Future Vehicle Types and Characteristics: Reducing fuel consumption through shifts in vehicle segments and operating characteristics

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B.A. Science, Technology, and Society
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SUBMITTED TO THE ENGINEERING SYSTEMS DIVISION IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE IN TECHNOLOGY AND POLICY
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

JUNE 2015

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Abstract

Light duty vehicles represent a notable target of regulation in the United States due to their environmental, safety, and economic externalities. Fuel economy regulation represents one of the more prominent attempts to limit the environmental externalities of passenger vehicles entering the U.S. fleet, but focus intently on technology improvements rather than encouraging the sale of more fuel-efficient vehicle segments. More precisely, the current fuel economy standards, which will be phased in between 2012 and 2025, reflect an approach that is explicitly intended to be neutral with regard to the size and types of vehicles sold, with the stringency of the standard scaled to vehicle footprint, or the area between the four wheels. In light of this size-neutral approach to fuel economy regulation, as well as a lack of precedent in the automotive literature, the author examined the extent to which shifts in demand for different light duty vehicle segments can impact fleet-wide LDV fuel demand. Shifts in the demand for LDV segments have occurred in recent decades, with the market share of conventional passenger cars decreasing from more than 80 percent in the early 1980s to just over half today, replaced largely by sport utility vehicles (SUVs) and crossover utility vehicles (CUVs). Though many factors influenced this transition away from conventional passenger cars, available literature suggests that misalignment between fuel economy policy and prevailing market conditions, combined with some protectionist tax policies for the domestic auto industry, were the main culprits. Moreover, a fleet model analysis suggests that the impact in terms of fleet-wide fuel consumption was not trivial, with vehicles sold between 1985 and 2010 consuming, over their entire useful life, over 100 billion gallons of petroleum *more* than if 1985 LDV market segments have prevailed over that period.

This historical analysis provided motivation and justification for exploring the potential for shifts between segments in the LDV market to influence LDV petroleum demand over the next several decades, in order to illustrate the potential missed opportunities of implementing fuel economy regulations that do not encourage the sale of smaller, more fuel-efficient vehicle segments. Using a spreadsheet-based accounting model of the vehicle fleet, the author's analysis suggests that plausible shifts in the market shares of different LDV segments could increase or decrease LDV petroleum demand by up to seven percent, relative to a reference case provided by the U.S. Energy Information Administration (which, in itself, suggests a modest decrease in the demand for SUVs and CUVS through 2040).

The author also explored the potential of a more radical –yet still plausible – change to LDVs to impact fleet-wide fuel consumption over the next few decades. Automating passenger vehicle controls has long been imagined by futurists and tested in various forms by automotive manufacturers since the 1950s, but recent developments stemming from a series of competitions sponsored by the Defense Advanced Research Projects Agency between 2007 and 2011 suggest that increasingly automated vehicle features may soon become a production reality. Though intended primarily as a means of improving safety, automated vehicle systems have the potential to also decrease fuel consumption. Also using the fleet model, the author evaluated the potential of a highway-only partial automation system – akin to systems reportedly being introduced to the market by General Motors and Tesla, among others, within the next two years – to reduce fleet-wide LDV fuel consumption. Results suggest that, depending on a wide range of variables, reductions in fleet-wide fuel consumption of up to two percent are possible by 2050 relative to the Energy Information Administration reference case.

Though the results of the analysis explored in this thesis may seem modest, they are notable nonetheless. Most importantly, they represent reductions in fuel consumption that are possible to achieve *in addition to* those likely to be driven by current fuel economy regulations. Therefore, the changes to passenger vehicles explored in this thesis represent potential strategies for reducing LDV fuel consumption as manufacturers reach the limits of technological improvements to engines.

Thesis Supervisor: John B. Heywood
Title: Professor of Mechanical Engineering

Acknowledgements

First and foremost, I must thank Professor John Heywood for his constant guidance, advice, feedback and encouragement over the past two years. He has been an incredibly supportive, insightful, motivating and, most of all, kind advisor and has made my time at MIT an enjoyable and enriching experience. I also thank my loving and supportive wife for providing constant encouragement and for her patience in returning to a life where we are both free on weekends. I also wish to thank my parents and family for their love and support. Finally, I thank my professional colleagues for loaning me to MIT for two years and being unbelievably accommodating and flexible.

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1. Introduction

1.1. Overview

The world's relationship with the automobile is characterized by tradeoffs. In just over a century, automobiles have enabled mobility for billions of people, yet this newfound freedom has also resulted in extreme dependence on limited natural resources. Motorized nations experience tremendous freedom of movement but must also put up with the significant environmental, public health, and economic impacts that occur as a result. Modern vehicles, therefore, reflect a tradeoff between meeting the needs and expectations of consumers and satisfying policy-driven requirements intended to minimize their externalities, or costs that are incurred by an individual but "paid" by society.

