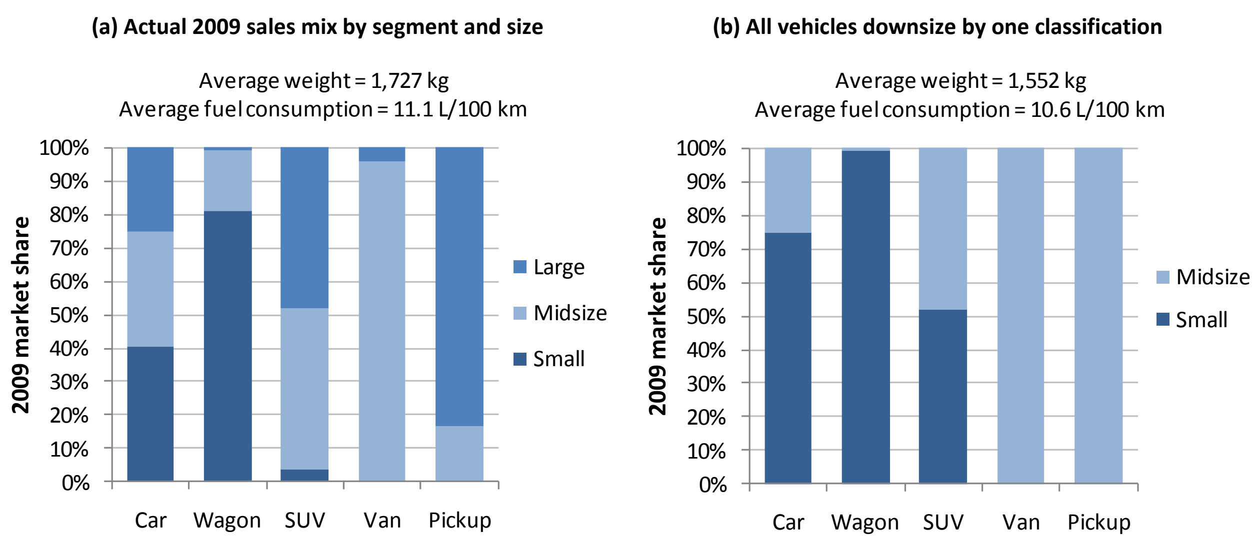
[10] The definition of small cars plotted in this chart differs in various auto markets. A small car in the U.S. has an interior volume of less than 110 ft^3. A Chinese small car has a wheelbase of less than 2.65 m. The length of an Indian small car measures less than 4.7 m. A Japanese small car's engine displacement does not exceed 2,000 cc. A Toyota Corolla is considered a small car by all of these definitions.

Figure 3-8. Effect of light truck sales on the average new vehicle weight and (EPA-adjusted) fuel consumption



Downsizing can also take place within, and not just across vehicle segments from light trucks to cars. If all vehicles were to downsize by one EPA size classification, while the market split by segments remain the same, it is found that the average curb weight in 2009 will drop by 175 kg (10%). That is, every large car, wagon, SUV, van or pickup buyer opts for a midsize version instead, and likewise diverting sales from midsize vehicles to small. With this drastic market shift, the average (EPA-adjusted) fuel consumption declines from 11.1 to 10.6 L/100 km (see Figure 3-9). So if much higher levels of fuel economy are desired in the future, one should not neglect the possibility of vehicle downsizing.

Figure 3-9. Effect of downsizing within vehicle segments on the average new vehicle weight and fuel consumption



3.5 Brief note on safety implications

As vehicle weight and size reductions are considered to improve fuel economy, the potential impact on vehicle safety is often raised. This is an important issue. We assume little or no compromise in safety when reducing the weight and/or size of the vehicle for two reasons. Firstly, it is possible to design and build small vehicles with similar crashworthiness to larger and heavier ones. By reinforcing the structural stiffness of the vehicle at critical points, including side airbags, and introducing crumple zones to absorb energy in case of a collision, automakers are already making smaller cars that protect their occupants better. For example, the 2010 MINI Cooper scored 4 out of 5 stars in the NHTSA's frontal and side rear passenger crash ratings, and 5 stars for the side driver ratings. Secondly, aside from the crashworthiness of the vehicle, there are other facets to the safety discussion to be considered, including rollover risk, aggressiveness of vehicles to other road users, and vehicle crash compatibility. Considering the effect on overall road safety, some of the larger and heavier SUVs and pickups can actually pose greater safety risks for their drivers and other road users. [47] So safety might actually improve if the heaviest vehicles were removed or made lighter.

3.6 The cost of vehicle weight reduction

It would be incomplete to discuss ways to reduce passenger vehicle weight without mentioning the associated cost. Cost is an important consideration, because while we can detail the benefits of weight reduction, this approach is only practical if it remains at an acceptable cost of implementation. We now review the literature for estimates on the manufacturing cost of alternative lightweight automotive material technology. The incremental cost of redesigning a vehicle for minimal weight and for developing smaller vehicles is not deemed to be large; thus the primary focus will be on the cost of material substitution.

3.6.1 Literature review

To ascertain the cost of using lightweight materials in automotive applications, technical or process-based cost modeling is a common approach in the literature. This methodology captures the cost implications of both material and the process variables by first identifying critical cost elements or drivers like raw material and energy, labor, equipment, and tooling. The sensitivities to parameters like production volume, part count, and raw material prices are subsequently examined. With technical cost models, one is able to determine how the cost of a lightweight vehicle component depends on the nature of the manufacturing process, and also how it relates to the production volume.

To get a sense of potential applications of lightweight materials in vehicles and their corresponding manufacturing costs, results from select case studies available in the literature are summarized in Table 3-7. Most of these case studies focused on the vehicle's body, where there is greatest lightweighting potential and benefit in the form of secondary weight savings in the rest of vehicle. Effort was made to compare the cost from various sources at similar, high volumes of production when full scale economies are reached.

Cost estimates in the literature are found to vary widely from -$2 to $14 per kilogram of weight savings ($/kg), depending on the type of material, the design of the vehicle component, and the scale of production. In general the cost per unit weight savings is lower for HSS, and is followed by aluminum and polymer composites. The negative cost values associated with using high-strength steel (HSS) imply cost savings that will result from using this alternative material. Automotive composites remain prohibitively expensive given high raw material prices and long production cycle times, and we expect HSS and aluminum to remain popular substitutes for steel in passenger vehicles in the near-term. The cost estimates for using HSS and aluminum are plotted in a chart with weight savings on the horizontal axis, and cost on the vertical axis in Figure 3-10.

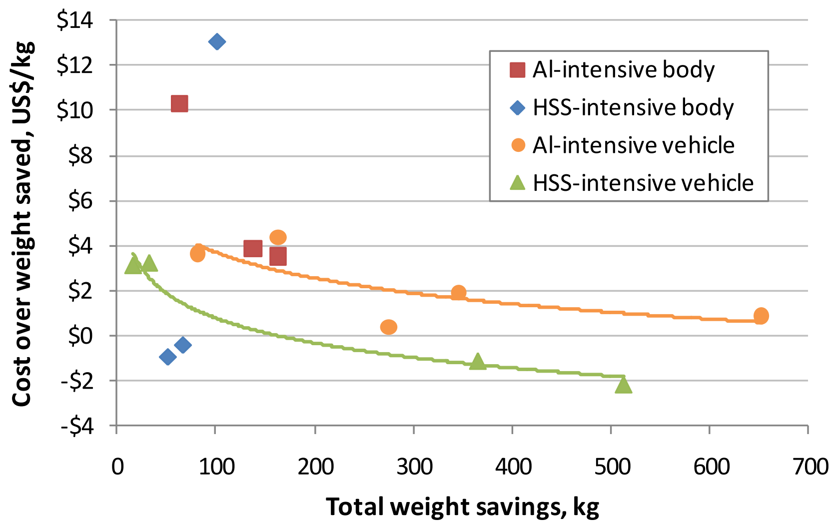
It is important to distinguish between the cost of lightweighting a single vehicle component, versus lightweighting an entire vehicle. In the latter, one should also account for the effect of secondary weight savings. For instance, a vehicle that is optimized for minimal weight is likely to use a downsized powertrain and suspension following primary weight savings in the body. If so, both the additional cost and weight savings in these components, if any, should be accounted for in the total $/kg estimate. In general, the cost estimates in the literature for lightweighting on a vehicle level are lower than on the component level.

Table 3-7. Case studies and cost of vehicle weight reduction from the literature

Lightweight component / vehicle	Incremental OEM cost, US$	Weight reduction, kg	Cost over total weight saved, US$/kg	Volume per year	Source
General lightweight vehicle	$51	16	$3.11	-	[17]
General lightweight vehicle	$105	33	$3.22	-	[17]
General lightweight vehicle	$297	82	$3.64	-	[17]
General lightweight vehicle	$713	163	$4.37	-	[17]
High strength steel-intensive					
Front end	-$13	11 kg	-$1.20	-	[48]
SUV frame	-	(-23%)	$0.68	220,000	[49]
Body-in-white	-$32-52	52-67 kg	-$1.00 to -$0.47	225,000	[50]
Body structure	-	101 kg	$13.08	1,000/day	[24]
Vehicle	-$1,102	556 kg	-$2.00	225,000	[50]
Vehicle	-$409[11]	365 kg	-$1.12	-	[35]
Aluminum-intensive					
Unibody	$537	138 kg	$3.88	500,000	[51]
Unibody	$650	63 kg	$10.30	200,000	[52]
Body-in-white	-	163 kg	$3.51	"high"	[53]
Vehicle	$661[12]	346 kg	$1.91	200,000	[54]
Vehicle	$103	275 kg	$0.37	"high"	[53]
Vehicle	$557[12]	653 kg	$0.85	-	[35]
Polymer composite-intensive					
Body (glass fiber)	$400	127 kg	$3.16	100,000	[55]
Body (glass fiber)	$930	68 kg	$13.68	250,000	[56]
Body (carbon fiber)	-	-	$2.20 to $8.82	-	[30]
Body (carbon fiber)	$900	196 kg	$4.59	100,000	[55]
Body (carbon fiber)	$728	114 kg	$6.39	100,000	[57]
Body (carbon fiber)	$1,140	145 kg	$7.86	250,000	[56]
Vehicle (carbon fiber)	$2,926[13]	444 kg	$6.59	200,000	[54]

[11] OEM cost is estimated from Toyota Venza's, the baseline vehicle, retail price (MSRP) of $24,000, assuming markup of 1.4x.
[12] This estimate is the difference in raw material cost only.

Figure 3-10. Cost of vehicle weight reduction from the literature



On a vehicle level, logarithmic trend lines are added to the same Figure 3-10 to display the general relationship between manufacturing cost and total vehicle weight savings for HSS- and aluminum-intensive vehicles. It appears that the total cost of weight reduction declines as greater weight savings are sought. This is contrary to the expectation that vehicle weight reduction will get increasingly more difficult and expensive, as aggressive weight reduction will demand more novel designs and challenging material processing. It is noted that these trend lines are not linking data points from the same source, so they are intended as indicative rather than prescriptive. We observe that HSS-intensive lightweight vehicles will cost around -$2 to $3/kg, and aluminum-intensive vehicles will cost slightly more at $1 to $4/kg. Both material options are capable of achieving high levels of weight reduction – up to 560 kg using HSS (or -36% from baseline vehicle), and 650 kg using aluminum (-38%).

3.6.2 Cost comparison with other fuel-saving technologies

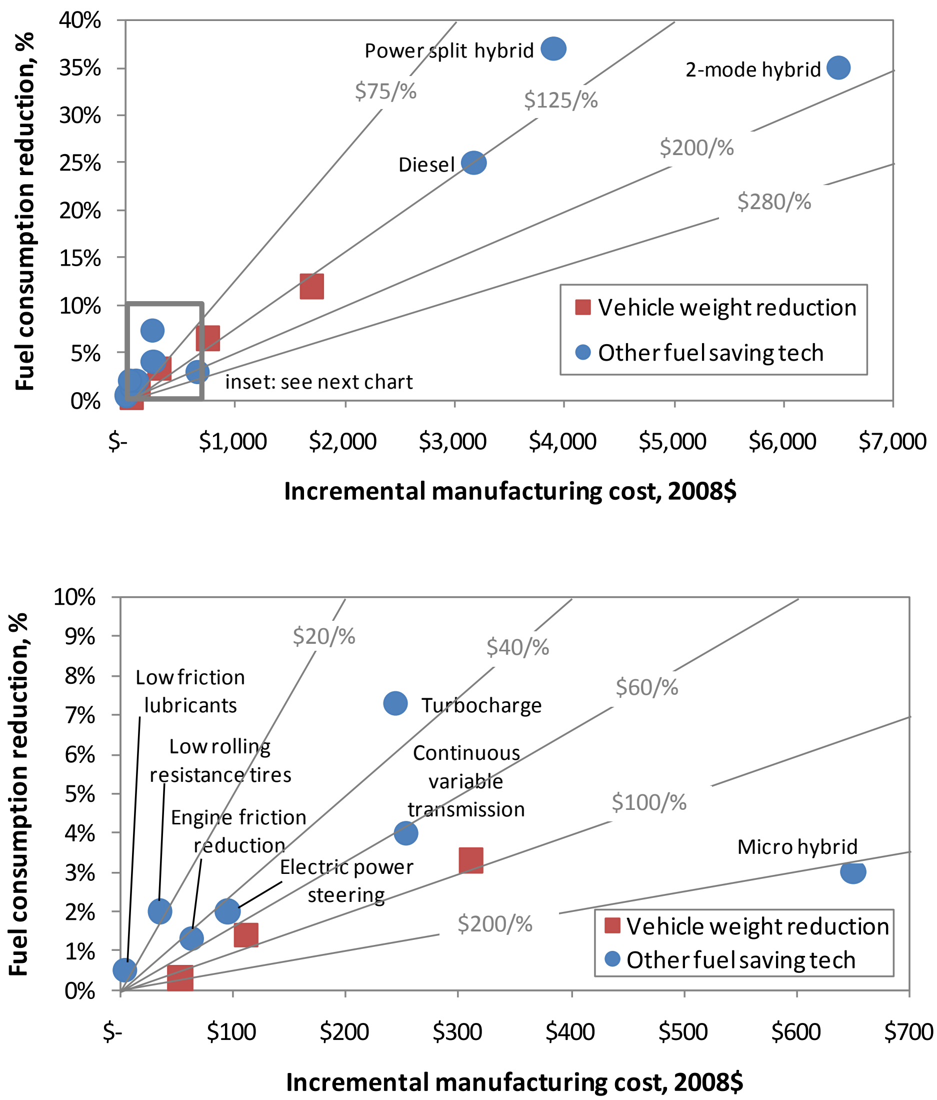
How does vehicle lightweighting rank against other technical options in terms of cost-effectiveness? Would it be cheaper to lightweight a car, or to introduce a car with a diesel powertrain, in order to decrease fuel consumption? It would be useful to compare the cost-effectiveness of lightweighting with various fuel-saving approaches. The $/kg figures are now converted to cost per unit of fuel consumption reduction ($ per unit change in L/100 km, or $ per percentage fuel consumption reduction) as a basis of comparison. Again, we will not attempt to carry out original cost modeling, but instead turn to the literature to gain insight.

The National Research Council (NRC) recently published a report assessing various technologies that will improve vehicle fuel economy. [17] Their data is used to create the charts below[13], which compares the cost-effectiveness of vehicle weight reduction with other approaches. The data from NRC refers to

[13] Chart design inspired by presentation by R.S. Bailey from Delphi, *Will Fuel Economy Sell And Can We Afford It?*, SAE Congress 2008.

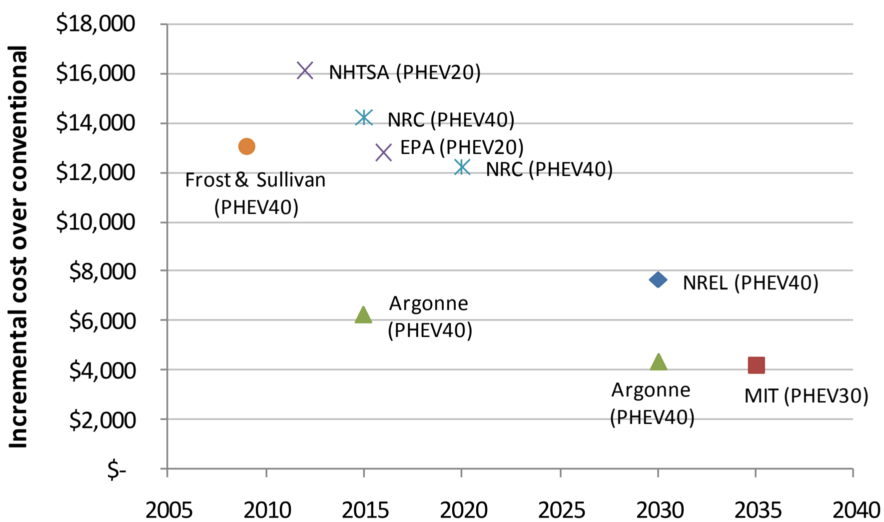
incremental manufacturing cost and fuel consumption improvement over a baseline vehicle defined as a midsize car with a 6-cylinder, 4-valve, dual overhead cam engine. In Figure 3-11, technologies located near the upper left hand-side of the charts offer better value in the sense of lower cost per percentage fuel consumption reduction. In the NRC assessment, vehicle weight reduction is estimated to cost around $3 to $4/kg of total weight saved, or $80 to $180 per percentage fuel consumption (L/100 km) reduction. This puts lightweighting as a relatively less cost-effective approach to reduce fuel consumption. In contrast, diesel technology costs around $130 per percentage fuel consumption reduction, while hybrid technologies cost $110 to $220/%. Both vehicle dieselization and hybridization can achieve much higher mileage per unit of fuel.

Figure 3-11. Cost-effectiveness of various fuel-saving vehicle technologies, data source: [17]



It is noted that there is high degree of uncertainty over the cost estimates of various fuel-saving vehicle technologies from the literature, especially regarding the cost of vehicle electrification, like we have seen on the cost of vehicle weight reduction. We reviewed the current literature for estimates of the incremental cost of manufacturing a plug-in hybrid electric vehicle (PHEV), and these are plotted in Figure 3-12 below (for full details, including references, see Appendix D). Within the next 5-10 years (2015-2020), PHEVs are projected to cost an additional $6,000-14,000 more than a conventional internal combustion vehicle. In general, the cost of this new technology is expected to fall as production increases and learning takes place. The uncertainty over these cost estimates stems primarily from the uncertainty in the rate of lithium-ion battery technology development, and expectations over when the cost of batteries will fall.

Figure 3-12. Estimates of plug-in hybrid cars' incremental manufacturing cost over conventional vehicles



3.7 Chapter summary

Reductions in vehicle weight can be achieved by a combination of (i) using lightweight materials; (ii) further vehicle redesign for minimal weight; and (iii) by downsizing the vehicle.

On lightweight materials, high-strength steel (HSS) and aluminum are promising alternatives that have the potential to replace substantial amounts of heavier steel and iron in the vehicle. These two material options are more cost-effective at large production volume scales, and their increasing use in vehicles is likely to continue. Cast aluminum is most suited to replace cast iron components, stamped aluminum for stamped steel body panels, and HSS for structural steel parts. Polymer composites are also expected to replace some steel in the vehicle, but to a much smaller degree given high cost inhibitions. Carbon fiber composites are likely to remain in low-volume applications.

Material substitution can be coupled with additional vehicle redesign to achieve further weight reduction. Following weight savings in the body, secondary weight savings can be achieved by downsizing subsystems like the powertrain (while maintaining the same power-to-weight ratio) and suspension. Another approach is to remove some content or features from the vehicle, but this requires sacrificing some utility. On a vehicle-system level, it would be possible to achieve up to 35% weight reduction by employing lightweight materials and optimizing the vehicle design for minimal weight.

The cost of manufacturing vehicle components using lightweight materials depends on several factors: the type of material, component design, whether or not secondary weight savings are included, and the production volume. HSS-intensive lightweight vehicles are expected to cost around -$2 to $3/kg of total weight savings, and aluminum-intensive vehicles will cost slightly more at $1 to $4/kg. Taking the high end of these estimates, and the finding from the previous chapter that every 100 kg weight reduction can result in 0.39 L/100 km reduction in fuel consumption, vehicle weight reduction will cost around $800 to $1,000 per L/100 km of fuel consumption reduction. So lightweight material technology is relatively expensive, but can in some instances be more cost-effective than some other fuel-saving vehicle technologies, like diesel or hybrid technologies, within the aforementioned limit.

Downsizing the passenger vehicle fleet can further reduce weight at minimal manufacturing cost increments. On average, a larger and heavier light truck weighs 535 kg or 27% more than a car. If the 2009 market share of trucks had been 30% instead of 49%, the average new U.S. vehicle curb weight will lower by 100 kg from 1,730 kg. If all new vehicles sold were downsized by one EPA size classification (large to midsize, midsize to small), the average new vehicle curb weight can decline by 175 kg (10%). So while the potential exists for U.S. to downsize its fleet, drastic size shifts must take place in order to curb vehicle weight significantly.

Combining all these approaches – lightweight material substitution, vehicle redesign, and downsizing – it will be possible to reduce the sales-weighted average new vehicle curb weight by up to 40%, or 690 kg. This can be achieved by redesigning the vehicle using lightweight materials to cut vehicle weight by 35%, and then replacing all large vehicles with midsize versions. If significant fuel consumption reduction is desired, this 40% weight reduction is achievable, although it will be costly and no doubt challenging to realize.

4 THE IMPORTANCE OF VEHICLE WEIGHT REDUCTION IN THE U.S.

4.1 U.S. vehicle weight and size trends

We have seen how the average weight of new vehicles sold in the U.S. has been increasing steadily over the past two decades. As previously shown in Figure 1-2, the sales-weighted average new American vehicle gained 402 kg since 1987, to reach a curb weight of 1,730 kg today. The increase can be ascribed to two principal causes: a shift to larger vehicle segments, and "weight creep" within segments.

The popularity of larger and heavier light trucks, especially sport utility vehicles (SUVs), is partly responsible for the upward trend. The market share of midsize and large SUVs has increased by more than a factor of 15, from less than 2% of the new light-duty vehicle market in 1975 to a third of the market today. Conversely, the market share of small cars has been declining steadily (see Figure 4-1).

Weight increase within vehicle classes or segments is also taking place. For instance, the weight of a new Toyota Corolla introduced in the U.S. is 140 kg heavier than the same model introduced ten years ago (Figure 4-2). One reason for this is that vehicle dimensions have been increasing. Today's vehicles tend to be longer, wider, and taller than before. Another reason is "feature creep" or the increasing number of new features that have been introduced into vehicles that improve utility, by adding comfort and safety. These features, like power folding seats, heated seats, navigation systems, extra gears, additional speakers, or side air bags, also add weight to the vehicle.

Chapter 4 sets up the topic of vehicle weight reduction in the context of the Corporate Average Fuel Economy (CAFE) program in the U.S. While vehicle weight has been creeping upwards over the past two decades, looming, more stringent fuel economy standards will require new vehicles to become lighter and more fuel efficient. This chapter explores the magnitude, possible combinations and timing of changes in the new vehicle fleet – including vehicle weight reduction – necessary to meet future fuel economy mandates, using scenario analysis. A commentary on the aggressiveness of the new 2016 fuel economy standard is included.

Figure 4-1. Historical market share of new vehicles by segment, data source: [2]

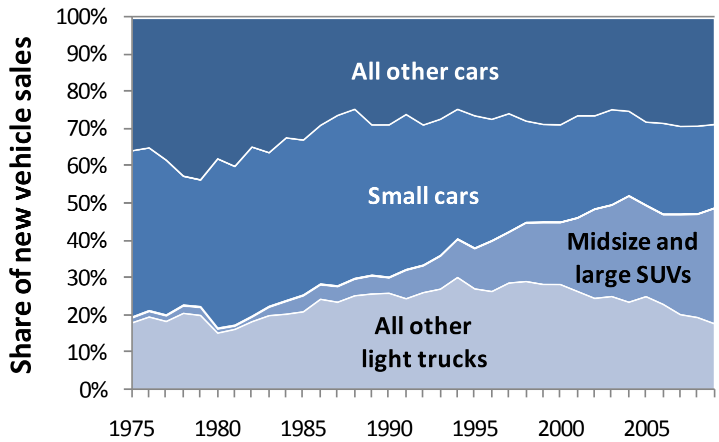
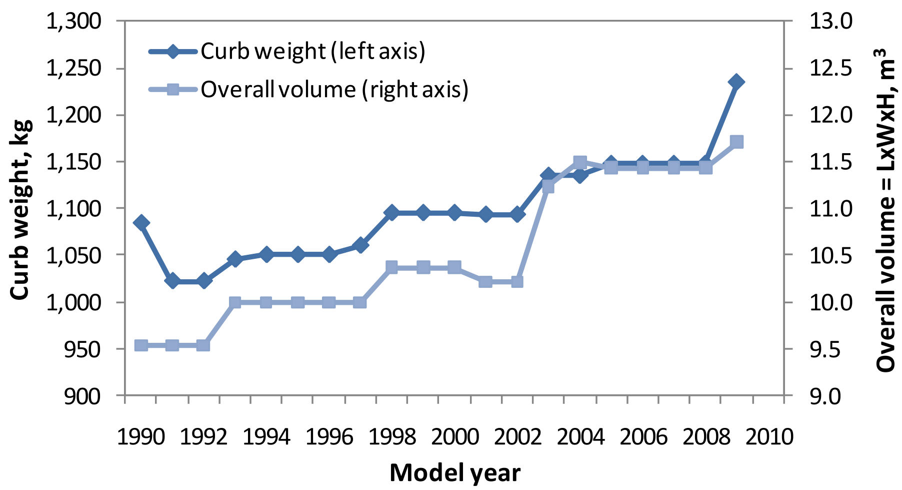


Figure 4-2. Curb weight and overall volume of Toyota Corolla introduced in the U.S., model years 1990-2009



4.2 Response to fuel economy mandates

Given that new U.S. passenger cars and light trucks are required on average to improve their fuel economy to at least 34.1 miles per gallon (MPG) by 2016, we expect that these weight and size trends will reverse, but by how much? Some automakers have already announced intention to reduce vehicle weight in the near term, by pursuing strategies like engine downsizing and turbocharging, optimizing steel design, or using aluminum and magnesium in the body, and vehicle downsizing (see Table 4-1). To study this question more carefully, we will explore scenarios of the future vehicle fleet that will achieve the targeted average fuel economy in this chapter.