The first fifty years of the automobile's history, particularly in the United States, reflects little concern for these externalities. Early automobiles were barely fast enough to cause serious injury and were surely an improvement over the horses they replaced. A link between the exhaust produced by internal combustion engines and human health concerns – let alone global changes in climate – was not postulated until the 1950s and dependence on foreign sources of oil and the resulting vulnerability to political conflict would not arise until the 1970s (U.S. Environmental Protection Agency, 1994). As a result, early automobile evolution progressed unencumbered, with little attention paid to fuel economy, emissions, or safety. Vehicle design through the 1960s reflected this relative lack of constraints, with the vast majority of models characterized by large and powerful engines, questionable handling performance, and a "bigger is better" mentality toward vehicle size. Fuel economy – if measured at all – rarely exceeded 20 miles per gallon (mpg) and could be measured in single digits in many models. A generally booming economy allowed automobile ownership levels to grow dramatically and led to increased demand for product differentiation.

In the 1960s, however, the environment began to change. Ralph Nader released *Unsafe at Any Speed*, a scathing indictment of the automotive industry's indifference to product attributes that interfered with its ability to turn a profit. In response to both Nader's accusations and growing concerns about vehicle pollution and traffic deaths, Congress passed two historic pieces of legislation: the Motor Vehicle Air Pollution Control Act of 1965 and the National Traffic and Motor Vehicle Safety Act of 1966. Subsequent laws have imposed increasingly stringent standards on the automobile industry but these represent the first significant sources of regulatory influence on vehicle design and engineering.

In the ensuing decades since the passage of the first vehicle pollution and safety laws, vehicle design has evolved dramatically in response to many factors. Regulation has played a significant role in this evolution but its interactions with other factors have at times been even more notable. When regulations and other factors – economic indicators, demographic trends, consumer expectations – align, such laws can be tremendously effective. However, when these factors clash, regulation can be equally effective in producing perverse effects.

As the automobile enters its second century of mass adoption, awareness of its impacts is higher than it has ever been. New policies have entered force with a renewed focus on limiting these impacts but they focus primarily on the adoption of new engine technologies and, in fact, are explicitly intended to be neutral in terms of the sizes and types of vehicles on the market. However, the vehicle types that consumers choose to buy have just as much potential to influence overall fuel consumption as the technology content of the engines that power them. A central focus of this thesis, therefore, will be on the potential for shifts in the relative market shares of vehicle segments to influence fleet-wide fuel consumption over a long-term horizon. A fleet analysis will quantify the benefits of encouraging consumers to adopt smaller, lighter types of vehicles, or conversely, the disbenefits of allowing polices to remain agnostic to vehicle types and sizes. A secondary focus will be on the potential for emerging automated vehicle technology to reduce overall fuel consumption of the light-duty vehicle (LDV) fleet. Combined, these two areas represent an attempt to understand the extent to which anticipated changes to motor vehicles over the next several decades – exclusive of changes to engine technology or fuels – can contribute to fleet-wide reductions in fuel demand.

1.2. Motivation

Previous studies have examined the evolution of light duty vehicles since the 1970s in a largely performance-oriented context, focusing on measures like fuel economy, weight, horsepower, and performance. Though extremely useful, particularly in the context of evaluating policy interventions, these studies must necessarily sacrifice specificity in certain areas and representativeness in others. Specifically, quantifying change in the automotive industry through vehicle performance measures offers an attractive level of precision and clarity, but also masks the heterogeneity in vehicle characteristics that matter to individual consumers. For example, examining the parallel trends of steadily declining fuel economy, increasing vehicle mass, increasing engine size and power, and improved acceleration times (measured in seconds to accelerate from zero to 60 miles per hour) during the 1980s and 1990s provides an overall view that vehicles became heaver, more powerful, and quicker during the period. However, this view masks the fact that vehicle sales during this period also became significantly more diverse, with sales of traditional passenger cars dipping below 50 percent for the first time in 2004.