Table 4-1. Automakers targets for vehicle weight reduction in North America [58, 59]

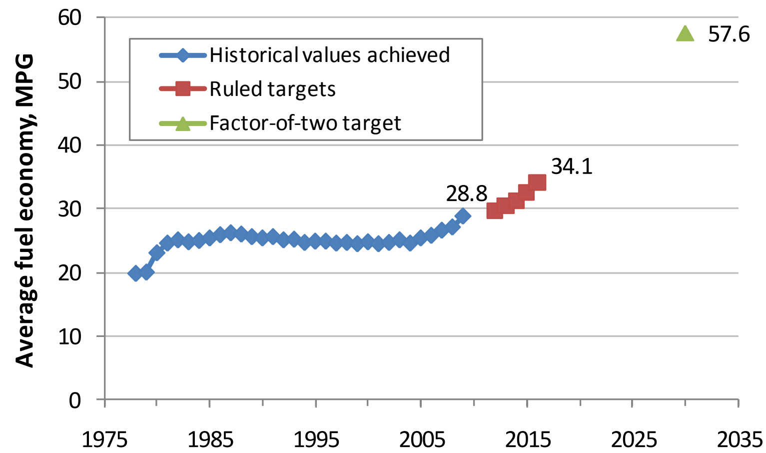
OEM	Weight target
Ford	110-340 kg reduction between 2012-2020
GM	Reduce body-in-white weight by 10-20% by 2015
Hyundai	20-25% reduction within 10 years
Mazda	At least 100 kg reduction between 2011-2015
Nissan	15% reduction by 2015
Toyota	10% reduction for midsize car models by 2015

It is recognized that the two government agencies responsible for regulating CAFE, the U.S. National Highway Traffic Safety Administration (NHTSA) and the U.S. Environmental Protection Agency (EPA), have made extensive modeling efforts to examine how future vehicles can comply with the proposed standards, as part of the rulemaking procedure. [4] Both begin by identifying a set of available fuel-saving vehicle technologies, which are then applied to vehicles until the targeted fuel economy is achieved. While their models are detailed and grounded in technical analysis, they have two basic shortcomings. Firstly, the improvements in technologies over time are not accounted for, so the fuel consumption reductions attributed to each technology remain unchanged over time. In addition, both models have assumed that the performance and utility of vehicles will remain unchanged going into the future, which is contrary to the historical trends.

In our modeling effort, we adopt a simpler approach and focus on the key technology options, as our purpose is to provide broader insight on the difficulty of the challenge. Unlike the NHTSA and EPA models, we take into account timing effects and discuss rates of expected changes. The new vehicle sales mix will be considered as a whole, and the strategic response of individual carmakers will not be examined. We will also not discuss the economic impact of meeting these targets, or structural details of the new standard, such as flexible and transferable credits. Instead, we focus on assessing the technical challenge that lies ahead.

Beyond 2016, we are also interested in the weight and size of future vehicles if a doubling of the fuel economy from today's average value is attempted over the next two decades. This is motivated by the expectation that the U.S. government will continue to impose more stringent fuel economy standards over time. On May 2010, President Barack Obama announced plans to develop further standards for MY2017 and beyond. The factor-of-two goal selected for analysis would require the new vehicle fleet to attain 58 MPG by around 2030, continuing the trajectory of improvement defined by the new standards. By examining the possible response to the various fuel economy targets, we would like to shed light on the changes that are required in order to meet the 2016 mandate, and how the future new vehicle fleet might evolve over the next two decades.

Figure 4-3. Average fuel economy of new passenger vehicles (NHTSA-reported CAFE)



As noted earlier in Section 3.4, the new fuel economy mandates for vehicles are size (footprint)-based, and are defined separately for cars and light trucks (see Table 4-2). Cars and trucks with smaller footprints are required to achieve higher fuel economy. As such, automakers face more stringent targets if they downsize their fleet. The aforementioned sales-weighted average target of 34.1 MPG by 2016 implies a car/truck market share split of 65/35. That is, car sales make up 65% of the market in year 2016. If automakers choose to sell more cars, the target will increase. Vice versa, if automakers sell fewer cars, the target will be lower. This feature of the mandate will be accounted for in our future vehicle scenarios.

Table 4-2. Average required fuel economy (MPG) under final CAFE standards [60]

Model year	2011	2012	2013	2014	2015	2016
Cars	30.4	33.3	34.2	34.9	36.2	37.8
Light trucks	24.4	25.4	26.0	26.6	27.5	28.8
Combined cars and trucks	27.6	29.7	30.5	31.3	32.6	**34.1**

4.3 Other nearer-term fuel-saving strategies

To meet future fuel economy targets, vehicle lightweighting will only be one of several fuel-saving strategies that automakers are expected to pursue. We must therefore consider the combinations of technologies, in addition to cutting vehicle weight, likely to be employed.

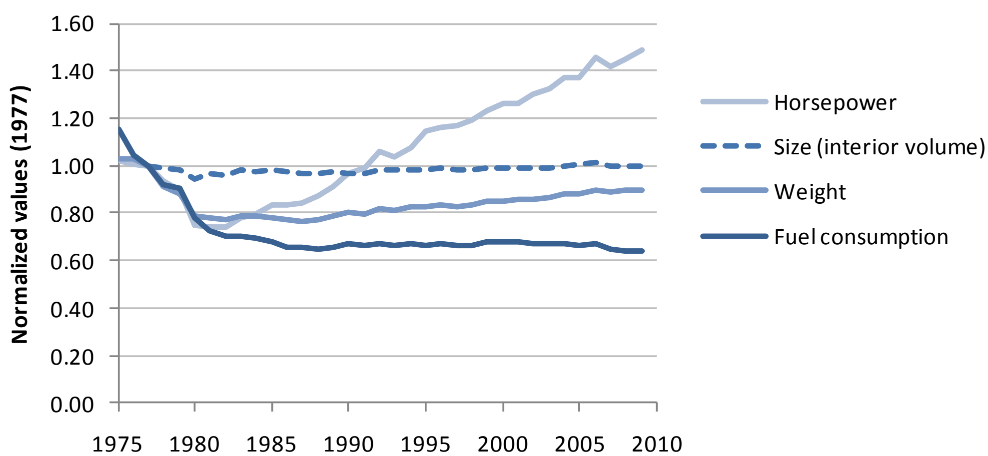
There are many fuel-saving technologies and approaches to improving vehicle fuel economy, previously mentioned in Chapter 2. They include improvements in the engine and transmission, minimizing losses in accessories, use of alternative, more efficient powertrains like hybrid electric drives, and reducing the road load by reducing the inertial forces and resistances encountered by the vehicle, including its weight. The National Research Council's 2010 report [17] on the efficacy and cost of these individual technologies, which may be applied in the next 15 years, is a useful summary.

We will elaborate on two additional approaches, other than vehicle weight and size reduction, that are available in the near- to medium-term: (i) de-emphasizing vehicle acceleration and horsepower performance improvements; and (ii) promoting sales of more fuel-efficient vehicles that use improved or alternative powertrains. Embedded in the analysis is the assumption that all other available vehicle and engine improvements will take place and be introduced into new vehicles incrementally over time.

4.3.1 De-emphasize vehicle horsepower/acceleration performance

Automotive engineers have worked hard to steadily improve the fuel efficiency of vehicles. With various engine and vehicle improvements, vehicles today can more effectively convert fuel energy into useful work than their predecessors. These advances in vehicle technology, however, have not resulted in reducing the vehicle's fuel consumption. As seen in Figure 4-4 below, the average fuel consumption of the new cars remained largely unchanged since 1980. This should not be mistaken for lack of gains in technical efficiency. The gains have been taking place, but have instead been used to offset the negative fuel consumption impacts of improving other vehicle attributes such as vehicle horsepower, comfort, and size.

Figure 4-4. Trends of average new U.S. car characteristics, 1975-2009, data source: [2]

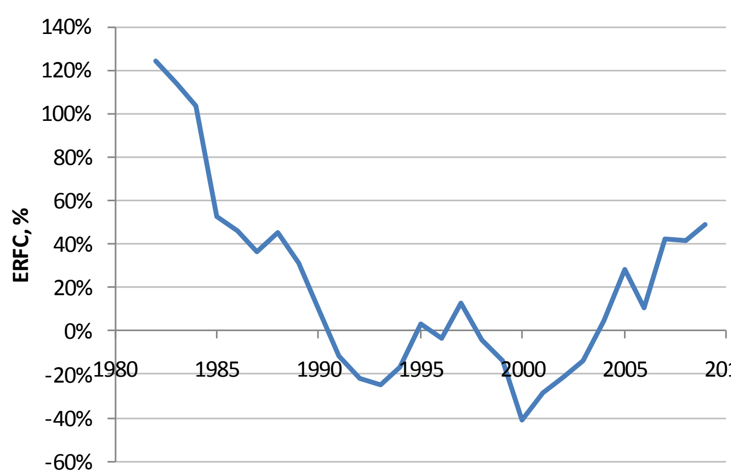


In general, improved vehicle technical efficiency can be used to either reduce the fuel consumption of a vehicle or to offset improvements in performance and weight attributes such as acceleration and power or some combination thereof. For example, reducing vehicle weight using lightweight materials leads to the possibility of downsizing the engine, which consumes less fuel while delivering the same level of performance. Or the engine size could be left unchanged in a lighter weight vehicle, resulting in better acceleration performance. This is an explicit design decision. While earlier studies have recognized and discussed this design tradeoff [61, 62], little effort has been made to quantify it. To better evaluate this design tradeoff, we have introduced a metric called Emphasis on Reducing Fuel Consumption (ERFC). [63]

ERFC measures the degree to which improvements in technology are used to reduce the vehicle's fuel consumption per distance traveled (measured in liters per 100 km). In any future vehicle, ERFC is defined as the actual fuel consumption reduction realized, divided by the fuel consumption reduction achievable keeping size and performance constant, over a specified time frame, and is expressed as a percentage. At 100% ERFC, all of the improvements in vehicle technology over time are assumed to realize reduced fuel consumption, while vehicle size and performance attributes remain constant. In contrast, without any emphasis on reducing fuel consumption (0% ERFC), the fuel consumption of new vehicles will remain at current values, and all of the efficiency gains from technology improvements are used to offset the increase the horsepower and acceleration performance instead. A negative value implies that fuel consumption actually worsened and increased.

Historically, ERFC in new U.S. passenger cars has varied (see Figure 4-5, Appendix B describes calculation details). The highest values were recorded prior to 1985, as spurred by the oil crisis and the introduction of the CAFE program. During this time, ERFC even exceeded 100%, meaning that vehicle performance regressed from earlier years. ERFC levels have since steadily declined, since little of the advances in vehicle efficiency were dedicated to reducing fuel consumption in cars, and ERFC has started rising again in this decade. Had ERFC been maintained at 100% from 1985, today's average new car is estimated to achieve 39 MPG rather than the actual 25 MPG (EPA adjusted figures, again see Appendix B). The tradeoff is that this car would take 13 seconds to accelerate from 0 to 60 mph, 4 seconds more than the average car today.

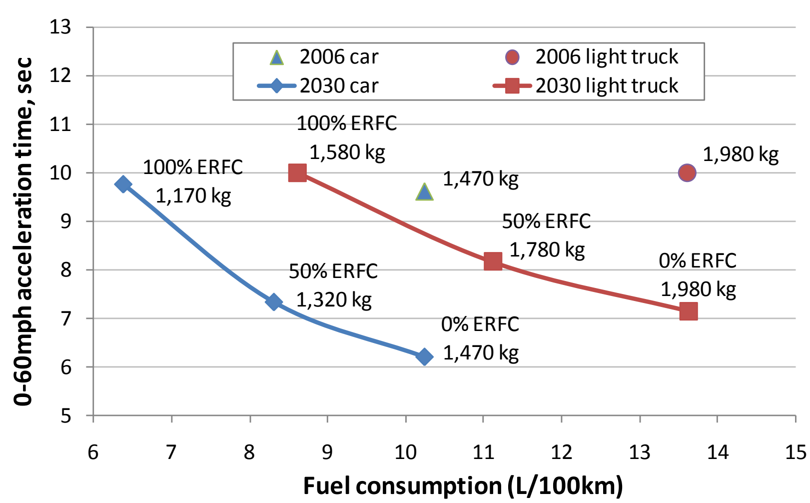
Figure 4-5. Historic Emphasis on Reducing Fuel Consumption (ERFC) for average new U.S. car [64]



Looking ahead, this ERFC concept can be used to examine the impacts of future vehicle technologies. The first step is to assess the fuel consumption reduction potential in a future vehicle. Kasseris and Heywood [65] estimate that if the size and acceleration performance of a representative midsize conventional gasoline car and pickup truck in the U.S. are kept constant through 2030, the fuel consumption of these vehicles could be reduced by a third. Part of this fuel consumption reduction is achieved by reducing vehicle weight by 20%, while the rest comes from expected improvements in engine efficiency and reductions in aerodynamic drag and rolling resistance. These results are used to characterize the 100% ERFC vehicles in the future.

Figure 4-6 shows the characteristics of 2006[14], as well as similarly-sized 2030 gasoline vehicles at different levels of ERFC. The lines reflect the trade-off between acceleration performance (time taken to accelerate from 0 to 60 miles per hour, or 0 to 100 km/hr in seconds) and fuel consumption (in liters per 100 kilometers, EPA adjusted) in future vehicles. These are obtained by carrying out computer simulations of representative car and light truck models which embody the expected improvements. Vehicle curb weight is assumed to decline linearly with ERFC, so the future vehicle weighs less if more emphasis is placed on reducing fuel consumption. At 100% ERFC, the average new car in 2030 is lighter-built with a curb weight of 1,170kg, as compared to 1,470 in 2006. The time taken to accelerate from 0 to 60 mph remains around the same as its current counterpart – 9.6 seconds – but this future car has the potential to consume a third less fuel.

Figure 4-6. Trade-off between acceleration performance and fuel consumption in average 2030 gasoline vehicles

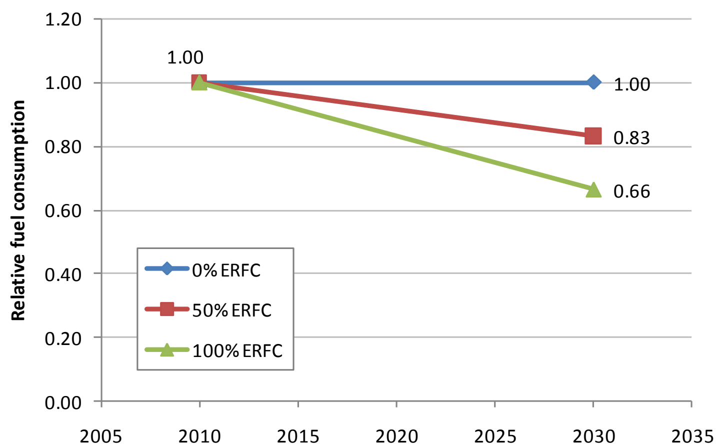


For simplicity, we assume that the future reduction in fuel consumption based on the degree of ERFC will decline linearly between years 2010 and 2030 (see Figure 4-7). Technical progress in internal combustion engines has historically been roughly linear and relatively well-behaved [66, 67], which

[14] 2006 was current, or a representation of "today's" vehicle, when these simulations were carried out.

supports the straight-line assumptions going forward. If full emphasis (100%) is placed on reducing fuel consumption, the fuel consumption of the average new gasoline car will decrease by 10% in 2016, and 34% by 2030, from 9.7 L/100 km in 2009 (reference, EPA adjusted). 100% ERFC also means an increase in the average fuel economy of the new vehicle fleet of 2.2 MPG and 11.3 MPG within these 2016 and 2030 timeframes, while performance and size remain constant. So even with full emphasis on seeking reduction in fuel consumption, the factor-of-two goal of achieving 58 MPG by 2030 will not be attained and additional options will need to be employed.

Figure 4-7. Relative fuel consumption of an average new U.S. gasoline car at varying levels of ERFC



To summarize, the performance and fuel consumption of future vehicles depend on how improvements to conventional vehicle technology are utilized. A metric – the degree of emphasis on reducing fuel consumption (ERFC) – expresses the impact of this design decision in future vehicles. Increasing ERFC is one of several options that is assessed to achieve the desired fuel economy.

4.3.2 Alternative powertrains

Alternative powertrains, such as turbocharged gasoline engines, diesel engines, and hybrid-electric systems, can provide additional fuel efficiency over mainstream internal combustion gasoline engines. A turbocharger, by increasing the amount of air flow into the engine cylinders, allows an engine to be downsized while delivering the same power. Diesel engines operate by auto-igniting diesel fuel injected directly into a cylinder of heated, pressurized air. This allows a high compression ratio, enables combustion with excess air, and eliminates throttling losses to increase engine efficiency. A hybrid-electric system provides the ability to store energy in a battery and operate the vehicle using both an engine and electric motor. This improves efficiency by decoupling the engine from the drivetrain at lighter loads where the efficiency is low, and also allows use of more-efficient alternatives to the Otto cycle engine, such as the Atkinson cycle with lower pumping losses. By having the electric motor to make up the low-speed power of an Atkinson cycle engine, the combination propels the vehicle more efficiently. Hybridization also allows turning the engine off while idling, and storing the vehicle's kinetic energy with regenerative braking—all of which reap secondary benefits from downsizing to a smaller and lighter engine. In plug-in hybrid-electric vehicles, the battery packs are larger and they can be charged using electricity from the grid.

Based on vehicle simulations that we ran, the relative gasoline-equivalent (liquid) fuel consumptions of these powertrains at 100% ERFC are shown in Figure 4-8 for new cars and light trucks in 2009, 2016 and 2030 (see *On the Road in 2035* report [68] for details on the simulations). Today's (2009) conventional, naturally-aspirated gasoline vehicles have been set as the reference, which consume 9.7 L/100 km (24.2 MPG) and 12.9 L/100 km (18.1 MPG, all EPA adjusted figures) for the car and light truck respectively. For comparison, our results for 2009 vehicles lie within the range of results reported in the National Research Council's 2010 report assessing technologies for improving vehicle fuel economy. [17] From our assessment, today's turbocharged gasoline, diesel and hybrid cars consume 10%, 16% and 30% less fuel than a conventional gasoline midsize car respectively. According to the NRC report, these improvements range 6-9%, 15-35% and 24-50% respectively.

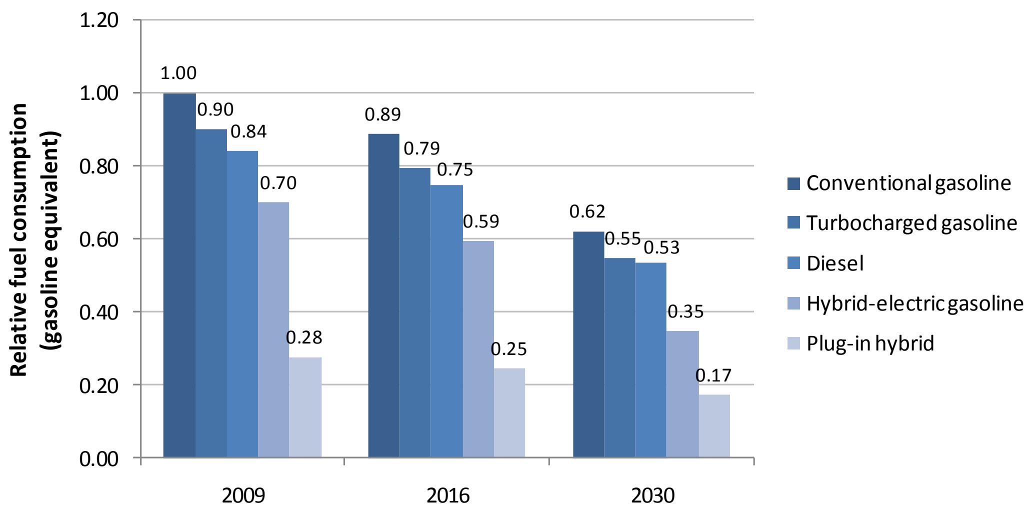
It is recognized that there are a variety of hybrid-electric systems currently available in the market. The hybrid vehicle (HEV) model that was assessed is a full power-split hybrid with a parallel architecture, which for cars, is similar to a Toyota Camry hybrid. The plug-in hybrid (PHEV) assessed is one with an electric driving range of 30 miles. As mentioned, a hybrid car consumes 30% less (liquid) fuel, and the PHEV 72% less than the conventional gasoline car currently. To clarify, the relative fuel consumption of the PHEV indicated in Figure 4-8 does not include electricity required to charge the vehicle, as the initial focus is on reducing petroleum consumption.

The 2016 values in Figure 4-8 are linearly interpolated from the 2009 and 2030 values. Recall that at 100% ERFC, the maximum potential reduction in fuel consumption is sought, while performance remains unchanged at 2006 values. All powertrains, including the conventional gasoline internal combustion engine, are expected to improve fuel consumption significantly if performance is held constant.

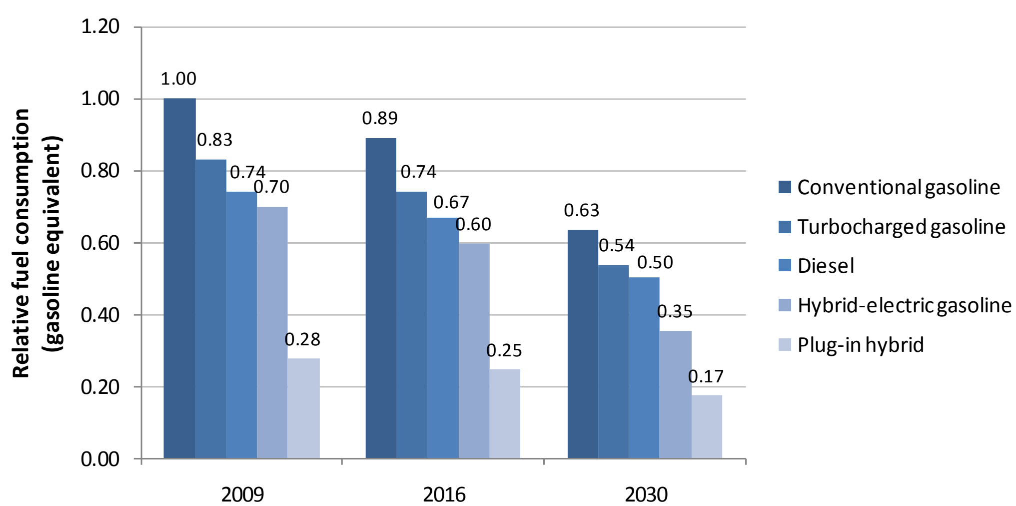
Today, alternative powertrains only garner some 6% of the U.S. market. To meet the proposed fuel economy standards, the market penetration of these alternative vehicles needs to increase and replace the relatively less efficient conventional gasoline vehicles.

Figure 4-8. Future fuel consumption improvements at 100% ERFC, by powertrain

(a) For cars



(b) For light trucks



4.4 2016 vehicle sales mix scenarios

Four approaches to meeting future fuel economy targets have been introduced – vehicle weight and size reduction, emphasizing fuel consumption reduction over horsepower or acceleration performance improvements, and turning to alternative powertrains. We now explore possible combinations of these options by constructing deterministic scenarios of the future average new vehicle fleet. Used in conjunction with studying historical trends, scenario analysis is a tool that helps one explore the range of possible solutions in an uncertain future. These scenarios are not intended as forecasts or predictions of the future, but are meant to illustrate the extent of necessary changes in response to the new CAFE mandate. The approaches are combined in a spreadsheet model, which considers the fuel-saving effect of each approach to determine the future sales-weighted average new vehicle fuel economy as the outputs. A screen capture of the model is shown in Appendix F.

Key assumptions made in the model are as follows:

- Based on the assessment of weight reduction approaches in Chapter 3, the maximum possible vehicle weight reduction by material substitution and vehicle redesign is 25% (430 kg) from today's average new vehicle by 2016, and 35% (600 kg) by 2030.
- We allow for downsizing by shifting sales away from larger and heavier light trucks to cars. The weight effect of this sales shift is distinct from the abovementioned approaches to weight reduction, although the net weight reduction will be reported. We assume that the share of light trucks in the domestic U.S. market will not decline below 20%. So as casual truck drivers diminish and return to using cars, core truck drivers will continue to occupy at least a fifth of the market. Since 1975, the historical low for the light truck share had been 17% in 1980. If downsizing is pursued, it is acknowledged that the required fuel economy in 2016 will be higher due to the attribute- or size-based feature of the CAFE standard. In 2030, we assume that this attribute-based feature of the standard is abolished. So automakers are no longer penalized for pursuing a downsizing strategy to gain fuel economy, and the target is fixed at 58 MPG.
- The weight-fuel consumption relationship for new vehicles is as described in Chapter 2. For cars, every 100 kg vehicle weight reduction leads to 0.39 L/100 km (adjusted) fuel consumption reduction in 2016, 0.31 L/100 km in 2030. For light trucks, every 100 kg vehicle weight reduction leads to 0.48 L/100 km fuel consumption reduction in 2016, 0.36 L/100 km in 2030.
- ERFC is initially fixed at 75% in the 2016 scenarios. This reflects an expectation that manufacturers will still offer some performance improvements, but to a significantly lesser degree in an effort to improve fuel economy. Recall that ERFC had been less than 50% over the past two decades, although it did reach 100% a decade prior. The effect of varying ERFC will be explored later.
- There is no predefined market penetration limits for alternative powertrains in the U.S., but the market shares of alternative powertrains are assumed to be proportionately fixed in order to constrain the solution space. In 2016, the ratio of turbocharged gasoline (Turbo gas) to diesel to HEV to PHEV is fixed at 6 : 2 : 2 : 0.1. In 2030, this ratio is updated to 6 : 2 : 2 : 1. These ratios are not intended to be precise predictions of the future fleet composition, but to reflect plausible market trends in light of stricter fuel economy regulations. Of the four alternative powertrains described, turbocharger technology is the least costly to introduce, although its fuel saving benefit is lower. Diesels offer the next best value proposition, but we expect sales in the U.S. to be similar to hybrids given diesel fuel prices, limited availability of low-sulfur diesel fuel, and negative image of diesel vehicles in the market (see Appendix D for an elaboration on the market potential for diesels. The relative cost of these powertrains was reviewed in Section 3.6.2). Finally, the share of PHEV is expected to remain small initially and then increase if much higher fuel economy is desired by 2030. Although supply-side constraints as well as constraints on market acceptance will certainly limit the rate of market penetration of different

powertrains, we leave this option unconstrained for now in the scenarios and observe the results.

- The market penetration of alternative powertrains is assumed to be the same for both cars and light trucks.
- Turbocharged gasoline vehicles are assumed to weigh the same as conventional gasoline vehicles. Diesel vehicles are assumed to weigh 5% more, HEVs with nickel metal hydride (NiMH) batteries 7% more, HEVs with lithium-ion batteries 8.5% more, and PHEVs 20% more. For the electric vehicles, much of the weight gain can be attributed to the added battery.

Four different scenarios of the new vehicle fleet that meet their respective 2016 targets are shown in Table 4-3, in contrast with the characteristics of the 2009 fleet. The targeted and achieved sales-weighted average fuel economy (CAFE)[15], which is based on the car-truck sales mix, is shown in the right-most column. The first three scenarios in Table 4-3 employ different strategies – 1a. aggressive vehicle lightweighting, 1b. aggressive vehicle downsizing, and 1c. aggressive market penetration of alternative powertrains. In each of these scenarios, the selected strategy is pursued to its assumed limits until the target is met. If insufficient on its own to meet the target, other options will be employed. Otherwise, all other options are kept unchanged in order to understand their individual effects on the average new vehicle fuel economy. Note that the average new vehicle weight reported in the third column of this table includes the effect of downsizing the vehicle fleet by shifting sales away from trucks to cars (indicated in the fourth column), as well as the weight reduction associated with ERFC. 75% ERFC includes some weight reduction, which explains why the weight declines in all scenarios, and not just in Scenario 1a. The final Scenario 1d depicts a scenario that combines some degree of all approaches in order to fulfill the mandate.

In the aggressive lightweighting Scenario 1a, the average new vehicle's curb weight has to decrease by 15%, or 270 kg, in order to meet the CAFE target of 32.8 MPG. This target is lower than the targeted 34.1 MPG because the market share of cars, as opposed to light trucks, remains unchanged at 51%. If aggressive downsizing is pursued instead (Scenario 1b), the market share of cars is pushed to the maximum of 80%. So 8 out of every 10 vehicles sold must be a car. However, the target becomes more stringent at 35.6 MPG and will not be met with downsizing alone, so vehicle weight is further reduced until the target is met. The final average new vehicle weight in Scenario 1b is 1,330 kg, which is even lower than that in the lightweight Scenario 1a. This final weight figure includes the effect of a downsized fleet. Of the total weight removed, about a third comes from increasing the market share of cars from 51% to 80% (downsizing), and the remaining two thirds from lightweighting the vehicle using alternative materials or by vehicle redesign. Given the size-based structure of the standard, aggressive downsizing is therefore an unlikely scenario. In both Scenarios 1a and 1b, the share of alternative powertrains in the market remains unchanged.

[15] Readers are reminded of the difference between EPA adjusted vs. NHTSA CAFE fuel economy, as explained on page 14.

Table 4-3. U.S. passenger vehicle sales mix scenarios that fulfill the 2016 fuel economy mandate

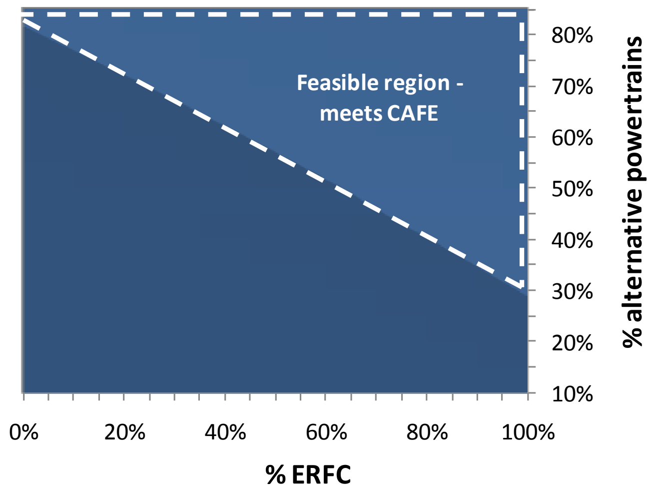
Scenarios	% ERFC	% weight reduction (average new vehicle weight in parenthesis)	% car (vs. light trucks)	% Market share by powertrains						CAFE, MPG
				Conv. gas	Turbo gas	Diesel	HEV	PHEV	Total alt. powertrain	
2009	-	-- (1,730 kg)	51%	94%	4%	0%	2%	0.0%	6%	28.8
2016 scenarios										
1a. Lightweight	75%	15% (1,460 kg)	51%	94%	4%	0%	2%	0.0%	6%	32.8
1b. Downsize	75%	23% (1,330 kg)	80%	94%	4%	0%	2%	0.0%	6%	35.6
1c. Alt. powertrain	75%	6% (1,630 kg)	51%	62%	23%	8%	8%	0.4%	38%	32.8
1d. Combination	75%	12% (1,520 kg)	65%	70%	18%	6%	6%	0.3%	30%	34.1

If there are more alternative powertrains in the market, both weight and size need not decline as much to meet the 2016 mandate. In Scenario 1c, 38% of all vehicles sold in 2016 must be fuel-saving alternatives to the conventional naturally-aspirated gasoline powertrain (Conv. gas), mostly downsized and turbocharged gasoline engines, in order to meet the target of 32.8 MPG.

Finally, Scenario 1d is selected to illustrate the degree of changes needed if advancement is made on all fronts. In this scenario, vehicle performance improvements are similarly curbed, vehicle weight declines by 12%, a majority (65%) of vehicles sold are cars, and 30% of the market must use alternative powertrains. Despite this moderation from the values presented in Scenarios 1a-c, these are still marked differences from today's new vehicle fleet. In this scenario, hybrid sales grow at a compounded annual rate of 27% per annum over 7 years (2009-2016), which is very aggressive. In contrast, the most rapid growth of diesel penetration in European passenger cars took place between 1997-2004, at a compounded rate of 12% per annum (based on data from European Automobile Manufacturers' Association, ACEA [43]). Other scenarios with less aggressive sales mix changes exist, but they would demand greater weight and/or size reductions.

The ERFC in these four 2016 scenarios had been fixed at 75%, meaning that more of future vehicle technical efficiency improvements are dedicated to reducing fuel consumption, rather than offsetting performance improvements. When ERFC is varied, the results reveal strong sensitivity to this parameter. Figure 4-9 portrays the sensitivities of two variables – ERFC on the horizontal axis, and the market share of alternative powertrains on the vertical axis. In this figure, the market share of cars, as opposed to trucks, is fixed at 65%, and there is no additional weight reduction over and above that included with the degree of ERFC. Points that lie within the triangle bounded by the dashed line meet the mandate, meaning the average new 2016 vehicle achieves at least 34.1 MPG, whereas points below will not.

Figure 4-9. Two-way sensitivity plot – points within the triangle achieve ≥34.1 mpg in 2016



In general, reliance on alternative powertrains becomes less necessary if car buyers can accept less performance improvements in the future. In the scenario depicted in Figure 4-9, at 100% ERFC, alternative powertrains must capture 30% of the market within the next 6 years. This market penetration must be greater if ERFC is lower and more performance improvement is desired. At 0% ERFC, the historical average since 1990, aggressive rates of powertrain technology deployment becomes necessary to fulfill the new mandate. If steady improvement in fuel economy is sought, the historical performance trend cannot continue. Auto manufacturers can no longer forgo fuel economy improvements and continue to offer ever faster and higher horsepower vehicles.

4.5 2030 vehicle sales mix scenarios

Suppose a doubling of the fuel economy of today's vehicles is eventually desired, and auto manufacturers are allowed more lead time to meet these more demanding standards. Another set of scenarios that achieve 58 MPG by 2030 are shown in Table 4-4, which continue the mileage improvement steadily over a longer timeframe. It is acknowledged that there will be greater uncertainties looking this far ahead, and the intended target year for doubling the fuel economy is not a precise estimate. However, we would like to explore scenarios that achieve this in around two decades.

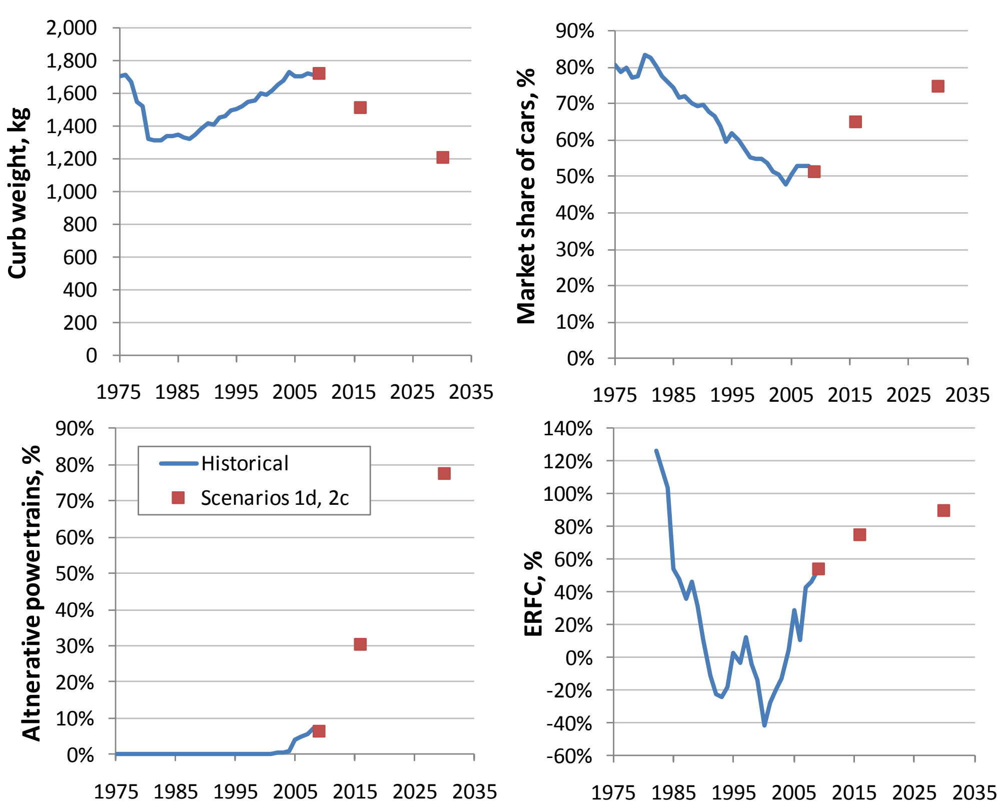
ERFC is again locked, but this time at 90% (from 2010), assuming greater effort to reduce fuel consumption. As expected, the required weight and size reductions are greater in order to meet this factor-of-two target, and fewer new vehicles will continue to use conventional gasoline powertrains. Recall that we assume a greater proportional share of PHEVs in 2030. Given this longer time frame, the deployment rate of hybrid powertrains is almost halved – 13% p.a. in combinatorial Scenario 2c up to 2030, compared to 27% in Scenario 1d in 2016. That is, hybrid (HEVs only) sales grow at a rate of 14% per year from 187,000 in 2009 to 2.6 million in 2030 in Scenario 2c, as opposed to 27% per year to 988,000 in 2016 in Scenario 1d.

Table 4-4. U.S. passenger vehicle sales mix scenarios that double the fuel economy by 2030

Scenarios	% ERFC	% weight reduction (average new vehicle weight in parenthesis)	% car (vs. light trucks)	% Market share by powertrains						CAFE, MPG
				Conv. gas	Turbo gas	Diesel	HEV	PHEV	Total alt. powertrain	
2009	-	-- (1,730 kg)	51%	94%	4%	0%	2%	0.0%	6%	28.8
2030 scenarios that double the 2009 average fuel economy										
2a. Lightweight and downsize	75%	40% (1,040 kg)	80%	51%	27%	9%	9%	4%	49%	57.6
2b. Alt. powertrain	75%	21% (1,370 kg)	65%	0%	54%	18%	18%	9%	100%	57.6
2c. Combination	75%	30% (1,220 kg)	75%	22%	42%	14%	14%	7%	78%	57.6

To illustrate the degree of changes required, Figure 4-10 contrasts historical values of the new vehicle fleet characteristics, with those in these scenarios 1d and 2c. These are scenarios that employ a combination of all approaches to fulfill the standards. We see that the required changes counter historical trends, and the rates of technology improvement imposed by this longer-term mandate will not be trivial. The targets will require making significant changes to new vehicles starting soon.

Figure 4-10. New vehicle fleet characteristics – historical and a future "combination" scenario



4.6 The importance of lead time in setting fuel economy standards

The future vehicle scenarios presented suggest that in addition to the magnitude, the timing of more stringent fuel economy standards is also important in determining the feasibility of meeting the requirements. Standards that are set well in advance allow time for (a) new vehicle technologies be developed and made robust, (b) automakers to plan and incorporate these requirements into their product portfolio with adequate lead time, and (c) for the improved vehicles to be deployed into the market. Each of these steps is nontrivial and one should consider the necessary timescales for vehicle development, production, and marketing. The timing of the standard should therefore consider: How long does it take to develop a new vehicle powertrain, or to redesign and incorporate a lightweight component? Can automakers refresh their vehicle portfolio in time to meet the targets? What are reasonable rates of market penetration for hybrids?

Through conversations with practitioners in the auto industry and by reviewing the literature, it is estimated that the time taken to develop a new vehicle architecture with a new appearance and powertrain is around 3 to 5 years. This is assuming that the new technologies to be incorporated into vehicles are already commercially available. The development time includes the stages of concept generation, product planning, product engineering, and process/manufacturing engineering, until the start of production. There has been effort to compress this development time to gain competitiveness. For example, General Motors is reported to have reduced this cycle time to around 18 months, in part with use of information technology to facilitate collaboration with suppliers. [69] Cycle time is also compressed by having multiple vehicles share the same platforms, so that the basic architecture of new vehicles, such as the chassis, steering and suspension components, need not be reworked.

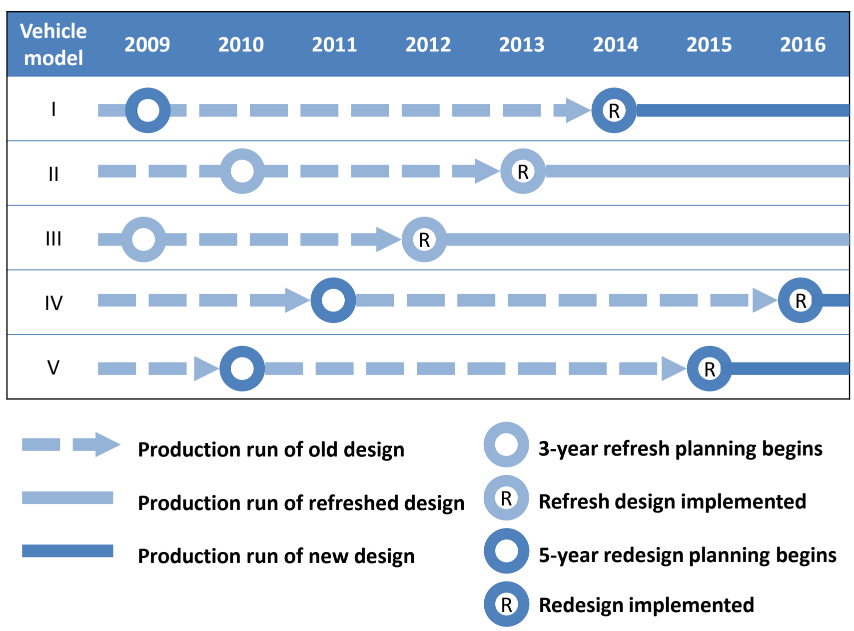
Despite accelerated vehicle development cycles, there are several reasons why it is still difficult to expect significant changes to the new vehicle fleet within the next 6 years. Firstly, automakers do not always start with a clean slate and work on brand new designs for all their product lines, although the fuel economy improvement potential is greater. Making incremental changes within a platform is more typical, and vehicle parts are often carried over because they have undergone necessary tests and validation to establish reliability or durability. This vehicle "refresh" process to make these more minor changes, facelifts, or upgrades occurs mid-cycle and requires less time – around 2 to 3 years. [4] However, these less extensive vehicle modifications, such as minor changes to appearance, moderate powertrain upgrades, and small changes to the vehicle's features or safety content, would not reduce fuel consumption significantly.

Secondly, for automakers with multiple product lines, not all vehicle programs are due for redesign or refresh at the same time. A typical vehicle model remains in production for 4 to 5 years between major redesigns. [70] Figure 4-2, the chart depicting the historical weight and size of a new Toyota Corolla model reveals this, where one can see how these characteristics tend to remain fairly level over 5-year time periods. So, each manufacturer's several vehicle programs would be at different stages of the 4- to 5-year production run. This is in part to optimize use of limited engineering resources within the company, which are spread over multiple vehicle programs over time. As such, a fraction of an automaker's portfolio will include models that just started production in 2010, and are not yet up for redesign until at least 2014.

On a related note, vehicles portfolios in model year 2011, and likely 2012 as well, are already locked in. During the vehicle development cycle, vehicle attributes like its size, performance, drivetrain, and other major technology options are set during the first 6 to 12 months. There is little redesign flexibility after the design freeze, and it is difficult to expect making changes to the vehicle production line-up too soon.

These constraints can be illustrated in the following example: assuming that it takes 5 years to redesign a new vehicle model, 3 years to refresh a vehicle, a vehicle production run lasts 5 years, and that an automaker's distribution of vehicle models along the production cycle is even, the rough product plan would look like that depicted in Figure 4-11. This schematic shows that if an automaker or OEM begins to overhaul its vehicle portfolio from 2009 to achieve greater fuel economy under these constraints, all of its vehicle models can embody new or refreshed designs by year 2016. However, only 60% can contain brand new, more technically complex designs that require more time to implement, such as vehicle weight reduction greater than 10%, or conversion to diesel and hybrid vehicles. The rest can only employ less complex options, including moderation of performance improvements by tuning the engine, or conversion to a turbocharged, downsized engine. Since the more complex changes, or a vehicle redesign take 5 years to develop, the earliest year of introduction into the market is 2014 (5 years from 2009 when the standards were first proposed). The less complex changes can be introduced during the refresh cycle, but only from 2012.

Figure 4-11. Illustrative OEM product plan, showing time taken to update the entire vehicle portfolio



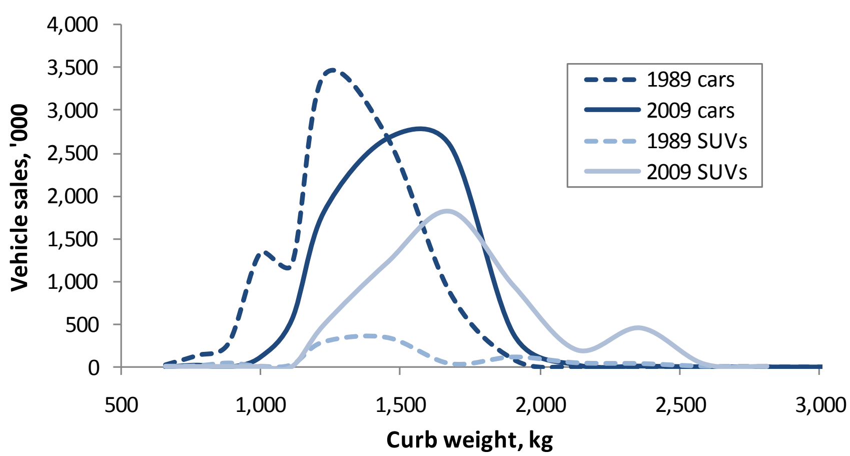
Given these reasons, we estimate that automakers would need at least 8-10 years to budget and plan their complete vehicle portfolios. Expecting automakers to update all their product lines within the next 6 years in order to fulfill the new regulations would be a departure from the norm, demand an expansion of available resources, and increase risks.

In addition to the time constraints in developing and launching new vehicles, there are also demand-side time constraints in the commercialization of new vehicle offerings, especially those that embody new technologies like plug-in hybrid-electric powertrains. These vehicles need time to gain consumer acceptance through their initial deployment into the market. Customer take rates would certainly be inhibited if the cost of new technologies is high. While we are not including demand modeling in the scope of our work, we would like to highlight two other time scale-related subtleties concerning the diffusion of new technologies. Both have to do with the concept of the "average" new future vehicle: -

First, there is added time delay in reducing the average vehicle's fuel consumption, because the average new vehicle sold does not embody the leading-edge, best-in-class fuel-saving technology. For instance, given that major automakers have multiple product lines, each at different points along their production run, engines in vehicles sold in any year could be brand new engine designs, recent designs, or older designs. So the average new vehicle's fuel consumption always lags those of the newest and best available powertrain technology, likely by at least a few years.

Next, the changes described in the scenarios are for the sales-weighted average new vehicle. So all new vehicles sold, as a whole, must evolve in order to meet the standards. Figure 4-12 shows the distribution of curb weights for new passenger cars and SUVs sold in the U.S. in 1989 and 2009, which shows the spread of vehicles by weight, and the increase in weight over time. If there are a few vehicle models offered in the market that weigh more than the average weight depicted in any of the scenarios, then more vehicles that weigh less must be sold in order to make up the difference. Along the same line, introducing new and more fuel-efficient vehicles in small production volumes will not be sufficient. These vehicles must sell in higher volumes to make a difference in the average fuel economy.

Figure 4-12. Distribution of curb weights for new U.S. passenger cars and SUVs sold in 1989 and 2009, data source: [2]



Considering these production and deployment realities, CAFE targets that are defined at least a decade in advance would be helpful for the auto industry, since the scenarios suggest that large increases in average fuel economy will require companies to implement substantial changes across essentially their entire product lines. This echoes a similar recommendation by Plotkin [71], that regulators should allow 10-12 years for automakers to achieve targets that can be met by commercially-ready technology, and possibly more time if consumer preferences for new technologies remain uncertain.