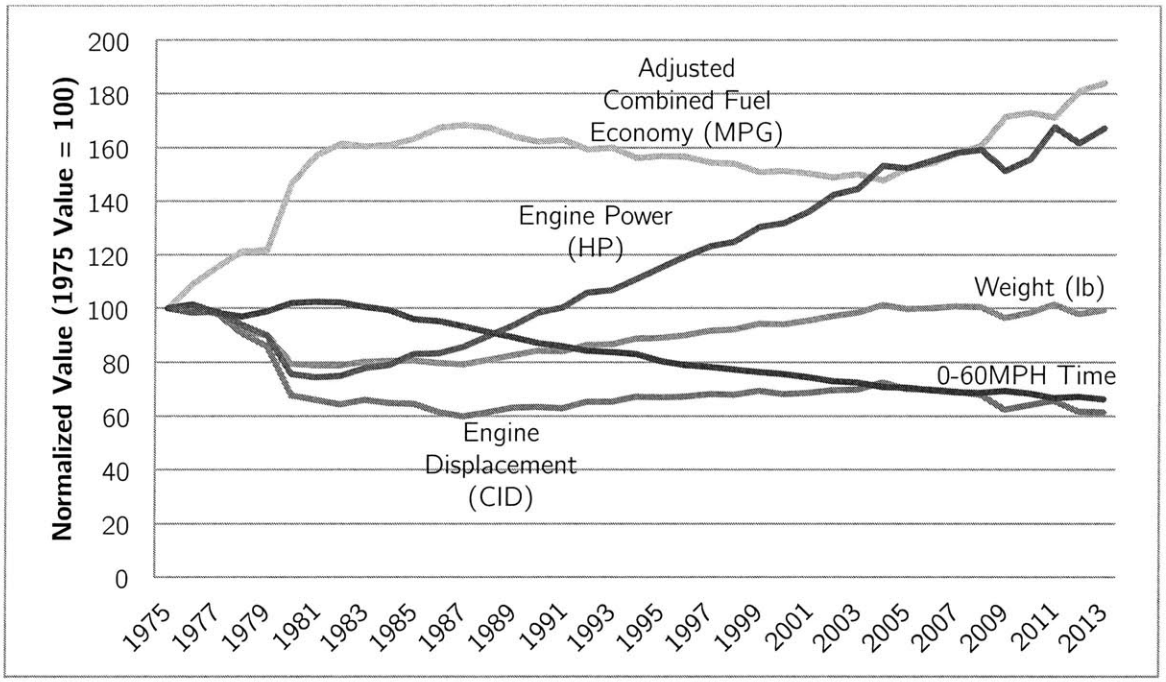

Figure 1: Trends in light duty vehicle performance, 1975 through 2013 (Source: Environmental Protection Agency, 2014)

This thesis, therefore, seeks to build upon previous work by looking at vehicle characteristics that span and influence a range of vehicle performance indicators as well as more broadly at attributes that are likely to change the nature of light duty vehicles as significant energy consumers, substantial household expenditures, a major focus for policy and regulation, and a part of the transportation system. The central focus will be on the potential for new vehicle types to emerge and become significant in the market. Vehicle types refer to different classes of vehicles differentiated based on size, drivetrain characteristics, capabilities, and performance. Although vehicle classifications vary by market and data source, this thesis will rely on those defined and tracked by the United States Environmental Protection Agency (EPA) in its annual *Light Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends* report (U.S. Environmental Protection Agency, 2014). Section 2.2 will provide more in-depth rationale behind using these vehicle type definitions but, in short, the EPA's classifications offer a valuable level of consistency extending back through 1975.

Vehicle types represent an important focus for understanding vehicle evolution, yet they are an underrepresented focus in existing literature. These types represent perhaps the most significant characteristic that consumers examine when making a new vehicle purchase and therefore play an influential role in the overall performance of the light duty vehicle fleet. Unlike most other vehicle attributes that impact performance metrics, vehicle types are not restricted by technology, but are solely determined by consumer demand and market availability. Therefore, they represent an intriguing public policy lever for influencing fuel consumption and emissions. Section 2.3 will also examine how vehicle types can be used as tool to avoid the impact of public policies when they are misaligned with the factors affecting consumer demand.

Changes in vehicle types represent evolutionary forms of changes in vehicle design that are likely to take place in the next three decades, yet more revolutionary changes have recently started to emerge that are likely to significantly shift how light duty vehicles operate. Under development for more than a decade – and imagined for far longer – the potential to automate vehicle controls has quickly captured the attention of the public and automotive industry alike. Futurists and engineers have long envisioned that automation would become a prominent feature of light duty vehicles and despite efforts dating back to the 1950s, the possibility of commercially-available automated vehicles has only become real in the last ten years and has accelerated rapidly over the last five. A series of challenges sponsored by the U.S. Defense Department's Defense Advanced Research Projects Agency (DARPA) between 2004 and 2007 reignited interest in the prospect of truly driverless cars, though Google's 2010 announcement that it had been testing automated vehicle prototypes on public roads and subsequent coverage of its progress has garnered attention from the public as well as major automakers. In fact, at the 2015 Consumer Electronic Show, a trade show typically dominated by personal electronic devices, vehicle automation was one of the most prominent technologies on display, with major concept vehicles or announcements from Mercedes-Benz, Ford, and Audi (Wood, 2015). Other manufacturers, namely Nissan and General Motors, have already made bold announcements stating that they plan to sell vehicles with increasing levels of automation within the next five years (Rosenbush, 2014) (Colias, 2014). This level of involvement and commitment from major manufacturers, along with the demonstrated capabilities of prototypes, suggests a promising future for vehicle automation.