4.7 Chapter summary

Setting minimum fuel economy standards for future new U.S. passenger vehicles is a step in the right direction to reduce the nation's fuel use and greenhouse gas emissions. In this chapter, we explored the magnitude, timing, and combinations of technical changes in vehicles, including vehicle weight and size reduction, that are necessary to meet new standards in year 2016 and 2030 by studying scenarios of the future new vehicle fleet. The scenarios presented reveal these insights:

1) The new 2016 fuel economy standards in the U.S. are aggressive. The targets can be met, but will require significant changes in vehicle technology starting soon. To meet the targets, future vehicles need to be lighter and are more likely to incorporate alternative powertrains. In addition, vehicle acceleration and horsepower performance will not be able to improve significantly, which is counter to the historical market trend.
2) There are tradeoffs to be made between using these different approaches. If aggressive lightweighting is not pursued, or if greater performance improvements are sought, this must be achieved by introducing more vehicles with more fuel-efficient powertrains. The response will require combining all these approaches, and taking into account tradeoffs to be made among them.
3) Given the attribute- or size-based feature of the CAFE standard, automakers are discouraged and are unlikely to pursue vehicle size reduction as a strategy to improve fuel economy. This is unfortunate, as the potential for U.S. vehicles to downsize is high, and downsizing can alleviate the reliance on more costly weight reduction and alternative powertrain technologies. However, proponents continue to argue that this feature of the standard is more equitable for domestic manufacturers with larger vehicle lines and promotes safety.
4) Finally, the challenge of meeting the fuel economy targets is defined not only by the magnitude, but the timing as well. The lead time given for automakers to meet the new mandate is important, as it affects the viability of the solutions employed. A single new vehicle program takes a few years for design, development, and production planning. Changing the entire vehicle portfolio would require at least 8-10 years. It also takes time for new vehicle technologies to gain customer acceptance and penetrate the market. More stringent targets in the near-term, like the newest set of targets announced for years 2012-2016, are particularly challenging because a rapid rate of technology deployment becomes necessary. Increases in the standards that are announced further in advance, such as doubling the fuel economy by 2030, are more feasible, predictable and allow the auto industry to better plan and respond appropriately.

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5 VEHICLE FLEET FUEL SAVINGS

Chapter 5 introduces a U.S. vehicle fleet model to help quantify the annual fuel savings that can result from the CAFE program, part of which is credited to vehicle weight reduction. The fleet model captures the stock of vehicles on the road each year, and the effect of lighter, more fuel-efficient vehicles entering the fleet, as well as heavier, older vehicles retiring from the fleet.

5.1 The importance of a dynamic, vehicle fleet-level perspective

The value of the appropriate system perspective for a product has been alluded to in the first chapter of this thesis. In particular, it is useful to examine the evolution of the vehicle fleet over time for several reasons:

1) It is observed that it takes time for lighter and more fuel-efficient vehicles to gradually penetrate the existing vehicle fleet and make an impact on fleet fuel use. Following the oil crises in the 1970s, vehicle weight and fuel consumption both declined rapidly (see Figure 1-1 and Figure 1-2) during the latter half of that decade. However, fleet fuel use only started dropping slightly from 1978 onwards, suggesting a lag time and a dampening effect on the fleet-level;
2) Similarly, it takes time for retiring vehicles and scrap material to exit the fleet, which could constrain the amount of recycled/secondary material available for new vehicles. So there are implications on material recycling and scrap availability;
3) The energy intensity of material processing is another time-varying element that has been declining historically. These efficiency improvements are expected to continue into the future and would lower the energy demand during the auto material processing phase.

So a dynamic (versus static) and vehicle fleet system-wide perspective allows one to explore these evolving changes, and estimate the magnitude and timing of benefit more accurately going into the future. The fleet-level analysis reveals how much, how soon, and how transportation energy savings can be achieved through vehicle weight reduction.

The latter two effects will be explored in detail in Chapter 6. Now, we begin by describing the structure of the vehicle fleet model, which is designed to estimate the annual fuel use by the vehicle fleet.

5.2 Vehicle fleet model

There are about 250 million passenger vehicles being driven on U.S. roads today. Over the past 5 years, 10 to 16 million new vehicles entered the fleet each year, while 10 to 14 million older vehicles were retired annually. A spreadsheet-based fleet model that was originally developed at MIT by Anup Bandivadekar [68] in our research group has been further developed and used to model the annual stock of cars, SUVs and other light trucks being driven on the roads, or the “vehicle parc”, based on assumed vehicle sales and scrappage rates. With this model, one is able to determine the age of vehicles within the fleet, as well as the number of vehicles, by year of production, that leave the fleet every year from 1975 up to 2030.

Inputs to the model are annual vehicle sales and scrappage from 1975-2030. Historical sales data were obtained from the U.S. Environmental Protection Agency. [2] Projecting ahead, new vehicle sales are assumed to recover to 16.2 million by 2014, which is the short-term forecast of the U.S. market by R. L. Polk & Co. in 2009, given the current economic conditions. [72] Subsequently, it is assumed that new vehicle sales will grow at a rate of 0.8% per year until 2035, in tandem with the expected U.S. population growth.

Prior to 2008, historical vehicle scrappage is estimated by using a logistic function and assumed median lifetimes to characterize the survival rate of vehicles, or the fraction of vehicles remaining in-use within the vehicle fleet:

$$r(t) = 1 - \frac{1}{\alpha + e^{-\beta(t-t_o)}}$$

Where,

$r(t)$	=	Survival rate of vehicle at age t;
α	=	Model parameter, set to 1;
β	=	Model parameter that determines how quickly vehicles are retired. A fitted value of 0.28 is used for cars, and 0.22 for light trucks;
t	=	The age of the vehicle, which is the difference between the calendar year of interest and its model year; and
t_o	=	Median lifetime of the vehicle.

Estimates of the median vehicle lifetimes (t_o) for model years (MY) 1970, 1980 and 1990 are obtained from Oak Ridge National Laboratory’s Transportation Energy Data Book (TEDB) [1], and linearly interpolated for the years in between (see Figure 5-1). For MY1990-2008, the model assumes that the median vehicle lifetime remains at 16.9 years for cars, and 15.5 years for light trucks, including SUVs. Figure 5-2 shows the survival rate for cars only, arising from the assumed median lifetime of 12 years for a MY1975 car, and 16.9 years for MY1990-2008 cars.

Figure 5-1. Assumed median vehicle lifetime

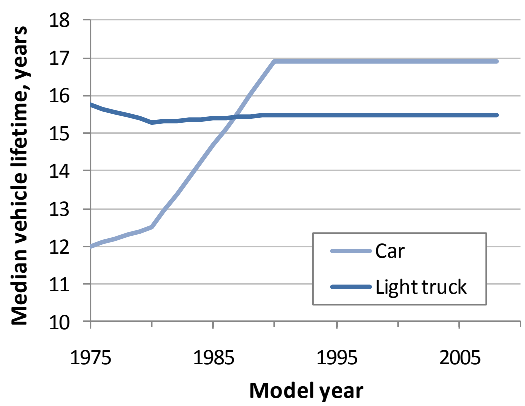
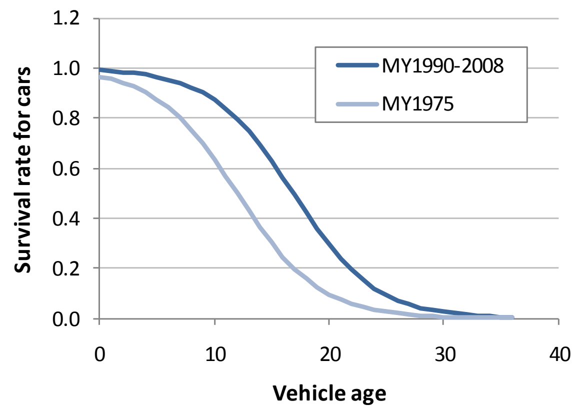


Figure 5-2. Survival rate for MY1975 and MY1990-2008 cars



From 2008 onwards, scrappage is fixed at 80% percent of sales, which is based on the observation that scrappage tends to be around 70-80% of sales.[16] We also assume that the scrapped mix of vehicles by segment (cars, SUVs, other light trucks) is the same as the sales mix of vehicles by segment in every calendar year. In addition, scrappage in each year is distributed among the different model years following the distribution that was observed in 2007, i.e. more middle-aged vehicles tend to be scrapped in a given calendar year.

Figure 5-3 shows the U.S. light-duty vehicle sales and scrappage used in the model, and Figure 5-4 shows the resulting size of the vehicle parc over time. The modeled vehicle parc, or the number of vehicles in use/operation, compares well with other estimates of this figure by The Polk Company and the Federal Highway Administration (FHWA, via [1]), as shown in Figure 5-5. The modeled number of vehicles in use is also checked to not exceed the estimated vehicle ownership saturation level of 850 vehicles per 1,000 people, based on income and population density [73], which is calculated from the projected U.S. population published by the U.S. Census Bureau.[74]

[16] With the exception of the past two years, where scrappage equaled and then exceeded sales in 2008 and 2009. This phenomenon is due to depressed sales in the recent years, and is not expected to persist in the long run.

Figure 5-3. Model inputs: U.S. passenger vehicle sales and scrappage, 1975-2030

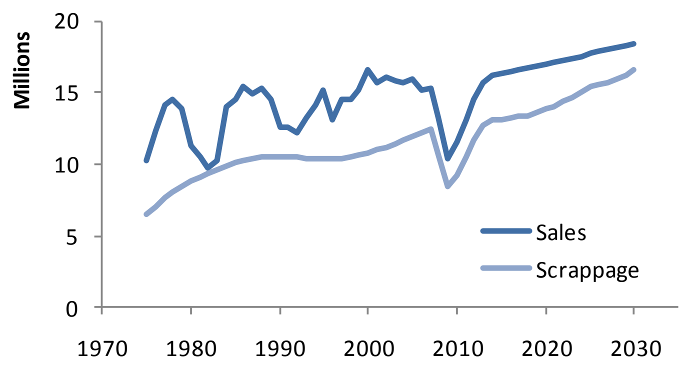


Figure 5-4. Model output: U.S. passenger vehicle stock by segment, 1975-2030

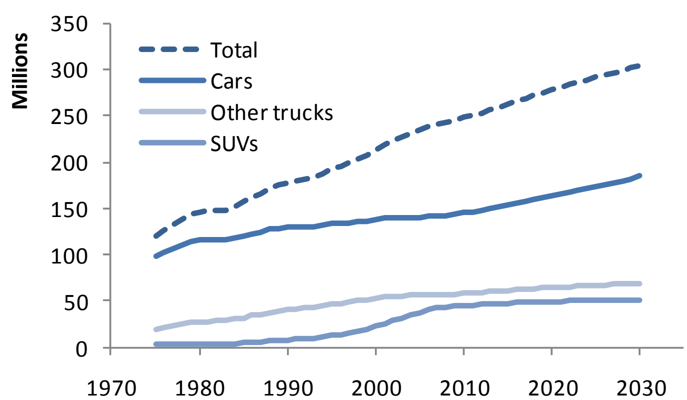
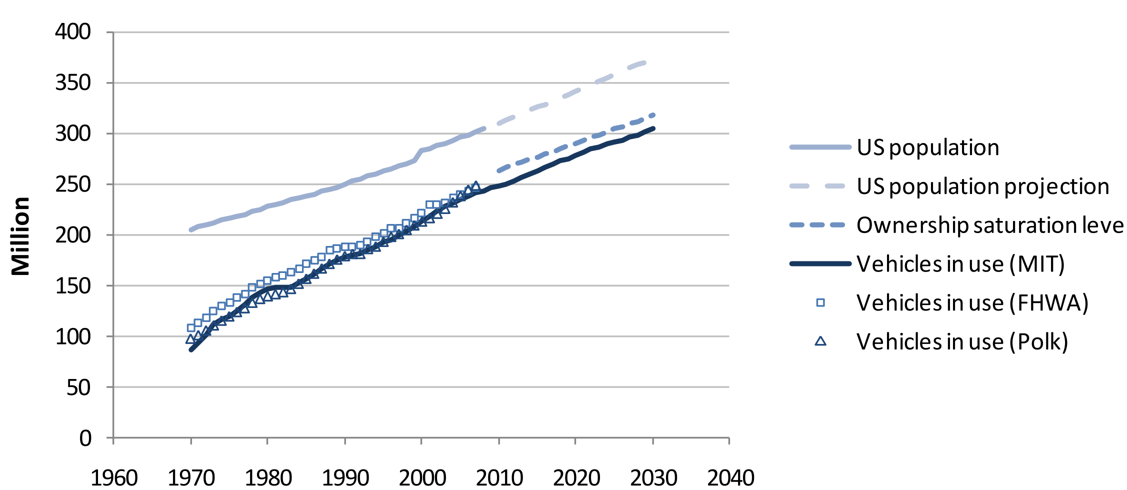


Figure 5-5. Comparison of modeled passenger vehicle stock with other estimates

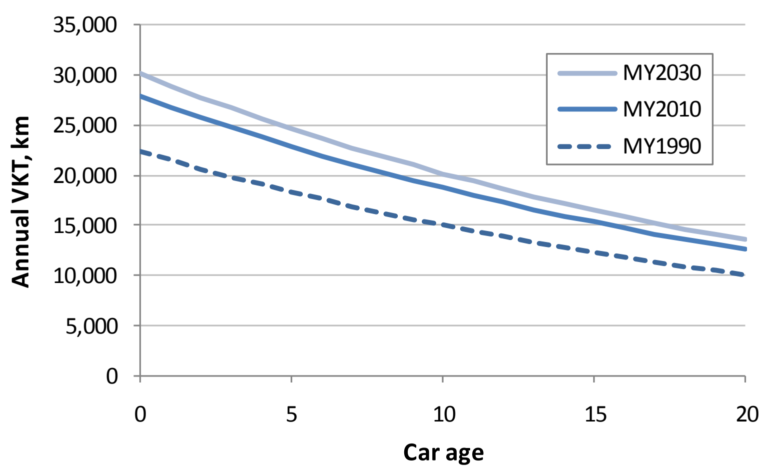


5.3 Results: Fuel use savings

Now that the vehicle fleet model reveals the vehicle stock by vintage, i.e. the distribution of vehicles on the road by model year (number of vehicles), we can combine this with the vehicle-kilometers traveled (VKT in km) and (adjusted, or "real-world") fuel consumption of new vehicles (L/100 km) to obtain the annual fuel use by the entire vehicle fleet from today to 2030 (billion liters).

The assumed annual vehicle kilometers traveled (VKT) is based on data from Oak Ridge National Laboratory's TEDB [1] and assumptions made by Bandivadekar [68]. It is assumed that the annual VKT declines with vehicle age, and that for MY1990, 2010 and 2030 cars are shown in Figure 5-6. A MY2010 car is driven around 351,500 km (227,200 miles) over its lifetime, and a light truck 295,200 km (183,400 miles). VKT has risen over the years, driven upwards by investments and growth in highway infrastructure, low gasoline prices, income growth, and demographic trends like greater labor force participation. Note that we did not account for a rebound effect[17], or the situation where improved fuel economy in future new vehicles reduces the fuel cost of driving and leads to increased vehicle miles traveled. So future VKT is independent of improvements in fuel economy.

Figure 5-6. Annual vehicle kilometers traveled for cars from different model years



The modeled historical fleet fuel use in gasoline-equivalent billion liters is compared against the fleet's petroleum consumption data reported in TEDB [1] in Figure 5-7. They are found to be similar. TEDB's data is slightly higher at times, partly because it includes fuel consumed by vehicles weighing up to 10,000 lb in gross vehicle weight, whereas the EPA sales data that we use only includes vehicles up to 8,500 lb.

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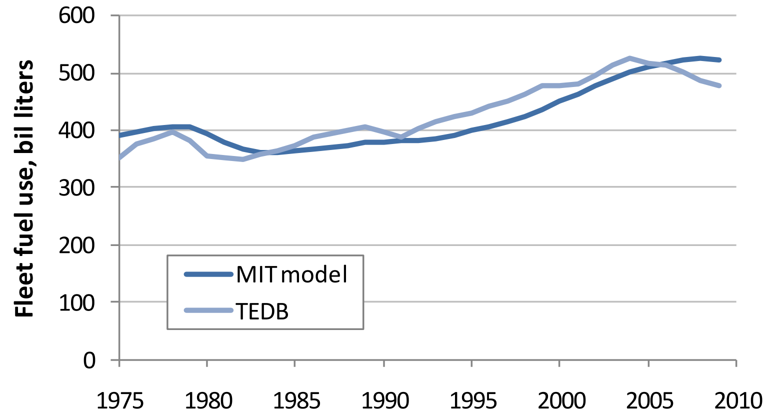
[17] Estimates of this effect vary from 10-30%. That is, a percentage decrease in the fuel needed to drive a certain distance will lead to an increase of 0.1-0.3 times the same percentage in driving.

Figure 5-7. Comparing modeled passenger vehicle fleet fuel use with data from the Transportation Energy Data Book



The following inputs, which are prescribed by the future vehicle sales mix scenarios introduced in the preceding chapter, are entered into the model for subsequent years from today-2030:

- New vehicle sales mix by segment (cars, SUVs, other light trucks) and powertrain (conventional or naturally-aspirated NA SI gasoline, turbocharged gasoline, diesel, HEV, PHEV);
- Average new vehicle fuel consumption, by segment and powertrain.

The fleet fuel use under the different scenarios are similar, since the average new vehicle fuel economy in 2016 and 2030 for all scenarios are close to 34.1 MPG and exactly 57.6 MPG respectively. As such, we will only describe scenarios 1d for 2016, and 2c for 2030 here. Both of these "combination" scenarios employ several approaches – lightweighting, downsizing and alternative powertrains – to achieve the targeted fuel economy. The vehicle sales mix by segment and powertrain over time for these scenarios are depicted in Figure 5-8 nd Figure 5-9, and the resulting average new vehicle fuel consumption and weight in the next figure. For the years in between, an S-shaped growth curve could be defined, but we have simply assumed a linear rate of change.

Figure 5-8. Passenger sales mix by segment under scenarios 1d and 2c

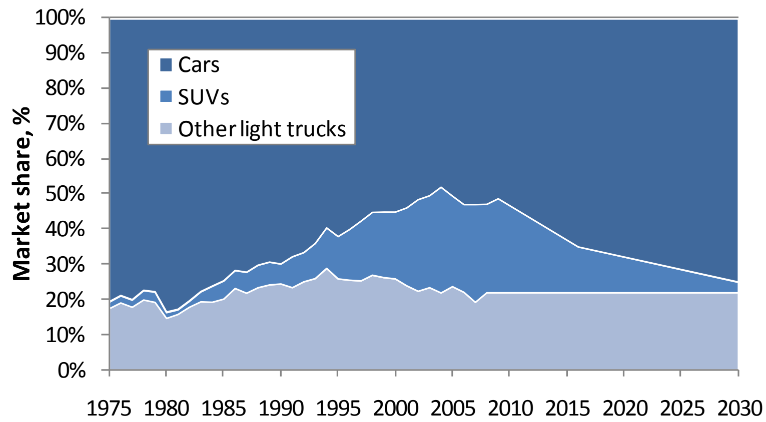


Figure 5-9. Passenger vehicle sales mix by powertrain under scenarios 1d and 2c

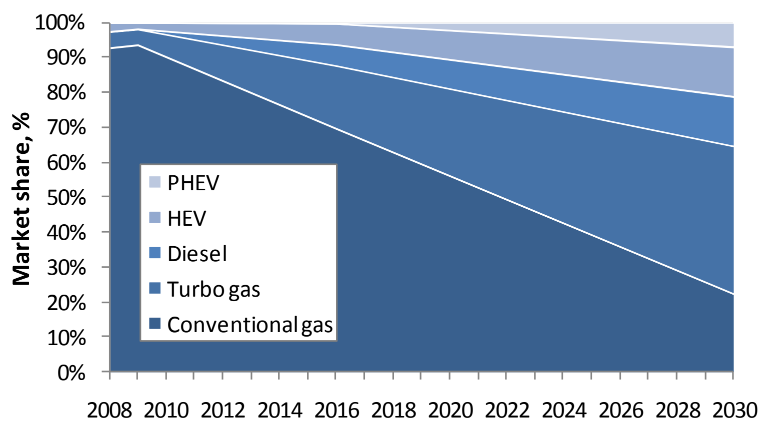
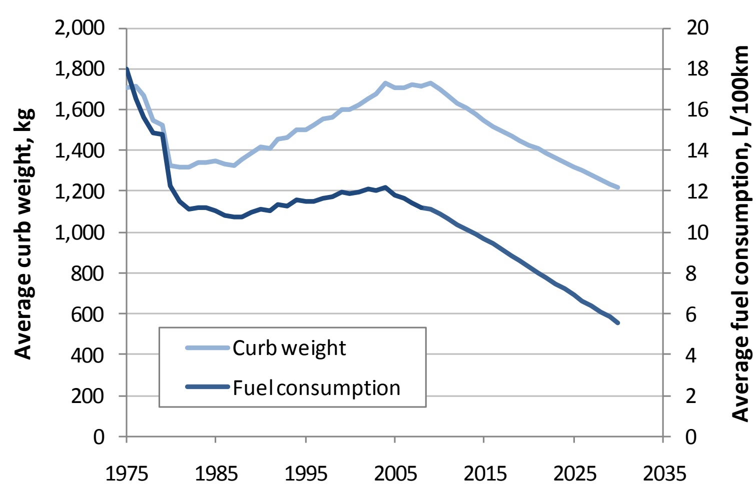
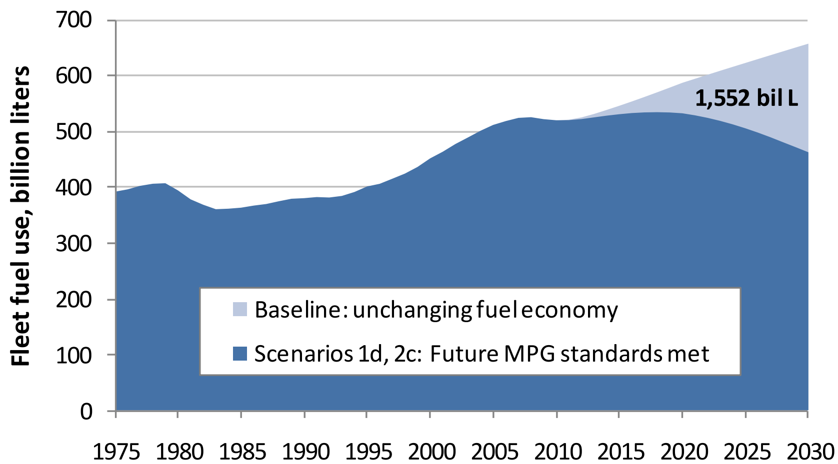


Figure 5-10. Average new vehicle curb weight and (EPA adjusted) fuel consumption under scenarios 1d and 2c



Based on these inputs, the resultant fleet fuel use is finally shown in Figure 5-11. This is compared against a “business as usual” baseline of unchanging fuel economy, weight, and other vehicle fleet mix characteristics from today, assuming no CAFE rules are in place. We find that introducing CAFE standards in 2016 and the factor-of-two fuel economy target by 2030 can realize significant cumulative fuel savings of 1,552 billion liters over this period. Through 2020, fleet fuel use will not decrease, but will remain level despite growth in the vehicle stock and VKT.

Figure 5-11. Annual U.S. passenger vehicle fleet fuel use



6 AUTOMOTIVE MATERIAL PRODUCTION ENERGY AND RECYCLING IMPACTS

Chapter 6 looks carefully into the material production energy impact of producing lighter-weight and more fuel-efficient vehicles. It takes into account the evolving material composition of new vehicles, and efficiency improvements in material processing over time – traits of a more comprehensive, temporal life-cycle assessment. Key automotive material flows through the vehicle fleet are also captured to shed some light on the implications of weight reduction on the secondary material supply from retiring automobiles.

6.1 Methodology and scope

A spreadsheet-based model has been developed to track the annual material stocks flowing in and through the U.S. passenger vehicle fleet historically, with the capability of evaluating the future scenarios described in Chapter 4. These projections are built up by combining (a) a sub-model of the number of vehicles in the in-use vehicle fleet by age in each year; with (b) the average material content in new vehicles sold in each model year. The stock and flows of materials used in automobiles are direct derivatives of these inputs.

An energy assessment of the corresponding automotive material production is also carried out by combining the above with (c) the energy use per unit of material produced by year. These are the energy inputs required to produce materials embodied in vehicles. It comprehends material extraction and processing steps, but the transportation of materials and assembly of the vehicle have been excluded.

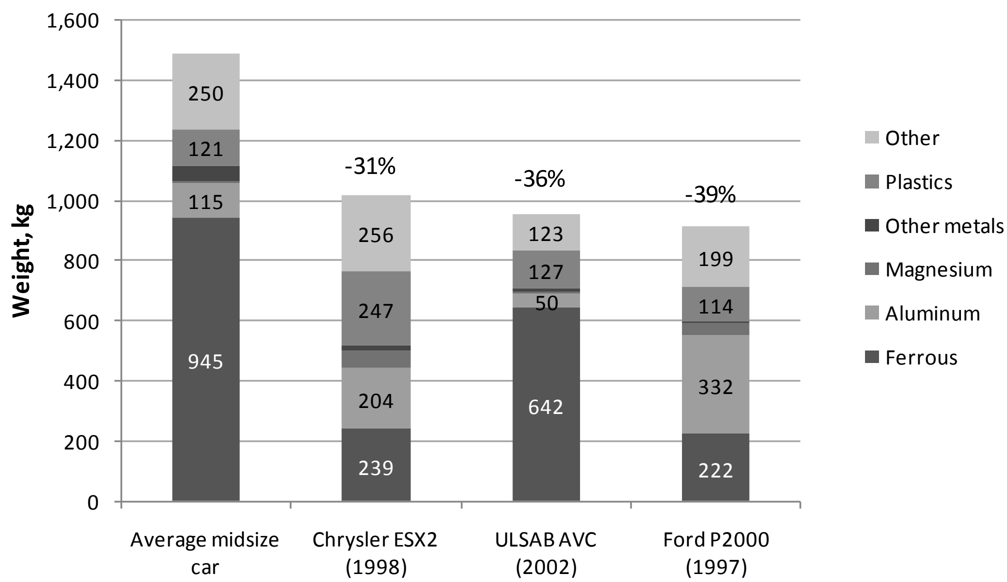
Earlier, the first sub-model on characterizing the in-use vehicle fleet has already been introduced in Chapter 0. Let us now look into the material composition of future vehicles, and the energy intensity of automotive material production.

6.1.1 Material composition of future vehicles

Earlier in Chapter 3, we reviewed the material composition of a current new U.S. vehicle. Looking ahead, what is the expected material content of a future vehicle? This depends on the degree of lightweighting, choice of lightweight materials, and the powertrain of the future vehicle.

Regarding the first two factors, we examine concept lightweight vehicles to obtain a sense of the material content. Figure 6-1 shows the material breakdown for three concept lightweight vehicles, all midsize sedans – Chrysler's plastic-intensive Dodge Intrepid ESX2, the UltraLight Steel Auto Body's-Advanced Vehicle Concept (ULSAB-AVC), and the aluminum-intensive Ford P2000. These are contrasted against the estimated material breakdown of today's midsize sedan, and the resultant percentage weight savings for each concept vehicle from this reference is indicated. The material use within the reference vehicle is estimated by applying the compositional breakdown of an average 2007 vehicle as reported in the Transportation Energy Data Book (see Figure 3-2) to the average curb weight of a midsize sedan sold in the same year. As expected, the material composition of a future lightweight vehicle could vary, depending on the choice of lightweight materials.

Figure 6-1. Material breakdown of various concept lightweight midsize sedans

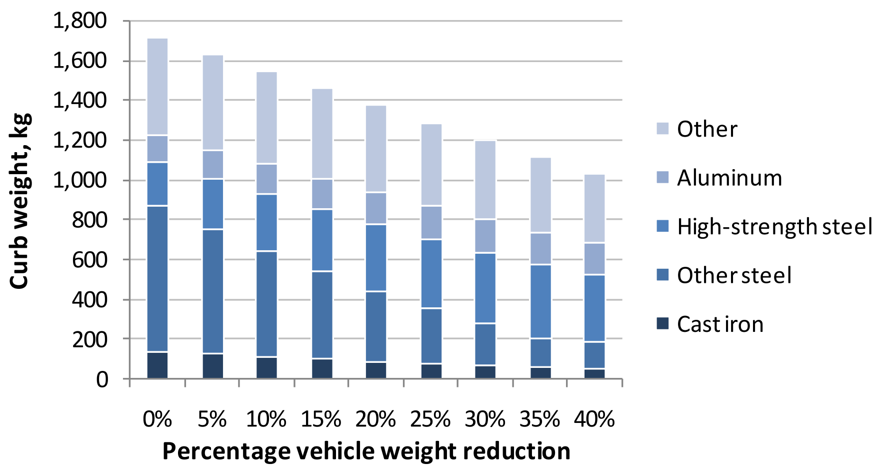


The future lightweight vehicle is likely to use a combination of available lightweight materials. The material choice will be based on cost of both raw material and processing. From Chapter 3, we have learnt that aluminum and high-strength steel (HSS) are more cost-effective at large production volume scales, and their increasing use in vehicles is likely to continue. Cast aluminum is most suited to replace cast iron components, stamped aluminum for stamped steel body panels, and HSS for structural steel parts. Polymer composites are also expected to replace some steel in the vehicle, but to a much smaller degree given high cost inhibitions. Carbon fiber composites are likely to remain in low-volume applications.

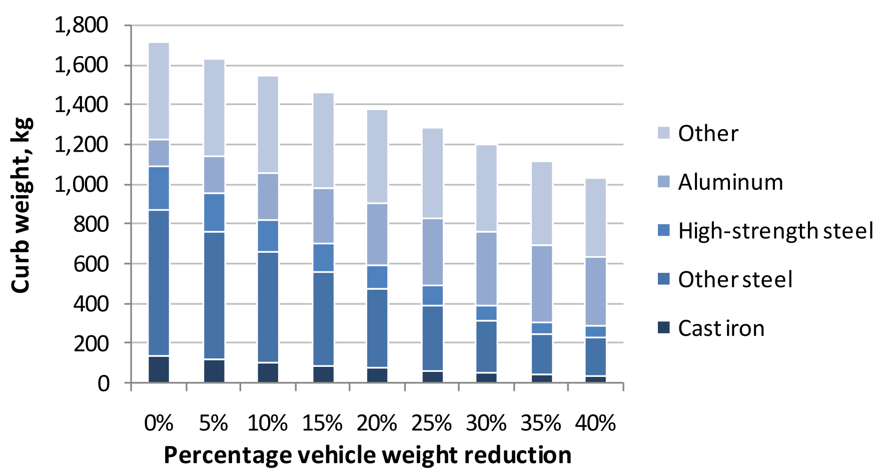
With this assessment, we will assume two likely material pathways for vehicle lightweighting going into the future – one HSS-intensive, and one aluminum-intensive. So it is possible to achieve up to 40% total vehicle weight reduction following either pathway. The material breakdown of the future average conventional gasoline HSS- or aluminum-intensive vehicle at different degrees of weight reduction is shown in Figure 6-2. Both pathways are based on concept vehicles. For the HSS-intensive vehicle, we use the recent European SuperLIGHT car body concept and the weight-optimized ULSAB-AVC for the rest of the vehicle to determine its material breakdown at 40% weight reduction. This vehicle relies primarily on innovative use of higher-strength steel, but also employs greater use of aluminum to reduce its weight. The material breakdown of today's average new vehicle is shown at 0% weight reduction. The values in between are simply linearly interpolated. Similarly, the material breakdown of the aluminum-intensive vehicle which weighs 40% lighter follows that of the Ford P2000 concept car. At this level of weight reduction, aluminum makes up a third of the vehicle by mass, compared to 8% today.

Figure 6-2. Material breakdown of a future lightweight vehicle, by degree of weight reduction

(a) High-strength steel-intensive pathway



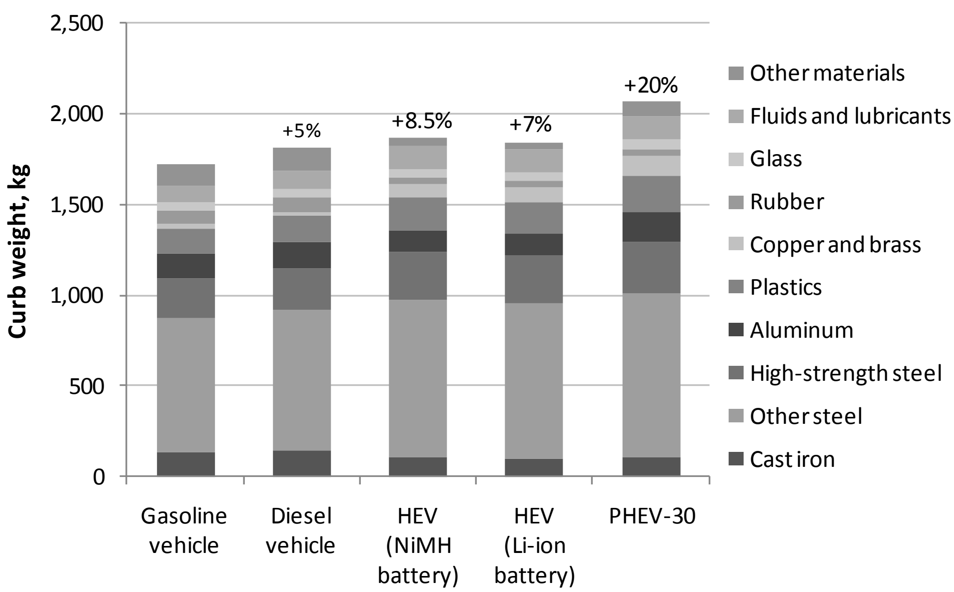
(b) Aluminum-intensive pathway



The material breakdown of a future vehicle will also depend on its powertrain. Vehicles with alternative powertrains weigh more than a gasoline vehicle. A comparison of the material composition of current vehicles with various powertrains is shown in Figure 6-3. Based on observations of existing vehicle models, turbocharged gasoline vehicles are assumed to weigh the same as conventional gasoline vehicles, and diesel vehicles are assumed to weigh 5% more. The material breakdown of hybrid electric vehicles (HEVs) is based on Argonne National Laboratory's GREET 2.7 vehicle cycle model. [8] It is assumed that the batteries in HEVs will transition from all consisting of nickel metal hydride (NiMH) cells, weighing 35 kg, today, to all lithium-ion-based chemistry (Li-ion) by 2020. The material breakdown of non-battery components will remain constant over time. All plug-in hybrid (PHEV) batteries will be made of Li-ion. The Li-ion batteries of an average HEV and PHEV-30 weigh 23 and 135 kg currently, and will decrease to 15 and 90 kg by 2020 as the energy density improves.[18] So HEVs with NiMH batteries will weigh 7% more than a conventional gasoline vehicle, HEVs with Li-ion batteries 8.5% more, and PHEVs 20% more.

For simplicity, it is assumed that the material breakdown of future vehicles will be the same for all vehicle segments (cars, SUVs, and other light trucks). Material use per vehicle will scale with curb weight, depending on the degree of lightweighting defined in the future scenario.

Figure 6-3. Material composition of 2009 vehicles, by powertrain



[18] The Li-ion battery of a Chevy Volt PHEV with a 40-mile all-electric range is reported to weigh 180 kg. The U.S. Advanced Battery Consortium's (USABC) battery weight goal for a PHEV-40 is 120 kg. These weight figures are scaled down for a PHEV-30 used in this analysis. We assume the USABC goal is attained by 2020 and then weight is held constant through 2030. A generic HEV's energy requirement is 2 kWh, as compared to the PHEV-30's 12 kWh. The HEV's Li-ion battery weight is thus scaled down (1/6)x.

6.1.2 Energy intensity of automotive material production

We are interested in the energy requirements for recovering raw materials, processing them, and during the manufacture of automotive components. For the example of primary aluminum, this includes the energy used to mine bauxite ore, refine the bauxite to alumina using the Bayer process, reduce the alumina using the Hall-Héroult process, produce the necessary carbon anodes used in this smelting process, and cast ingots for further forming as well as to form parts – stamped or cast. For secondary aluminum, this includes the recovery of scrap and scrap preparation (that is the activities involved in the consolidation and segmentation of aluminum scrap from other forms of waste), remelting and part manufacturing. Energy use for transport of the minerals and materials has been excluded. The energy required to produce replacement parts, such as tires, fluid, battery, etc. over the vehicle's lifetime are also not included in material production impact.

There are several life-cycle inventory (LCI) databases that we can turn to, to obtain the energy intensity data for various materials. We choose to use Argonne National Laboratory's Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET 2) dataset because it was specifically developed to compare vehicles used in the U.S., and also because it is freely and publicly available. It details the energy and emission effects of vehicle material recovery and production, component fabrication, vehicle assembly, and vehicle disposal/recycling for vehicles with conventional powertrains, and those using alternatives, e.g. hybrid electric, fuel cell vehicles. It is assumed that the energy intensity data that were compiled or sourced by Argonne is for year 2000. Other LCI databases that were considered for use in our assessment of U.S. vehicles, but ultimately unused are listed in Appendix H.

Table 6-1 shows the material breakdown of an average car in year 2000 (kg of material per vehicle), as well as the energy intensity of material production for the various materials from GREET (megajoules per kilogram of material produce, MJ/kg). Taking the sum of the products of these, the corresponding total energy required to produce materials embodied in a 2000 car is 66.2 gigajoules (GJ). To put this material production energy impact in context, it is only 6% of the car's total life-cycle energy demand. The life-cycle energy impact is dominated by the car's long, driven use phase in form of fuel consumed. Figure 6-4 plots the breakdown of the car's energy impacts by life-cycle phase, assuming a lifetime VKT of 324,000 km, and gasoline lower heating value of 32 MJ/liter. The fuel cycle, or the energy required to produce and distribute the gasoline fuel ("well-to-tank" impact), has not been included.

Notably, the energy required to process various materials has not been a constant over time. With continuous efficiency improvements observed in material processing historically, we want our model to capture the expectation that these improvements will continue into the future. The assumed variation in the primary energy intensities of producing ferrous metals and aluminum over time, which makes up 71% of a vehicle's weight, and 61% of its total production energy footprint, are shown in Figure 6-5. That for all other materials within the vehicle are assumed to remain constant for now. Data from the GREET model is used for figures for year 2000. Historical values are based on reports commissioned by the U.S. Department of Energy, and future values are based on published industry targets, while ensuring that they do not go below minimum theoretical limits. Values for the years in between data points are linearly interpolated.

Figure 6-4. Energy requirement of a 2000 car, by life-cycle phase

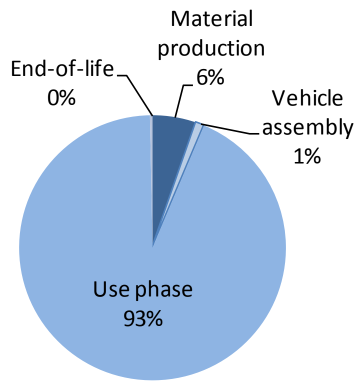
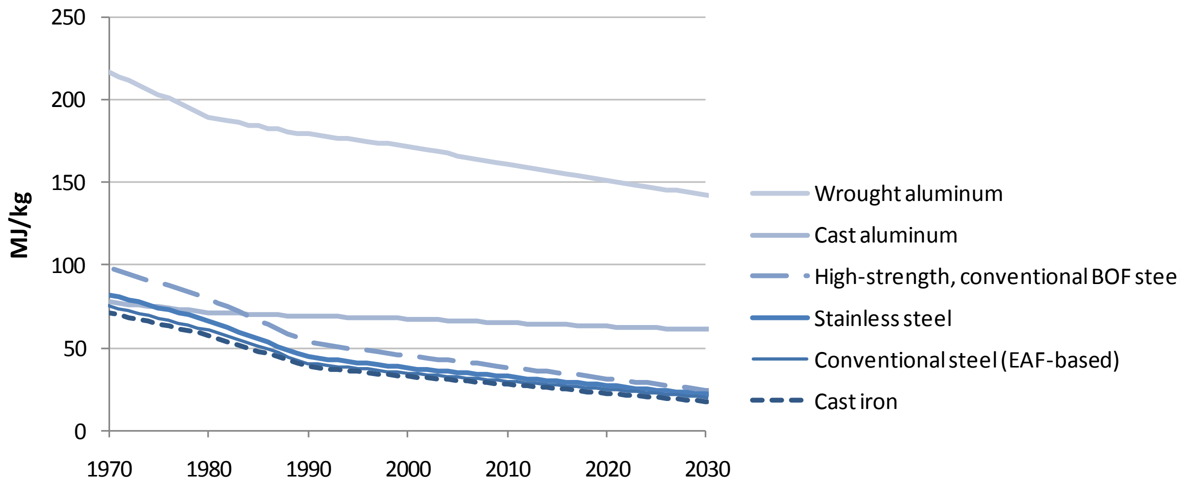


Table 6-1. Material composition of a 2000 car and the material production energy requirement

Material	Material content of 2000 car, kg	Energy intensity of material production, MJ/kg[19]
Cast iron	149	32.7
Conventional steel (BOF-based)	432	45.3
Conventional steel (EAF-based)	160	34.5
Stainless steel	22	37.7
High-strength steel	144	45.3
Cast aluminum	84	67.7
Wrought aluminum	20	172.1
Magnesium	3	379.4
Copper and brass	19	111.7
Zinc	5	119.2
Nickel	0	100.8
Cobalt	0	100.8
Rare earth metals	0	344.8
Lithium Oxide (LiO_2)	0	100.8
Manganese	0	119.2
Other metals	15	111.1
Graphite/Carbon	0	202.1
Plastics	105	60.9
Glass-fiber reinforced composites	0	72.9
Rubber	61	43.3
Glass	42	20.1
Fluids and lubricants	84	68.7
Electrolyte	0	24.0
Other materials	47	68.7
Total	**1,392 kg**	**66.2 GJ/vehicle**

[19] From GREET 2.7 database. The production energy intensity of "Other metals" is assumed to be the average for all metals. That of "Fluids and lubricants" and "Other materials" is assumed to be the average for all other materials.

Figure 6-5. Material production energy intensity over time



Elaborating on aluminum, the energy requirement for the electricity-intensive smelting process has been declining. From 1960 to 2000, the electricity requirement for smelting was successfully reduced by 35% [75] and the North American aluminum industry is targeting a further 27% reduction by 2020. [76] It is expected that technical efficiency improvements in primary aluminum processing will take place, focusing on developing more advanced Hall-Héroult cells. In this study, we assume that the aluminum smelting energy requirements will decline into the future at a compounded rate of -1.06% per annum, which is the historical rate of decline observed from 1960-2000, and is slightly less optimistic than the published industry target. We also assume that the energy demanded by all other aluminum processing steps other than smelting remains constant. For further details on aluminum, readers are referred to a paper that we authored, *Aluminum Stock and Flows in U.S. Passenger Vehicles and Implications on Energy Use*. [77]

For steel, the estimated energy intensity of steel production for the industry has declined by an impressive 62% from 1950-2000. [78] The improvements in the 1980s were due to the advent of continuous slab casting, which reduced ingot reheating energy requirements, and similarly in the 1990s due to growth in thin slab casting in mills with electric arc furnaces (EAF). Looking ahead, the American Iron and Steel Institute published a goal of reducing energy use in the industry by 38% for the integrated steelmakers (basic oxygen furnace, or BOF-based), and 35% for the electric steelmakers (EAF-based) by year 2025. [79] We assume that the energy intensity of HSS production is similar to that for BOF-based conventional steel. It is also checked that these values never go below the practical minimum energy requirements reported by Energetics, Inc., which is 13.3 MJ/kg for BOF steelmaking, and 3.51 MJ/kg for EAF steelmaking. [80]

It is acknowledged that there is also geographical variation in the energy intensity of material production [81, 82], which, depending on the source of the metal utilized in U.S. vehicles, will affect the analysis. However, this detail has been excluded from the scope of this study, and suggested for future work.

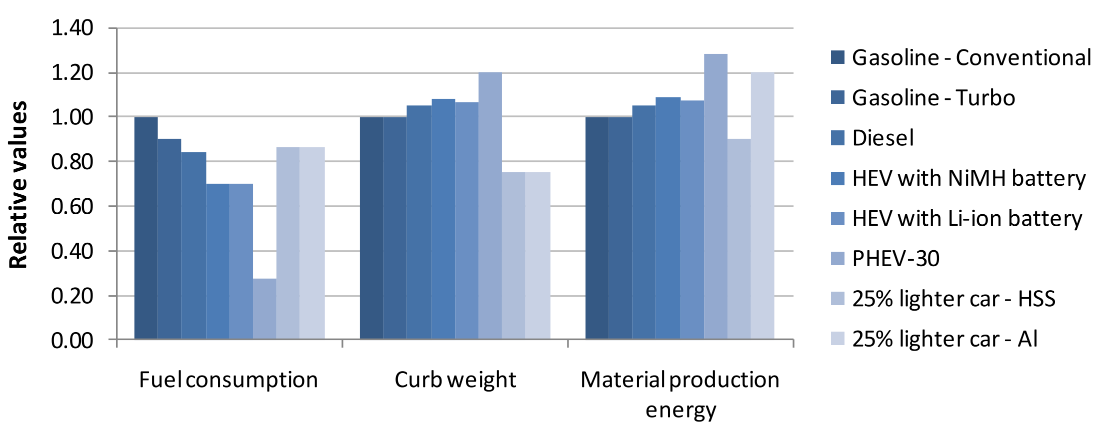
6.2 Results: Material production energy impact

Earlier, in Chapter 0, we saw how introducing the CAFE standards can realize cumulative fuel savings of 1.55 trillion liters by 2030. How about its effect on the material production energy requirements? We now have all the sub-models and information necessary to infer the automotive material demand and corresponding production impact for any type of vehicle, in any given model year, and for the entire new vehicle fleet.

First, let us compare the material production energy impact for single vehicles. For lightweight vehicles that achieve 25% weight reduction, this impact will depend on whether they rely on high-strength steel (HSS) or aluminum to reduce vehicle weight, as shown in the two material pathways in Figure 6-2. Using the material production energy intensity figures for today, we find that energy required to process materials embodied in a 2009 conventional gasoline car is 70.7 GJ, as opposed to 63.7 GJ for a HSS-intensive lightweight car, and 85.1 GJ for an aluminum-intensive version. So depending on the choice of lightweight materials, the material production energy demands may lower or increase.

We can also compare current vehicles with different powertrains. Using the material breakdown of vehicles with different powertrains shown in Figure 6-3, we find that the energy required to process materials embodied in 2009 diesel, hybrid (NiMH battery), hybrid (Li-ion battery), and plug-in hybrid cars are higher than that for a conventional gasoline car. These alternative powertrains would require more energy during the production phase – 74.2, 77.1, 76.0 and 90.9 GJ respectively. So while vehicles with alternative powertrains consume less fuel, they use more materials and require more energy to produce. The relative fuel consumption, curb weight, and material production impact of various 2009 cars are depicted in Figure 6-6, with the conventional gasoline car set as the reference. Note that the HSS-intensive lightweight car is the only one with both a lower fuel consumption, and lower material production energy demand.

Figure 6-6. Relative characteristics of 2009 cars driven by various powertrains



On an aside, the fuel-saving benefit of using lighter-weight materials, particularly aluminum, over the vehicle's life cycle has been well documented in several previous studies, including [14, 41]. Generally, when aluminum is used to replace iron or steel in a vehicle, the vehicle weighs less and consumes less fuel. Because of the long vehicle lifetime, the fuel-saving benefits realized over the vehicle's use phase will outweigh the additional energy investment associated with processing aluminum. As the focus here is on the production energy demands only, the lightweighting benefit will *not* be revisited in this analysis.

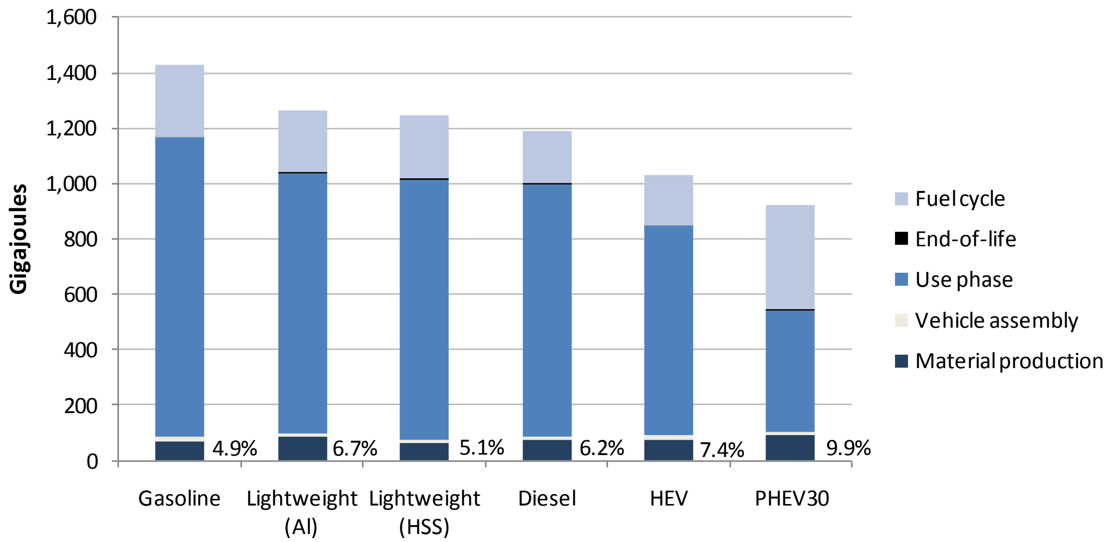
However, to put the vehicles' material production energy demand in context of the vehicle's life-cycle energy impact, Figure 6-7(a) shows the breakdown of the total energy demand of various 2009 cars by life-cycle stages, including the fuel cycle. This is the energy required to produce and distribute the fuel, and electricity in the case of the PHEV, or the "well-to-tank" energy impact. In addition to cars driven by alternative powertrains, cars that weigh 25% less than the average conventional gasoline car are also shown; they either embody more HSS or aluminum. We find that the material production energy demand for all vehicle types is small – only 5-10% of the vehicle's life cycle energy impact. For an average gasoline car today, it is around 5%. Here, we have assumed 349,800 km lifetime travel for cars sold in model year 2009. Factors to calculate the fuel cycle impact are obtained from our recent *On the Road in 2035* report [68] and Kromer [83]. To characterize the primary energy burden for the PHEV-30, we assume it is charged using electricity generated by the average U.S. grid.

New cars sold in 2030 that double the average fuel economy from today will have a lower total life-cycle energy impact, since the fuel consumed over their use-phase decreases significantly. New cars described in 2030 Scenario 2c are shown in the same Figure 6-7(b). This figure distinguishes the life-cycle energy demand of future gasoline and diesel cars that use either HSS or aluminum extensively to achieve 30% average vehicle weight reduction by 2030. Although the average fuel economy in 2030 is double that of today's, note that the use-phase energy demand for a gasoline car does not halve from the 2009 values, as one might expect. This is because part of the increase in the sales-weighted average fuel economy is achieved by selling more fuel-efficient alternative powertrains, and the lifetime vehicle kilometers of travel (VKT) is assumed to be higher in 2030 at 378,800 km lifetime travel.

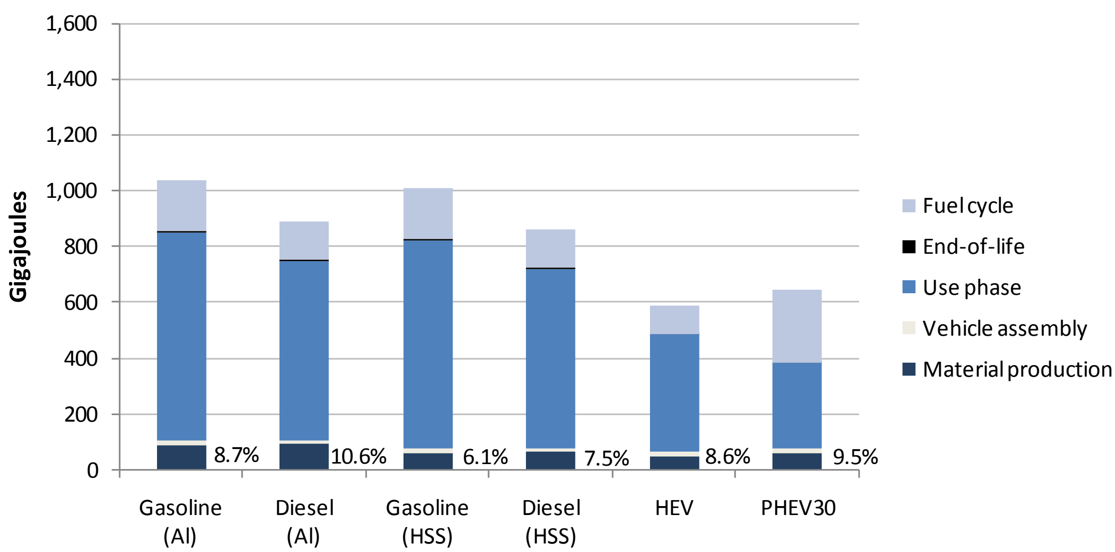
In 2030 cars, the material production energy demand as a fraction of life cycle will increase slightly, but still remain around 6-11%. This is a result of this use-phase energy demand decreasing, and several other effects taking place. Firstly, vehicle weight is reduced by using more HSS or aluminum within the vehicle. If more energy-intensive aluminum is used extensively, this drives the production energy demand upwards. Improvements in aluminum processing are also expected to occur over this time frame, which will counter this effect and depress the production impact. Otherwise, HSS-intensive lightweight cars and hybrid electric cars all have lower material production energy impact.

Figure 6-7. Total vehicle life-cycle energy demands by life-cycle stage for various cars

(a) 2009 cars



(b) 2030 cars



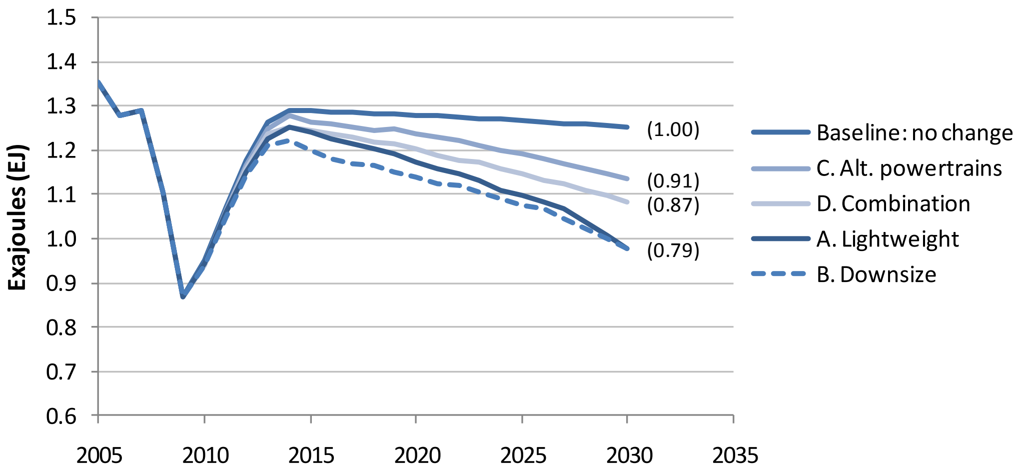
With the model, we can also examine the annual total material production energy demanded by all new vehicles over time, under different future scenarios described in Chapter 4. We will project these results up to 2030, which include the effect of meeting the 2016 CAFE target, and then doubling the 2009 fuel economy by 2030. Recall that the future vehicle scenarios 1a-d and 2a-c from Chapter 4 emphasize different strategies to improve fuel economy (see Table 4-3 and Table 4-4). The scenarios are renamed A, B, C and D, by grouping the 2016 and 2030 scenarios as shown in Table 6-2 below. In particular, Scenario D employs a combination of several approaches – vehicle weight and size reduction, emphasizing fuel consumption reduction over performance improvements, and alternative powertrains – to achieve the targeted fuel economy. Under the different scenarios, it is assumed that changes in the vehicle fleet will take place in a linear fashion from today to 2016, and from 2016 to 2030. The HSS-intensive material pathway will be followed to achieve the desired degree of vehicle weight reduction. The effect of following the alternative aluminum-intensive material pathway will be explored later. The results will be compared against a "no change" baseline of unchanging vehicle characteristics and sales mix from today.

Table 6-2. Future vehicle sales mix scenarios A-D

Future scenario combines…	this 2016 scenario and…	this 2030 scenario.
A. Aggressive lightweighting	1a	2a
B. Aggressive downsizing	1b	2a
C. Aggressive use of alternative powertrains	1c	2b
D. Combination of above approaches	1d	2c

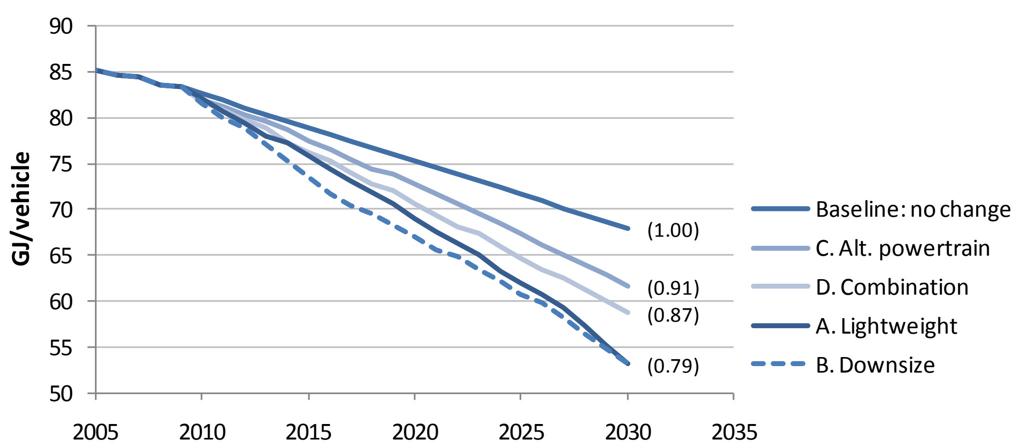
The annual automotive material production energy demand measured in exajoules (EJ, or 10^{18} joules) under the different scenarios is presented in Figure 6-8. This is the amount of energy required to produce/process materials embodied in new vehicles sold in each year. Note that the vertical axis does not begin from zero, in order to focus on the range of values prescribed by the scenarios. Values indexed to the baseline in 2030 are shown in parenthesis next to the respective scenarios. The historical impact tracks vehicle sales, as expected. Going forward, this energy demand will rise as vehicle sales recover, and from 2015, the baseline energy demand will remain fairly level despite increasing sales, as the effect of accounted efficiency improvements take place. Under the CAFE ruling, the production energy demands for the four scenarios will all eventually decline, and are not too dissimilar. It is the highest for Scenario C, which employs more advanced powertrains that weigh more and require more energy to process. Pursuing a downsized or lightweight strategy via a HSS-intensive pathway implies a lower production impact.

Figure 6-8. Annual automotive material production energy demand under various scenarios



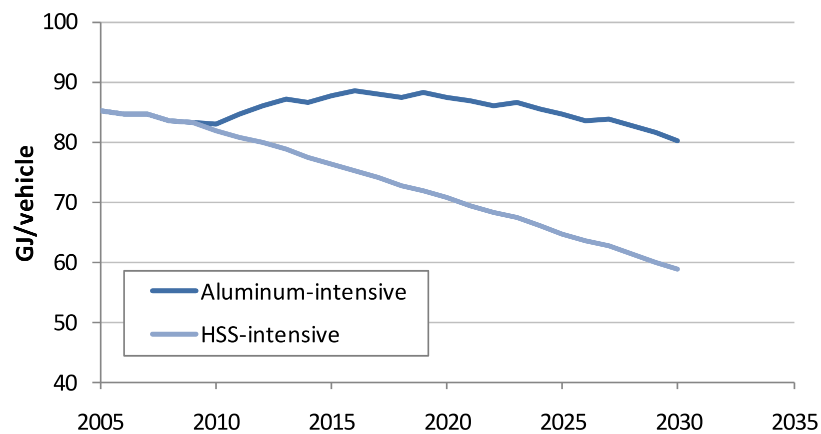
To isolate the effect of vehicle sales, the average material production energy demand per vehicle sold is plotted in the next Figure 6-9. The historical impact, in gigajoules (GJ, or 10^9 joules) per vehicle, tracks the weight of the average new vehicle sold. In the future, its decline can be explained again by efficiency improvements in materials processing, and due to the reduction in the average new vehicle weight to varying degrees depending on the scenario. Again, the material production energy impacts of Scenarios A and B, which emphasize lightweighting and downsizing, are found to be lower than in the other scenarios.

Figure 6-9. Average annual automotive material production energy demand per vehicle



If aluminum, rather than HSS, is used to achieve lightweighting however, the results will differ. Figure 6-10 shows the same average material production energy demand per vehicle sold for Scenario D only, under the two HSS- and aluminum-intensive material pathways. Due to the larger energy burden of producing aluminum, pursuing lightweighting with aluminum will increase the material production energy footprint per vehicle initially. This will peak in year 2016, and thereafter, the effects of efficiency improvements and declining vehicle weight will dominate and the energy impact will start to decline.

Figure 6-10. Material production energy demand per vehicle for Scenario D under different material pathways

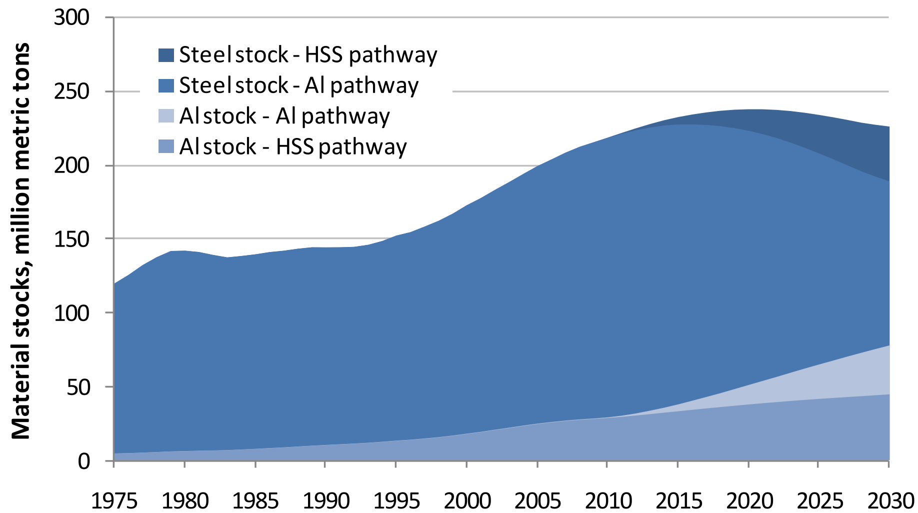


6.3 Results: Automotive material stocks and flows

By combining the model of the vehicle parc/stock by age with the average material content per vehicle in each year, it is possible to project the expected annual material stock and flows in the U.S. passenger vehicle fleet. We will focus on aluminum and steel, which make up most of a vehicle's weight, as well as specialty materials used in electric vehicles only, although the model is capable of assessing the stock and flows of any material used in passenger vehicles.

Figure 6-11 shows the historical and projected aluminum and steel stock from 1975-2030 under the "combination" Scenario D, following the two possible material pathways. This is the in-use, or "hibernating" stock of materials contained in passenger vehicles. The amount of aluminum contained in all vehicles in use today (2010) is 29 million metric tons (MMT), which is an order of magnitude less than the automotive steel stock at 219 MMT. This steel stock includes all types of steel – mild, stainless, high-strength. In the future, in the context of more stringent fuel economy standards, the aluminum content per vehicle is expected to rise along with the size of the vehicle fleet, and its rate of growth will depend on whether aluminum is extensively used to curb vehicle weight. If so, the aluminum stock in vehicles is projected to reach 77 MMT by 2030.

Figure 6-11. Material stocks embodied in the in-use passenger vehicle fleet, under two lightweighting material pathways

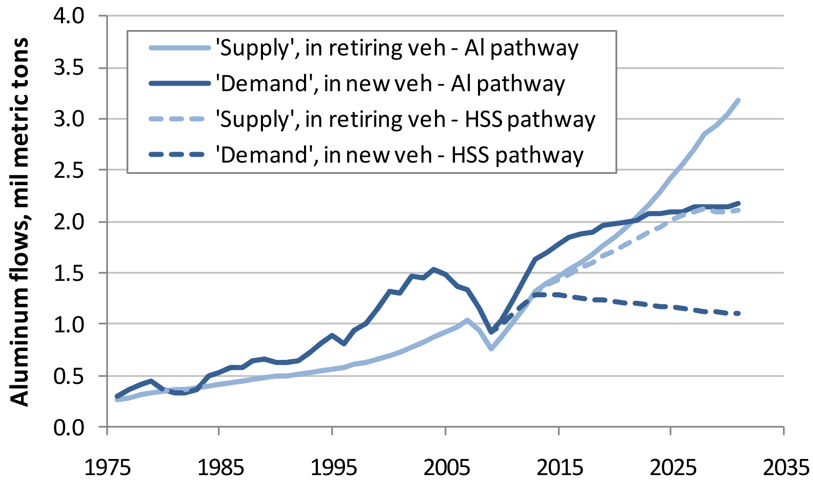


The model is also capable of anticipating the outflow, or supply of secondary metals from this large stock of materials for recycling. The stock of steel and aluminum contained in U.S. vehicles is a major potential source of secondary metals. However, given the around 16-year lifetime of vehicles, it takes time for the metal scrap from retired vehicles to enter the supply market.

Again for Scenario D only, Figure 6-12 shows how the aluminum scrap supply from, and secondary aluminum demanded by the new vehicle fleet evolves over time under the two possible material pathways. By "supply" and "demand" of secondary materials, we refer to the amount of the material embodied in retiring/scrapped vehicles, and the amount of recycled material used in new vehicles only. This is a simplified definition of supply and demand within the vehicle fleet system, as it does not consider new scrap generated during the manufacturing of vehicles, or external flows in form of imported components or vehicles. We also did not include a lag time between vehicle retirement and when the recycled material becomes available on the scrap market. To construct the demand curve, we have assumed that recycled aluminum is used in 80% of cast aluminum parts, and 10% of wrought[20] parts. This is the same assumption used in the ecoinvent Centre's ecoinvent life-cycle inventory database. These supply and demand curves include the effect of vehicle weight decreasing, and evolving material content in vehicles.

[20] A wrought product is one that subjected to mechanical working by processes such as rolling, extrusion, and forging. It is contrasted against a cast product, in which the shape has been produced by introducing molten aluminum into a mold.

Figure 6-12. Recycled aluminum flows in and out of the U.S. passenger vehicle fleet under Scenario D

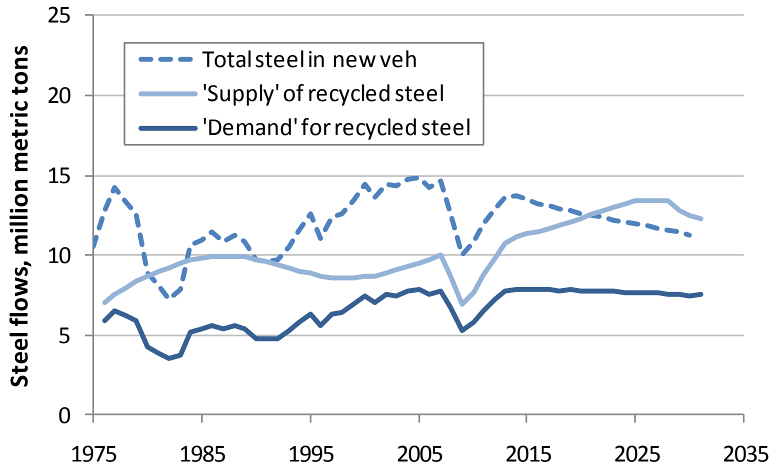


The model results suggest that historically, secondary aluminum demanded by vehicles always exceeded the supply from retired vehicles. So there was always a need to supplement this with other sources of secondary aluminum. Moving forward, this will eventually change, following either lightweight material pathway to achieve vehicle weight reduction. The supply of scrap aluminum from retired vehicles is projected to be sufficient to meet the demand for secondary aluminum for automotive parts, and it is expected that there would eventually be a positive contribution to the national scrap aluminum supply. By 2030, the total amount of scrap aluminum exiting the vehicle fleet is around twice that of secondary aluminum required within vehicles, following the HSS-intensive pathway, or around a 50% more than the requirement, following the aluminum-intensive pathway.

Similarly for steel, we chart the supply and demand for secondary steel for the vehicle fleet system following the HSS-intensive material pathway only in Figure 6-13. Notice that the recycled steel flows are an order of magnitude higher than aluminum. Here, it is assumed that recycled steel is used in 30% of steel made using a basic oxygen furnace (BOF) process, and 80% of parts made using an electric arc furnace (EAF) process. [84] For steel, the total amount of steel (both virgin and recycled) embodied in new vehicles is around twice that of the recycled steel demand, as shown in the figure. Unlike the case of aluminum, the supply of recycled steel supply always exceeds demand. So the fleet of passenger vehicles will always remain a source of recycled steel, i.e. the net outflow of recycled steel is always positive. Current design of steel use within vehicles does not support further use of recycled material, and this scrap steel surplus must be directed to other applications. For context, the apparent consumption[21] of iron and steel scrap in the whole of U.S., or an indication of national scrap demand, was 66 MMT in 2008. [85]

[21] Apparent consumption is calculated as production + imports - exports ± stock change.

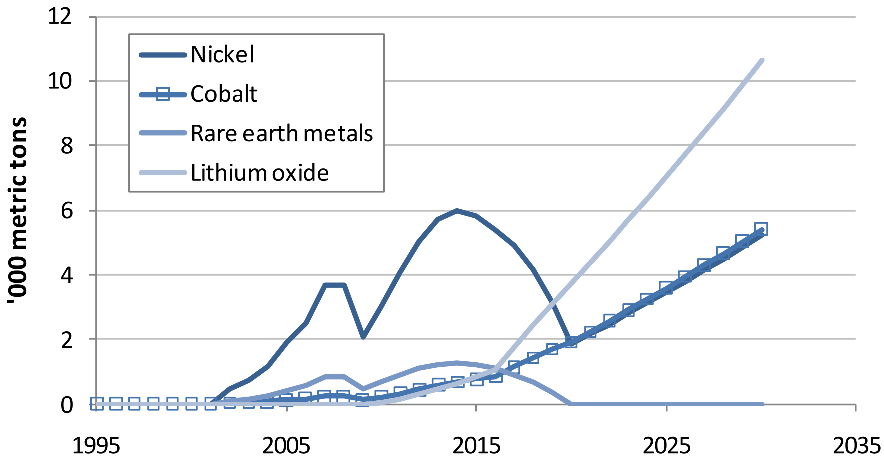
Figure 6-13. Steel flows in and out of the U.S. passenger vehicle fleet (Scenario D, HSS-intensive pathway)



Introducing CAFE standards in 2016 and beyond will also influence demand for materials required for the electrification of the vehicle fleet. Given the number of hybrid-electric vehicles required to meet the proposed standards, the demand for nickel, cobalt, lithium, and rare earth metals utilized in their batteries and motors are expected to increase. The annual demand for these materials under Scenario C is shown in Figure 6-14. This is the scenario which relies on aggressive penetration of alternative powertrains to meet future fuel economy targets, and can represent an extreme-case of high demand for such electric vehicle (EV) materials. Under this scenario, HEVs and PHEVs grow at aggressive annual compounded rate of 16.9% to capture 27%, or more than a quarter of the market by 2030.

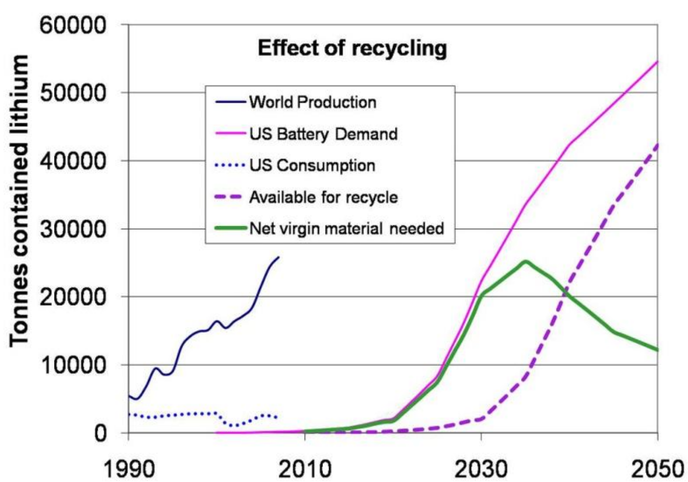
As Li-ion batteries gradually replace NiMH batteries completely in hybrid vehicles by 2020, we see that the demand for lithium oxide will rise rapidly, while that for nickel and rare earth metals will decline. This chart reflects the assumption based on the GREET model that rare earths appear in NiMH batteries only, and are not utilized in other parts of the vehicle. It is recognized that rare earths can also be applied in permanent magnets within electric motors, and estimates for the metal content in electric vehicles could reach up to 20 kg per HEV [86], and potentially higher for PHEVs. This has strong implications for the rare earth metals market, and is a suggested subject for further sensitivity analysis.

Figure 6-14. Annual demand for electric vehicle materials in U.S. vehicles under Scenario C



Given the anticipated rise in lithium demand, will we expect issues concerning lithium scarcity? Gaines and Nelson [87] of Argonne National Laboratory have explored this question of lithium availability and suggested that there is little reason for concern. Despite an even more extreme-case scenario of EV penetration, where 90% of all light-duty vehicle sales are some type of electric vehicle by 2050, U.S. demand for lithium for EV batteries will not strain current production levels, as shown in Figure 6-15. However, recycling must play an important role to ensure the material's availability.

Figure 6-15. Future lithium demand compared to historical production [87]



6.4 Chapter summary

In this chapter, we put together a methodology to characterize the material production energy impact of U.S. passenger vehicles by segment, powertrain and model year. In addition, a model of the annual stock and flows of materials in U.S. passenger vehicles from 1975-2030 under the context of more stringent fuel economy standards has been described. This dynamic material flow model has enabled a comparison of the material production energy demand across various future vehicle sales mix scenarios. Using this model, we arrived at the following findings:

- The material production energy demand, or the energy required to process materials embodied in a 2009 conventional gasoline car is 70.7 GJ, as opposed to 63.7 GJ for a HSS-intensive lightweight car, and 85.1 GJ for an aluminum-intensive version. So depending on the choice of lightweight materials, the material production energy demand per vehicle may vary.
- Alternative powertrains, like diesel, hybrid electric, and plug-in hybrid electric cars consume less fuel, but weigh more, use more materials, and require more energy during the production phase. The energy demand for processing materials embodied in diesel, hybrid (NiMH battery), hybrid (Li-ion battery), and plug-in hybrid cars are 74.2, 77.1, 76.0 and 90.9 GJ respectively.
- The total automotive material production energy demand for all new U.S. vehicles is substantial – 0.94 EJ in 2010. Under the 2016 CAFE ruling and beyond, the energy demand associated with processing materials contained in new vehicles is expected to rise along with recovering sales, and eventually decline due to expected efficiency improvements in material processing over time, and decreasing vehicle weight. Pursuing a downsized or lightweight strategy, especially by using high-strength steel extensively to lightweight the vehicle, will result in a lower production impact.
- The projected aluminum stock embodied in the U.S. in-use vehicle fleet is expected to accumulate upwards from 29 MMT today. The current steel stock in vehicles is much larger – 219 MMT – and will also rise, but eventually decline as vehicle weight is reduced.
- The automotive aluminum and steel stock represent a growing potential source of scrap metals, although it takes time for the material to enter the scrap market due to long vehicle lifetimes. The effect of this delay due to the evolution of the vehicle fleet has been captured in the model. Eventually, it is anticipated that the outflow of both scrap steel and scrap aluminum from retiring vehicles will exceed the amount of secondary metal required in new U.S. vehicles.
- As lithium-ion batteries gradually replace NiMH batteries completely in hybrid vehicles by 2020, we observe that the demand for lithium oxide by the U.S. automotive industry will rise rapidly, while that for nickel and rare earth metals will decline.

In sum, the dynamics of time-varying material use in vehicles and energy intensity of material production has been captured to quantify these effects in this important and growing product system. By detailing and carrying out a material flow and energy analysis, the implications of delays in the passenger vehicle fleet system on material recycling, and anticipated demand for new automotive materials are better characterized and understood.

7 CONCLUSION

7.1 Key findings

This thesis set out to assess the potential energy-saving benefit of vehicle lightweighting in the U.S. passenger vehicle fleet, by adopting more complete vehicle fleet system and product life-cycle perspectives. First, a thorough assessment of the various aspects of passenger vehicle weight reduction has been provided. We investigated the potential degree of weight reduction in future vehicles, its effectiveness in reducing fuel consumption, the associated cost, and its necessity in the U.S. context. The following are the key findings from this assessment:

1. *Vehicle weight reduction can be effective, but is a challenging way to achieve significantly greater fuel economy gains.*

   Reducing vehicle weight is an important way to reduce the fuel use and greenhouse gas emissions from passenger vehicles. We find that a 10% reduction in vehicle weight will reduce fuel consumption by about 7%. In absolute terms, every 100 kg weight reduction will yield a 0.39 L/100 km reduction in fuel consumption for a current average midsize gasoline car.

   Weight reduction can be practically achieved by a combination of (i) using lightweight materials such as high-strength steel and aluminum; (ii) further vehicle redesign for minimal weight; and (iii) by downsizing the new vehicle fleet by shifting sales away from larger and heavier segments to smaller ones. Combining all these approaches, we assess that it is possible to reduce the sales-weighted average new U.S. vehicle curb weight by up to 40%, or 690 kg, over the next two decades.

   However, implementing this fuel-saving approach will be costly and require extensive vehicle redesign. Applying lightweight materials will cost around $3 to $4/kg of resulting weight savings, or $800 to $1,000 per L/100 km of fuel consumption reduction. Vehicle redesign for minimum weight will require time for design, development, and production planning. For manufacturers, changing and downsizing their entire vehicle portfolio would require at least 8-10 years. However, while there is strong potential to downsize the U.S. vehicle fleet, the current structure of the CAFE standard effectively discourages downsizing. Even without any disincentives for downsizing, drastic size shifts will need to take place in order to reduce vehicle weight and fuel consumption substantially. In sum, material substitution is costly, the timescales required for vehicle redesign are lengthy, and the effect of size reduction on curbing weight and fuel consumption is modest.

2. *Future new U.S. vehicles are still expected to become steadily lighter, as automakers seek all means to achieve higher fuel economy.*

   Despite the challenges described, U.S. passenger vehicles are expected to overcome them and drop their weight in the future, as this will be necessary to fulfill more stringent Corporate Average Fuel Economy (CAFE) standards being imposed from 2012-2016. By year 2016, new U.S.

vehicles will need to achieve an average of 34.1 MPG, up from 28.8 MPG today. In response, the sales-weighted average new vehicle curb weight is expected to decline by 10-20% within this time frame. This will be achieved primarily by using lightweight materials and innovative material processing, and not by downsizing the new vehicle fleet.

3. *The new fuel economy standards for 2016 are aggressive, and will require rapid rates of new and improved vehicle technology deployment.*

   By analyzing scenarios of the future vehicle fleet, we explored the magnitude, timing, and combinations of technical changes in vehicles, including vehicle weight reduction that will be necessary to meet new standards. The 2016 target is found to be aggressive, and will require significant changes in vehicle technology starting soon. It is feasible for automakers to meet the mandate, but as mentioned, future vehicles will need to be lighter, and significant numbers will need to incorporate alternative powertrains such as turbocharged gasoline, diesel and hybrids. In addition, consumers must be willing to accept that vehicle acceleration and horsepower performance will not be able to increase significantly above today's level. These requirements are very different from recent historical trends.

4. *Given sufficient lead time, more stringent targets, like a doubling of fuel economy from today's values by year 2030, could be met. This can realize significant fleet fuel savings over time.*

   Beyond 2016, sustained and gradual increase in the CAFE targets can be practically realized by employing various vehicle technologies, as long as automakers are given sufficient lead time to plan these changes. It takes time to design and develop new vehicles, for production planning, and for new vehicle technologies to gain market acceptance. Increases in the standards that are announced further in advance, such as doubling the average new vehicle fuel economy by 2030, are predictable and allow the auto industry to better plan and respond appropriately. Spelling out these standards out to 2030 is therefore an important task.

   Mandating these minimum fuel economy standards can reduce fuel use by the passenger vehicle fleet significantly, part of which is credited to vehicle lightweighting. Compared against a "business as usual" baseline of unchanging fuel economy, weight, and other vehicle fleet mix characteristics, we find that the new fuel economy standards through 2016, and a doubling of the fuel economy by year 2030 can realize cumulative fuel savings of 1.55 trillion liters over this period.

Next, the material and further energy implications of vehicle weight reduction were explored by modeling the material production energy impact of U.S. passenger vehicles over time. The dynamics of time-varying material use in vehicles and energy intensity of material production has been captured to quantify these effects in this important and growing product system. We also created a model of the annual stocks and flows of materials in U.S. passenger vehicles from 1975-2030, which enabled a comparison of the material production energy demand across various future vehicle sales mix scenarios, and provided insight on the availability of recycled materials in retiring vehicles. This modeling effort has led to the following findings:

5. *More-fuel efficient vehicles, like those with more sophisticated propulsion systems, tend to require more energy during their material processing and production phase.*

   Alternative powertrains, like diesel, hybrid electric, and plug-in hybrid electric vehicles consume less fuel, but weigh more, use more materials, and require more energy during their production phase. An aluminum-intensive lightweight vehicle also requires more energy during the vehicle's production phase, due to the energy-intensity of processing aluminum. In contrast, lighter-weight vehicles that rely on high-strength steel can have lower material production energy requirements.

   This automotive material production impact is small, however, when compared to the vehicle's total life-cycle energy use. The material production energy demand for a current conventional gasoline car is 5% of its life-cycle energy impact. The energy expended over its long use-phase in form of fuel use dominates its life-cycle impact at 76%. However, the total automotive material production energy demand for all new U.S. vehicles is substantial at 0.94 exajoules in 2010.

6. *Comparing high-strength steel (HSS) vs. aluminum in lightweight vehicles: HSS is less costly, and has lower production energy demands. However, aluminum remains competitive in select applications.*

   Future vehicles will rely on multiple lightweight materials to reduce weight, and increasing use of both HSS and aluminum within new vehicles are likely to continue. There are several advantages of using HSS over aluminum: the energy demands for producing HSS are lower, as is the cost per kilogram of total weight savings at high production volumes. HSS-intensive concept vehicles have also demonstrated that it is possible achieve similar degree of weight savings as with aluminum. Aluminum, however, is preferred in cast components like the engine block and wheels, where HSS cannot compete in. This light metal will make some inroads in the body and chassis, but given its higher cost, aluminum content per vehicle is unlikely to overtake steel.

7. *Vehicle lightweighting and vehicle downsizing, coupled with efficiency gains in material processing over time can greatly reduce the production energy footprint of new vehicles.*

   Under the new 2016 CAFE ruling and beyond, the energy demand associated with processing materials contained in new vehicles is expected to rise initially along with recovering vehicle sales, and eventually decline due to expected efficiency improvements in material processing over time, and decreasing vehicle weight. Pursuing a downsized or lightweight strategy, especially by using high-strength steel extensively to lightweight the vehicle, can result in a lower production impact. So imposing the new fuel economy standards will not only save fuel, but also lower the energy requirements for the production of materials used in automobiles.

8. *The in-use stocks of materials embodied in U.S. vehicles represent a significant, dormant source of secondary materials.*

   The projected aluminum stock embodied in the U.S. in-use passenger vehicle fleet is expected to accumulate upwards from 29 million metric tons (MMT) today. The current steel stock in vehicles is an order of magnitude larger – 219 MMT – and will also rise, but eventually decline as vehicle weight is reduced. These automotive material stocks represent a growing potential source of scrap metals, although it takes time for the material to enter the scrap market due to long vehicle lifetimes. It is anticipated that the outflow of both scrap steel and scrap aluminum from retiring vehicles will eventually exceed the amount of secondary metal required in new U.S. vehicles.

7.2 Further work

There are several related further research opportunities that may be pursued, following this work on vehicle weight reduction in U.S. passenger vehicles.

The models that we introduced can be refined to more accurately reflect the characteristics of newer, alternative powertrains. In our work, the material composition assumptions for future lighter-weight vehicles using internal combustion engines (ICE) are described in detail, but not for lighter-weight hybrid vehicles (HEV or PHEV). In the existing model, the material use per vehicle for hybrid powertrains simply scales with curb weight, depending on the degree of lightweighting. Further work may be invested to more carefully define the material composition of a lighter-weight hybrid vehicle.

In addition, the impact of weight reduction on the fuel consumption of vehicles using alternative powertrains is expected to differ from the effect in gasoline vehicles using ICEs, which were carefully discussed in Chapter 0. In general, the fuel consumption reductions that result from weight reduction are reported to be less for alternative powertrains. [20-23] For diesel vehicles, the fuel consumption sensitivity is 14-29% lower, and for hybrid-electric vehicles, 23-59% lower than that of conventional gasoline ICE vehicles (on the absolute fuel consumption reduction per 100 kg mass reduction basis). So the model may be further refined by taking these differences into account.

Another possible aspect of model refinement is to investigate the temporal life-cycle impact of *all* materials within the vehicle, and not just ferrous metals and aluminum. While these materials make a majority of the vehicle by mass and production energy impact, further effort may be put into investigating the time-variation of energy requirements for processing the complete automotive bill of materials. Uncovering such temporal life-cycle inventory data would also be of interest to other products with similarly long lifetimes/use-phase.

Using the vehicle fleet and material flow models that have been developed, it would also be possible to build on this work and explore related research questions. The following two topics are outside the scope of this dissertation, but are potentially interesting subjects for further research.

- *What would it take to sell lighter and smaller vehicles in the U.S.?*
  Until recently, U.S. consumers seemed unwilling to buy lighter, smaller, and more fuel efficient vehicles. Reasons to resist vehicle downsizing include the perception that smaller cars are unsafe "econoboxes", the transaction cost of replacing a current vehicle, and potential loss in interior passenger/cargo space utility, prestige, and other amenities. On the flip side, consumers downsizing their vehicles can save money, project a green image or to express a genuine interest in reducing fuel use/GHG emissions. Further work could explore market acceptability and model the demand for lightweight/downsized vehicles in the U.S. This topic involves modeling consumer demand for size, fuel economy, and performance in vehicles by assessing multi-attribute utility functions, and sensitivity of demand to gasoline prices.

- *Will the supply of new automotive materials meet expected demand?*
  The scenarios that were investigated imply significant changes in automotive material use over time. A pragmatic question would then be: are there any issues associated with the supply of these materials? The material flow model that has been put together can help assess the resource demanded by the U.S. automotive industry, as well as quantify the return flow of secondary material. This is useful to assess the material supply-side risks or vulnerabilities associated with aggressive lightweighting or aggressive electrification of the future new vehicle fleet in the U.S. In particular, how stable is the supply of aluminum, copper, nickel and lithium – key materials used in lightweighting and hybridization? Furthermore, sensitivity analysis on material content of electric vehicles, e.g. rare earth metals in motors, or the copper content in Li-ion batteries should also be investigated, given the uncertainty in current estimates.

APPENDICES

A. Further notes on vehicle fuel consumption

The fuel efficiency of a vehicle may be expressed in terms of travel distance obtained per unit of fuel input, which is the fuel economy; or its inverse – the amount of fuel used or consumed per unit of distance traveled, which is the fuel consumption. Fuel economy (FE) is commonly expressed in miles per U.S. gallon (MPG), and fuel consumption (FC) in liters of fuel used per 100 kilometers traveled (L/100 km). A useful conversion factor to remember is:

$$FC = \frac{235.2}{FE}$$

We are mostly interested in the sales-weighted average fuel consumption of the future new vehicle fleet. This refers to the average fuel consumption of all new vehicles expected to be sold or introduced on the roads in a given year, and not that of the entire stock of vehicles in use, or the car parc, already on the road in those years. The sales-weighted average fuel consumption considers the car vs. light truck sales mix, the powertrain sales mix, and the relative fuel consumption of these different vehicles.

This average fuel economy of new passenger vehicles is reported by the U.S. Environmental Protection Agency (EPA) and National Highway Traffic Safety Administration (NHTSA) each year. EPA compiles the fuel economy for individual vehicle models, to certify their fuel economy and emissions performance. These are measured in a laboratory using standardized test procedures on a dynamometer. Each model's fuel economy is a composite based on mixed city and highway driving test procedures, to represent typical vehicle operation. City driving is 55% of total miles and highway miles are 45%. EPA adjusts the laboratory values downward to better reflect real-world driving conditions, taking into account more aggressive driving, the use of air conditioners and operation in cold temperatures. The adjusted EPA MPG appears on the window label of new vehicles to inform consumers, and are on average 20% lower than the laboratory figures.

NHTSA also reports the Corporate Average Fuel Economy (CAFE) for individual manufacturers, which are used to determine compliance with the standards. These are not adjusted to reflect the shortfall in on-road values, but are on average 2-3% higher than the EPA's unadjusted laboratory values due to differences in vehicle classification, test procedure adjustment factors, and alternative fuel credits. [2]

When comparing the fuel consumption of a diesel vehicle versus a gasoline vehicle, the diesel fuel used by the diesel vehicle is converted into a gasoline equivalent, in order to make it an even comparison on an energy-basis. This gasoline equivalent value is calculated based on the lower heating value of gasoline (42.6 kJ/g) and the density of gasoline (749 g/L). The lower heating value of diesel is 43.0 kJ/g, and the density of diesel is 850 g/L.

B. Calculating the Emphasis on Reducing Fuel Consumption (ERFC)

This section is an excerpt of an earlier paper by Cheah et al 2009 [63], in which we introduce the Emphasis on Reducing Fuel Consumption (ERFC) metric. ERFC is defined as the actual fuel consumption reduction realized, divided by the fuel consumption reduction achievable keeping size and performance constant, over a specified time frame. It measures the degree to which improvements in vehicle technology are realized into reducing fuel consumption (FC), as opposed to bettering other vehicle attributes:

$$\%ERFC = \frac{Actual\ FC\ reduction\ realized}{FC\ reduction\ possible\ with\ constant\ size\ and\ performance}$$

$$or$$

$$\%ERFC = \frac{FC_{previous} - FC_{realized}}{FC_{previous} - FC_{potential}}$$

To calculate ERFC, the time period over which to assess its value must be specified. In Figure 4-5, the historical ERFC for cars was calculated each year by MacKenzie [64], based on changes of vehicles attributes over the preceding five years. For example, in order to calculate the historical ERFC for year 2009, the potential fuel consumption reduction is measured from the average new car sold in year 2004. To be precise, this is the degree of emphasis on reducing fuel consumption of new cars between 2004 to 2009. Any time interval may be used, but estimating the ERFC over the preceding five years provides sufficient indication of the fuel consumption-performance tradeoff over time.

$$\%ERFC_{2004\text{-}2009} = \frac{FC_{2004} - FC_{2009}}{FC_{2004} - FC_{2009potential}} = \frac{10.2 - 9.6}{10.2 - 9.0} = 49\%$$

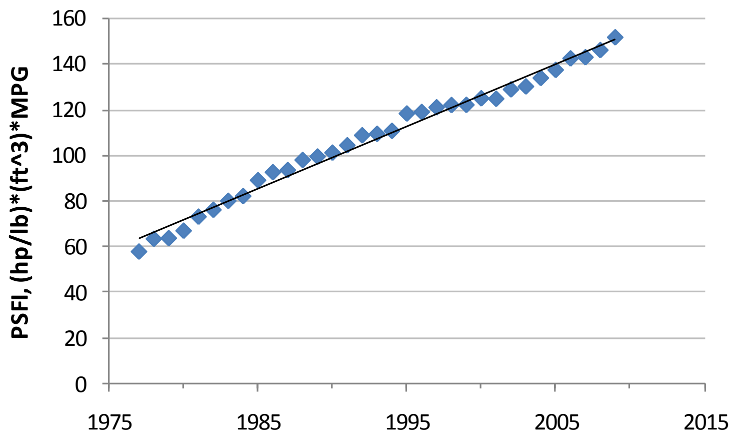
The fuel consumption reduction potential ($FC_{2009\ potential}$) in the denominator of the equation is the fuel consumption of a 2009 car if it had the size and performance of a new car sold back in model year 2004. This is determined using the expected Performance-Size-Fuel Economy Index (PSFI), introduced by An and DeCicco. [88] This Index correlates trends in new vehicle characteristics and provides insight into where technical efficiency gains have been realized. For cars, the PSFI is defined as follows:

$$PSFI = P.S.F = (hp/lb).ft^3.MPG$$

P is the performance index, defined as the ratio of maximum engine horsepower to vehicle inertia weight (hp/lb). The size index, *S*, is defined as the interior volume of the car in cubic feet (ft^3). The fuel economy index, *F*, is defined as the EPA adjusted fuel economy in miles per gallon (MPG).

Figure 0-1 shows the PSFI trend for cars from model years 1977 to 2009. As noted by An and DeCicco [88], the PSFI shows a remarkable long-term linear trend, which is useful for evaluating the trade-off between performance, size, and fuel consumption. In 2009, the Index has a value of 152 (hp/lb).ft^3.MPG. Fixing this, and replacing the performance (*P*) and size (*S*) indices with their 2004 values, the maximum potential fuel economy today is found to be 26.2 MPG, or equivalent to a minimum fuel consumption of 9.0 L/100 km. Using this, the ERFC for a U.S. car from 2004 to 2009 is calculated to be 49%.

Figure 0-1. Performance-Size-Fuel economy Index (PSFI) for U.S. cars, 1977-2009



The PSFI is also useful in assessing the maximum fuel economy potential today, if ERFC had been locked at 100%. For instance, if we kept the average car's performance and size unchanged from 1985, how many miles would today's car travel on one gallon of fuel? To estimate this potential, one divides the 2009 PSFI with the 1985 performance (*P*) and size (*S*) indices. Using this approach, today's average new car is estimated to achieve 39 MPG rather than the actual 25 MPG (EPA adjusted figures). The tradeoff is that this car would take 13 seconds to accelerate from 0 to 60 mph, like its 1985 counterpart. This is 4 seconds more than the average car today.

$$Maximum\ fuel\ economy\ potential\ \ from 1985 = \frac{PSFI_{2009}}{P_{1985} \cdot S_{1985}} = \frac{151.9}{0.0359 \cdot 108.2} = 39.1 MPG$$

C. Magnesium as a lightweight automotive material

Magnesium is another lightweight material that can be used in automotive applications. To construct designs with equal stiffness, magnesium offers around 60% weight reduction over steel, and 20% weight reduction over aluminum. [89] Besides reduced weight, magnesium also offers strength, durability and thermal stability. Another key advantage is the ability to consolidate parts using magnesium, which is suited for large die casting. For instance, an instrument panel cross-car beam made of high pressure die-cast magnesium can be a monolithic component, whereas one made of stamped steel consist of 20 or more parts welded together. So die-cast magnesium components are easier to manufacture, stiffer, and have less squeaks and rattles.

Given these advantages, use of magnesium in automobiles has been growing, although it remains a very small percent of total vehicle weight. Within an average U.S. vehicle, use of magnesium increased from 0.1% (1.8 kg) to 0.2% (4.5 kg) of total vehicle weight from 1995 to 2007, and is expected to rise to 10 kg by 2015. [90, 91] In contrast, current aluminum use is 140 kg per vehicle. Growth in magnesium within automobiles has been in die-cast components, such as instrument panel structures, cross-car beams, seat frames, steering wheels, intake manifolds, transfer cases, wheels and various brackets and covers.

Looking ahead, the potential for greater use of this light metal in automotive applications exists. The U.S. Automotive Materials Partnership estimates that magnesium content per vehicle could reach up to 170 kg. [28] However, there are several barriers that have and may continue to deter further uptake of magnesium, both technical and non-technical:

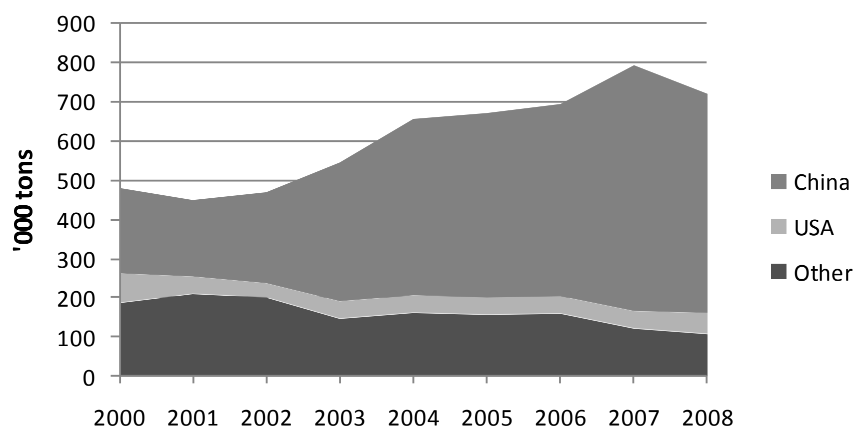
1) Corrosion issues – Magnesium is reactive and has to be protected with applied coatings to protect from corrosion. This leads to several related difficulties:
    a) Difficult to join – There are no good spot welding methods using magnesium, and only noninvasive bonding methods, such as adhesive bonding, may be used.
    b) Not suited for conventional painting operations – Magnesium alloy deteriorates in the phosphating and electrocoating procedures used in conventional automobile paint lines. It requires a separate pre-treatment procedure to protect its reactive surface.
    c) Need to prevent galvanic or bimetallic corrosion – When using magnesium in contact with another metal, fastening systems must be designed to be non-conductive.
2) Poor creep resistance – Magnesium does not have the creep resistance of aluminum, and is unlikely to be used in the engine block or other high temperature applications.
3) Wrought parts require costly hot forming – Use of the light metal in wrought parts (sheet or extrusions), such as body panels or rear suspension links, is limited since these parts require hot forming processes and are more costly to produce. Because of its crystal structure, fabrication of wrought magnesium parts must take place at elevated temperatures (200-300°C). [92]
4) Lack of design experience – Automakers have limited design experience with magnesium alloys, and there is lack of field validation or controlled testing data.
5) Insecurity of supply – While magnesium is abundant on earth, there are concerns about the security of its supply. China accounts for 78% of the world primary magnesium production in

2008, and prices have been fluctuating over the past few years (see Figure 0-2 and Figure 0-3). The lack of diversity of supply and volatility in prices is a disincentive for greater use of magnesium. [93]

6) Higher cost of magnesium – While magnesium prices have come down in the past decade with lower-cost imports from China, the cost of magnesium remains higher than aluminum or steel. In 2007, magnesium costs $4,960 per metric ton, as compared to $2,700 for aluminum, and $180 for steel. [85]
7) Magnesium production is energy- and GHG-intensive – Like aluminum, magnesium is energy-intensive to produce. Estimates of the primary energy required to produce magnesium ingot using the thermal Pidgeon process vary from 270 to 366 MJ per kilogram. [94-98] Obtaining the same ingot using an electrolytic process requires 3-5 times less energy. The greenhouse gas (GHG) impact also varies widely, with estimates ranging 27-47 and 6-24 kgCO_2-eq/kg magnesium ingot for the two processes respectively. However, the metal is recyclable and there is potential for recovery from vehicles at the end-of-life to reduce these impacts.

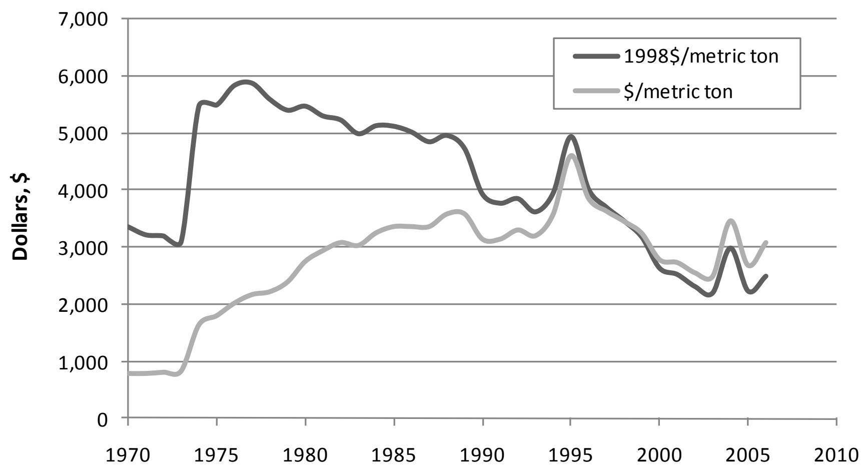
Most of these technical challenges can be overcome, but magnesium faces competition from other lightweight materials – high-strength steel and aluminum – that auto designers will sooner turn to. Unless there is strong impetus to lightweight a vehicle urgently, it will take a while before magnesium content within a vehicle increases by an order of magnitude.

Figure 0-2. World primary magnesium production by country, in '000 metric tons, data source: [99]



World production has been growing, reaching 719,000 metric tons in 2008. China currently produces 78% of the world output, using the lower-cost, but more energy- and labor-intensive Pidgeon process. This process is about 25% less costly than the electrolytic process used by Western producers. [28]

Figure 0-3. Historical magnesium price, data source: [85]



There is a general downward trend for magnesium prices since the mid-1970s, although prices have fluctuated quite significantly, especially in recent years.

D. The cost of vehicle electrification: A literature review

The objective of this review is to assess the cost of manufacturing hybrid electric vehicles (HEVs, PHEVs) in the U.S. These vehicles are expected to be added to automakers' vehicle portfolios as they strive to meet the 2016 Corporate Average Fuel Economy (CAFE) mandate. These costs are intended to be compared against the cost of other approaches to reducing vehicle fuel consumption, e.g. vehicle lightweighting.

Only more current references from 2005 onwards have been included in this review. Given the rapid rate of technology advancements in energy storage systems, cost estimates prior to 2005 have been excluded.

We are interested in the additional cost of the overall hybrid system over a comparable conventional vehicle utilizing an internal combustion engine. This should also account for the cost reduction in using a downsized engine and transmission in PHEVs.

Most of the literature only report the cost of manufacturing lithium-ion (Li-ion) battery systems for hybrid vehicles in terms of dollars per kilowatt-hour of energy storage ($/kWh). The battery is the most expensive component in an electric vehicle. Around 80% of the cost of a PHEV-40's drive system is due to the battery pack. [100] Other components include the electric motor, inverter, power control unit, and generator.

The battery's cost is not only due to the material, but also capital investment in battery manufacturing. This cost depends much on the battery production volume, and less so on the lithium chemistry. [101] The figures are expected to decline once batteries are mass produced.

Figure 0-4. Breakdown of a PHEV drive system cost by component, data source: [100]

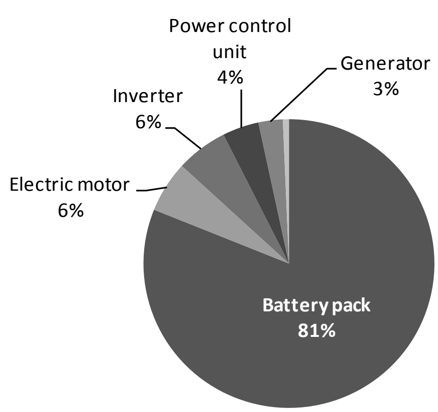
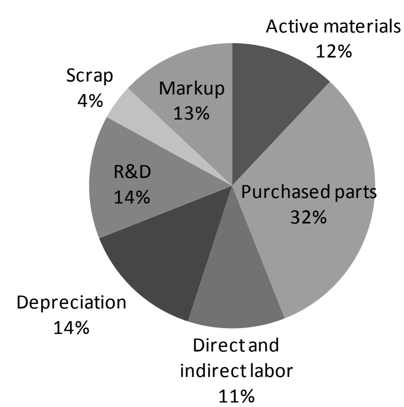


Figure 0-5. Electric vehicle battery cost structure, data source: [102]



The incremental vehicle system cost and battery cost numbers found in the literature are summarized and plotted in the next two tables, the figure below, and in Figure 3-12. Estimates for both categories vary widely. Within the next 5-10 years (2015-2020), PHEVs are projected to cost an additional $6,000-16,000 more than a conventional internal combustion vehicle. Even today, battery cost estimates vary widely from $260-$1,300/kWh. None of the battery cost estimates meet the U.S. Advanced Battery Consortium's goal of $200/kWh by 2016. It is noted that some of the estimates are likely to have been cross-referenced, so greater frequency of estimates need not necessarily indicate greater accuracy.

Table 0-1. Hybrid/electric vehicle system cost estimates from literature. All are production cost, unless otherwise stated.

Reference	Vehicle type	Year for estimation	Cost premium over conventional vehicle[22]
Simpson 2006 (NREL) [103]			Retail price increase:
	PHEV10	"Long-term"	+$6,300
	PHEV40		+$11,450
Bandivadekar et al 2008 (MIT) [68]	HEV car	2007	+$3,500
	HEV light truck	2007	+$4,500
	HEV car	2035	+$1,800
	HEV light truck	2035	+$2,300
	PHEV30 car	2035	+$4,200
	PHEV30 light truck	2035	+$5,900
Frost & Sullivan 2009 [100]			Cost of EV drive system:
	PHEV40	2009	$11,300-14,800
	BEV100	2009	$16,900-22,300
Plotkin & Singh 2009 (Argonne)[23] [104]	HEV car	2015	+$1,450
	PHEV10 car	2015	+$2,350
	PHEV40 car	2015	+$6,250
	HEV car	2030	+$1,110
	PHEV10 car	2030	+$1,770
	PHEV40 car	2030	+$4,370
EPA/NHSTA 2010 [4]	HEV midsize car	2012	+$2,742
	PHEV20 midsize car	2012	+$16,125
	HEV small truck	2012	+$2,377
	PHEV20 small truck	2012	+$14,721
	HEV large car	2016	+$5,377
	PHEV20 large car	2016	+$12,808
	HEV small truck	2016	+$4,856
	PHEV20 small truck	2016	+$11,984
NRC 2010 [105]	PHEV10	2015	+$5,200
	PHEV40	2015	+$14,200
	PHEV10	2020	+$4,500
	PHEV40	2020	+$12,200

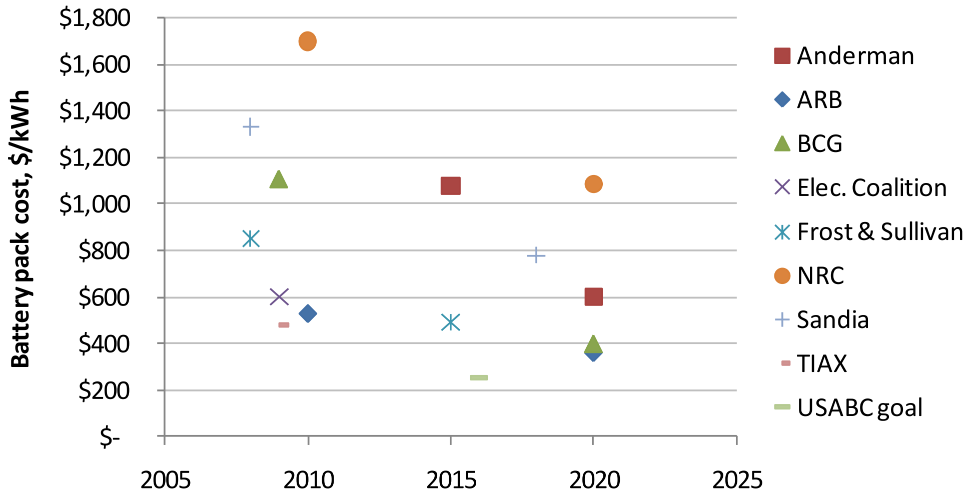
[22] To convert to retail price equivalents, markup factors for including additional indirect costs and profit used in the literature range from 1.5-2.1.
[23] Cites Kromer, M. and J. Heywood, 2007. Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet, Laboratory for Energy and the Environment, Massachusetts Institute of Technology, LFEE-2007-03 RP, co-authors of Bandivadekar et al 2008.

Table 0-2. Battery cost estimates from literature

Reference	Li-ion battery application	Year for estimation, or timeframe indication	Cost[24]
USABC (via Pesaran et al 2007) [106]	For PHEV10 For PHEV40	2016 goals, for reference only	$300/kWh, or $1,700 $200/kWh, or $3,400
Pesaran et al 2007 (NREL)[25] [106]	High energy batteries	2007	$800-1,000/kWh
Kalhammer et al 2007 (for ARB) [107]	For HEV For PHEV10 For PHEV40	Low volumes (500MWh/yr) High volumes (2,500MWh/yr) Low volumes (500MWh/yr) High volumes (2,500MWh/yr) Low volumes (500MWh/yr) High volumes (2,500MWh/yr)	$800/kWh, or $2,400 $550/kWh, or $1700 $575/kWh, or $3,300 $400/kWh, or $2,200 $380/kWh, or $7,100 $260/kWh, or $4,900
Ton et al 2008 (Sandia) [108]	Li-ion battery	2008 2018	$1,333/kWh $780/kWh
ARB 2009[26] [109]	For PHEV10 For PHEV40	Low volumes (500MWh/yr) High volumes (2,500MWh/yr) Low volumes (500MWh/yr) High volumes (2,500MWh/yr)	$480-600/kWh $340-400/kWh $450-560/kWh $320-370/kWh
Frost & Sullivan 2009 [110]	Li-ion battery	2008 2015	$700-1,000/kWh $470-510/kWh
Electrification Coalition 2009 [111]	Li-ion battery	2009	$600/kWh
Barnett 2009 (TIAX) [101]	Li-ion battery	2009	$260-700/kWh
NRC 2010 [105]	For PHEV10 For PHEV40	2010 2020 2010 2020	$1,650/kWh $1,050/kWh $1,750/kWh $1,120/kWh
BCG 2010 [102]	Li-Ni-Co-Al (NCA) battery	2009 2020	$990-1,220/kWh $360-440/kWh
Anderman 2010 [112]	For PHEVs For EVs	2015 2018-2020 2015 2018-2020	$900-1,260/kWh $675-900/kWh $500-700/kWh $375-500/kWh

[24] Assuming that the energy requirement for a PHEV-40 is 16 kWh, the cost of the battery can be calculated accordingly.
[25] Collaborates with TIAX, LLC.
[26] This is a review and update of Kalhammer et al 2007.

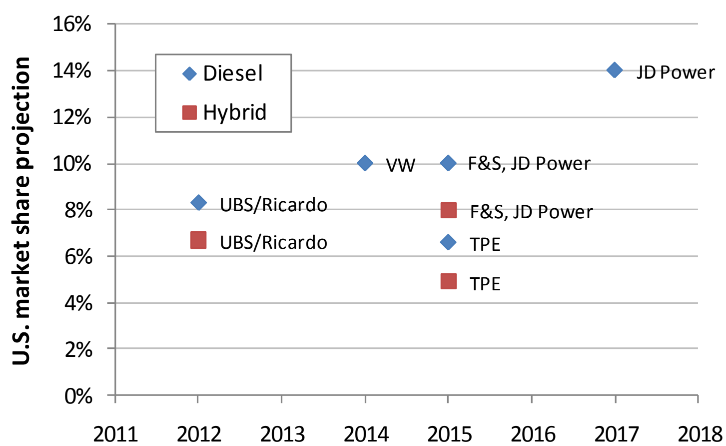
Figure 0-6. Estimates of PHEV Li-ion battery pack cost. Only mid-points of ranges, if any, are plotted.



E. Projections of diesel vs. gasoline hybrid-electric vehicle sales in the U.S.

Sales projections of diesel and hybrid powertrains in the U.S. light-duty vehicles vary somewhat, but all trend upwards. Both alternatives cost more, and offer improved fuel economy and low-speed torque performance over the gasoline internal combustion engine. Which is more likely to gain more market share? Industry analysts seem to believe that diesels will triumph over hybrids (see figure below).

Figure 0-7. Projections of diesel and hybrid shares in the U.S. light-duty vehicle market [113-116]



The strongest argument for this is cost – diesel technology is more mature, and a diesel vehicle can cost around +$2,000 more than a comparable gasoline model. Hybrid powertrains are more expensive, with additional components like the battery and electric motor. They are estimated to cost +$5,000 more than the conventional gasoline vehicle. [68, 114, 115] While the difference between these premiums is expected to diminish over time, the mass market is more likely to turn to diesels when seeking fuel economy improvements.

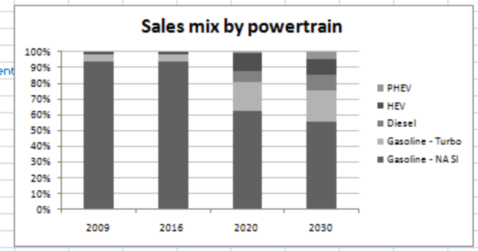
However, several challenges inhibit market penetration of diesels – more stringent emissions regulation, ensuring adequate supply of low sulfur diesel fuel, rising diesel prices over gasoline in recent years, and a negative market perception that diesels are more polluting than they actually are. In addition, only an estimated 40% of fueling stations carry diesel fuel. [117, 118] Given these arguments, we assume that the market share of diesels and hybrids will be the same in our future vehicle sales mix scenarios.

F. Screenshot of spreadsheet for analyzing future vehicle sales mix scenarios

Microsoft Excel - LDV stockv9

EXPLORATION OF SCENARIOS THAT MEET FUTURE FUEL ECONOMY TARGETS

		D	E	F	G	H	I	J	K	L
2	**EXPLORATION OF SCENARIOS THAT MEET FUTURE FUEL ECONOMY TARGETS**									
3										
4	**Inputs**	2016	2020	2030			Alerts			
5	Emphasis on reducing fuel consumption (ERFC), %	75%	75%	90%			2016 target not yet met			
6	Market share of hybrids, %	5.9%	12.0%	9.9%			2020 target not yet met			
7	Market share of cars (vs. light trucks), %	51%	70%	80%						
8	Additional weight reduction, % from 2008 curb	15.0%	0.0%	17.0%						
9	Resulting avg new vehicle curb weight reduction, % from 20	22%	13%	40%						
10										
11	**Results**	Avg fuel consumption, L/100km				Avg fuel economy, MPG				Combined 55/45, adjusted figures
12	Year	2016	2020	2030		2016	2020	2030		
13	2009 (today)	11.15	11.15	11.15		21.1	21.1	21.1		
14	Target	9.32	8.60	5.57		25.2	27.3	42.2		
15	Result	9.32	8.63	5.57		25.2	27.2	42.2		
16	% change from today	16%	23%	50%		20%	29%	100%		
17				Factor of 2						
18	**Converting targeted CAFE FE to equivalent adjusted FC**									
19	2009 CAFE, MPG	28.50	NHTSA CAFE > EPA's unadj/lab MPG due to "differences in vehicle classification, test procedure adjustment							
20	2009 EPA adj, MPG	21.10								
21	Target CAFE, MPG	57.00								
22	Equivalent adj FE, MPG	42.20	Same % increase in FE							
23	Equivalent adj FC, L/100km	5.57								
24										



		D	E	F	G	H	J	K	L	M	N	P	Q	R	T
25	**Vehicle characteristics**	**New cars**					**New light trucks**								
26	Year	2006	2009	2016	2020	2030	2006	2009	2016	2020	2030				
27	Relative adj fuel consumption (to 2006 gas NA SI)														
28	Gasoline - NA SI	1.00	0.95	0.89	0.84	0.66	1.00	0.95	0.89	0.84	0.67				
29	Gasoline - Turbo	0.90	0.86	0.80	0.75	0.58	0.83	0.79	0.75	0.71	0.57				
30	Diesel	0.84	0.80	0.75	0.71	0.56	0.74	0.70	0.67	0.64	0.53				
31	HEV	0.70	0.67	0.60	0.54	0.37	0.70	0.67	0.60	0.54	0.37				
32	PHEV	0.28	0.26	0.25	0.23	0.18	0.28	0.26	0.25	0.23	0.18	Assumed sales mix proportions			See other spreadsheet on how relative FC is estimated.
33	Sales mix by powertrain, %											2016	2020	2030	
34	Gasoline - NA SI	95.2%	93.6%	93.6%	62.1%	55.6%	95.2%	93.6%	93.6%	62.1%	55.6%				
35	Gasoline - Turbo	3.3%	4.5%	4.5%	18.9%	19.7%	3.3%	4.5%	4.5%	18.9%	19.7%	4.0%	3.0%	4.0%	Historical (2001-2009) turbo, diesel penetration from EIA's AEOs, historical (1975-200
36	Diesel	0.0%	0.1%	0.1%	6.3%	9.9%	0.0%	0.1%	0.1%	6.3%	9.9%	2.0%	1.0%	2.0%	For 2016+, assume same powertrain market penetration for cars and LT
37	HEV	1.5%	1.8%	1.8%	12.0%	9.9%	1.5%	1.8%	1.8%	12.0%	9.9%	2.0%	1.9%	2.0%	
38	PHEV	0.0%	0.0%	0.0%	0.6%	4.9%	0.0%	0.0%	0.0%	0.6%	4.9%	0.1%	0.1%	1.0%	
39	Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%				
40	Average gasoline veh characteristics														2006, 2009 values from EPA
41	Horsepower	194	198			195	235	253			209				Assume performance reduces proportionally to % ERFC
42	0-60 mph acceleration time, sec	9.6	9.5			7.9	10.0	9.6			9.4				acc t = 0.892*(hp/inertia lb)^-0.805, EPA equation
43	Inertia weight, kg	1,601	1,600	1,510	1,473	1,337	2,114	2,134	1,990	1,940	1,758				2006, 2009 inertia wt corrected to obtain EPA reported average (eg. cell D54=1466k
44	Curb weight, kg	1,465	1,464	1,374	1,337	1,201	1,977	1,998	1,854	1,804	1,622				Assume curb weight reduces proportionally to % ERFC. At 100% ERFC: -20% wt red i
45	Adj fuel consumption, L/100km	10.17	9.70	9.07	8.54	6.68	13.60	12.95	12.15	11.47	9.09				2006, 2009 FC corrected to obtain EPA reported average (eg. cell D55=10.09=23.3
46	Avg gasoline veh characteristics with additional weight reduction														
47	Additional weight reduction, kg			220	0	249			301	0	340				
48	Curb weight, kg	1,465	1,464	1,153	1,337	952	1,977	1,998	1,553	1,804	1,282				
49	Adj fuel consumption, L/100km			8.21	8.54	5.93			10.71	11.47	7.90				For cars, assume for every 100kg curb weight reduction, FC reduces by 0.39 L/100km
50	Sales-weighted average new veh characteristics														
51	Curb weight, kg	1,467	1,466	1,155	1,354	973	1,980	2,001	1,556	1,828	1,310				Assume diesels weigh 5% more than gasoline, NiMH HEV 8.5%, Li-ion 2020+ HEV 7
52	Adj fuel consumption, L/100km	10.09	9.60	8.12	7.88	5.25	13.46	12.78	10.56	10.40	6.87				
53															
54	**Average new vehicle characteristics**	2006	2009	2016	2020	2030									
55	Curb weight, kg	1,708	1,727	1,351	1,496	1,040									
56	Adj fuel consumption, L/100km	11.68	11.15	9.32	8.63	5.57									
57	Market share of cars (vs. light trucks), %	53%	51%	51%	70%	80%									2006, 2009 values from EPA
58	Sales, '000	15,104	10,400	16,460	16,993	18,403									
59															

In-N-Output / Veh stock / Production / MFA / ERFC / Fuel use / Data / Scenarios / **Exploration** / For paper

G. Monte Carlo simulation of 2016 vehicle sales mix scenarios

The 2016 “what-if” scenarios that fulfill the CAFE mandate described in Chapter 4 (Table 4-3) were developed using a deterministic approach, meaning combinations of input variables are manually chosen until the fuel economy target is met. To ascertain the likelihood of meeting the new fuel economy standard, when the combination of technology options to be employed is uncertain, we can use Monte Carlo simulation techniques. Monte Carlo simulation is a numerical approach to understanding the propagation of uncertainty in our inputs. By capturing random samples of the input variables to explore thousands of possible combinations, the full range of possible outcomes is better understood.

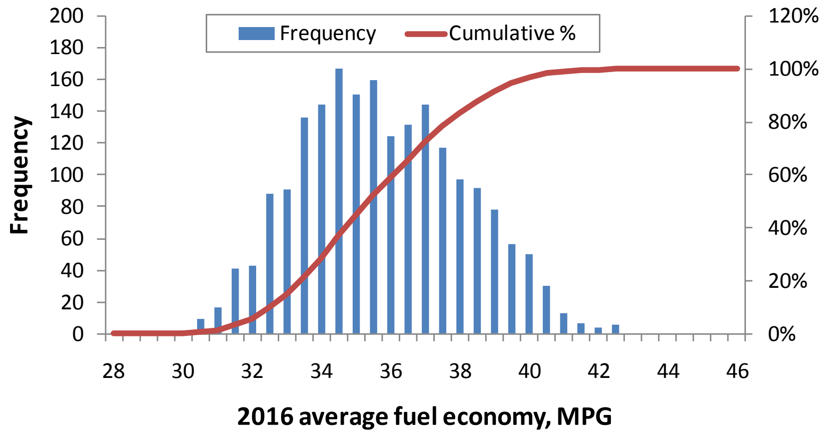
For the inputs, a triangular distribution is used to represent the degree of ERFC, with a mode at 75%. Simple uniform distributions are used to represent vehicle weight and size reduction, and the market share of alternative powertrains within predefined minimum and maximum values. This indicates our initial assumption that:

(a) ERFC will be higher and closer to 75% in 2016;
(b) There is equal probability that weight reduction of 0-25% will take place;
(c) The market share of cars will increase, with equal likelihood of falling in between 51% (current) and 80%;
(d) The market share of alternative powertrains will increase, with equal likelihood of falling in between 6% (current) and 40%;

The output of interest is the average new vehicle fuel economy in 2016. Running the simulation over 2,000 observations, we find that the average fuel economy exceeds the required minimum at 35.6 MPG (see Figure 0-8). In fact, around 70% of all possible input combinations will exceed the average target of 34.1 MPG. Certainly, the input variables are not random, but the Monte Carlo approach indicates that within the predefined limits for the inputs, most scenarios of the future vehicle fleet are able to fulfill the CAFE mandate.

Figure 0-8. Monte Carlo simulation inputs and results: histogram of the average new vehicle fuel economy in 2016

Random input variable	Assumed distribution	Minimum	Mode	Maximum
ERFC	Triangular	0%	75%	100%
Vehicle weight reduction from 2009	Uniform	0%	-	25%
Market share of cars	Uniform	51%	-	80%
Market share of alternative powertrains	Uniform	6%	-	40%



Sample size	2,000
Sample mean	35.5
Median	35.3
Standard deviation	2.4
Minimum	29.2
Maximum	42.5
25th percentile	33.7
75th percentile	37.2
Interquartile range	3.5

H. Life-cycle inventory databases considered

The following table compares various life-cycle inventory databases that were considered in our automotive life-cycle analysis. Ultimately, Argonne National Laboratory's GREET 2.7 database was selected for use.

Table 0-3. Comparison of automotive life-cycle inventory databases

LCI database, organization, year	Description
GREET 2.7, U.S. Argonne National Lab, 2007	Comprehensive list of materials. Brief methodology report included. Does not include transport of materials.
Ecoinvent v2.2, Swiss Centre for Life Cycle Inventories, 2010	Comprehensive list, Europe-centric.
Life Cycle Inventory Analysis of a Generic Vehicle, U.S. Automotive Materials Partnership, 1999	Detailed methodology for steel, Al, and plastics only. U.S.-centric using actual U.S. sources, data from 1995.
U.S. Life-Cycle Inventory database v. 1.6.0, U.S. National Renewable Energy Lab, 2008	U.S.-centric, incomplete list of materials.
Life Cycle Inventory for the Golf A4, VW, 2007	Compiled for purpose of comparing Volkwagen vehicles only.
Life Cycle Inventory Report for the North American Aluminum Industry, The Al Assoc. Inc., 1998	Aluminum only.
U.S. Energy Requirements for Aluminum Production, U.S. DOE, 2003	Aluminum only.
LCA of Aluminum: Inventory Data for the Primary Aluminum Industry, Int'l Al Institute, 2005	Primary production of aluminum only.
LCI data for steel products, International Iron and Steel Institute, 2000	Steel only.

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