1.3. Organization

The remainder of this thesis will be organized around the themes in vehicle evolution discussed above. Each section will begin with a review of relevant literature documenting the history of the relevant development, previous research where available, and relevant policy motivations. Each section will then discuss the trajectory of research and development and likely trends. Finally, each section will conclude with the results of a scenario analysis of the fuel consumption implications of each development based on a fleet model developed by previous students and significantly modified by the author for the purposes of this research.

1.4. Fleet Model Overview

The fleet model used in this study is a spreadsheet-based accounting model that uses publicly-available data from the EPA, the United States Department of Energy (DOE), and the United States Department of Transportation (DOT) to determine the composition of the American light duty vehicle fleet in future years in terms of vehicle types and vintages and their relative fuel economy performance. The fleet model uses data in four distinct areas for its calculations:

1.4.1. Sales

The fleet model contains sales data from model years 1975 through 2011 compiled from the EPA's *Trends Report* for 2014 for 13 vehicle types (vehicle type categories are discussed in greater detail in Section 2.2). Detailed sales data from prior to 1975 is not readily available but is also unnecessary for accurately characterizing the vehicle fleet from the present year into the future due to vehicle scrappage trends (discussed below). EPA sales data from after 2011 is available, but does not provide sufficient detail on vehicle types for this study. In 2012, the EPA began limiting its categories to five vehicle types (car, truck, van, sport utility vehicle (SUV), and car SUV) without size-based subcategories.

1.4.2. Scrappage

The fleet model uses a logistic function originally developed by Bandivadekar (2008) to approximate the rate at which light duty vehicles are "scrapped" or retired from the vehicle fleet. Based on median vehicle lifetimes for model years 1970, 1980, and 1990 provided by the DOE's *Transportation Energy Data Book*, Bandivadekar estimated median vehicle lifetime for the model years between 1970 and 1980 and between 1980 and 1990, assuming constant median lifetime from 1990 onward (Davis & Diegel, 2007). He then constructed a logistic curve for vehicle scrappage with the following form:

$$r(t) = 1 - \frac{1}{\alpha + e^{-\beta(t-t_0)}}$$

where:

- $r(t)$ = Survival rate of vehicle at age t (i.e., the percent of vehicles sold in a given model year in a future calendar year)
- t = Vehicle age (difference between calendar year and original model year)
- 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_0 = Median lifetime of vehicle for corresponding model year

The fleet model multiplies the sales from all model years by the survival rate for the relevant vehicle age and model year to provide a tally of vehicles from each model year that remain in the fleet during each calendar year. Not only does this provide an estimate of the total fleet size by calendar year, but also a breakdown of the entire fleet by vehicle age, original model year, and vehicle type.

1.4.3. Travel

The Oak Ridge National Laboratory reports average annual vehicle travel by vehicle age in its *Transportation Energy Data Book* (TEDB). The fleet model begins with the TEDB's reported annual mileage for new vehicles in 2001 and adjusts this figure based on historic and projected annual travel growth rates provided in the Energy Information Administration's (EIA's) *Annual Energy Outlook 2014* to derive annual travel figures for new vehicles in each calendar year (Davis, Diegel, & Boundy, 2014) (U.S. Energy Information Administration, 2014). Then, the model applies a uniform usage degradation rate of four percent per year of vehicle age. That is, the model assumes that each vehicle's annual mileage will decrease by four percent for each year it is in the fleet. This is consistent with the average mileage degradation observed in the data provided in the TEDB as well as research by the National Highway Traffic Safety Administration (NHTSA) on vehicle survivability and travel mileage schedules (Lu, 2006). Using vehicle stock and these vehicle travel figures adjusted for age and model year, the fleet model calculates total vehicle travel by vehicle age, original model year, and vehicle type.

1.4.4. Fuel Consumption

The EPA provides data on sales-weighted fuel economy for all vehicle types and sizes sold between 1975 and 2011 (U.S. Environmental Protection Agency, 2014). Combining these data with the data obtained for total annual vehicle travel by model year and vehicle age obtained earlier, the fleet model produces an estimate of total fuel consumption by calendar year. In order to match fleet model outputs with forecasts for LDV petroleum fuel consumption, the analysis only makes use of the EPA's figures for combined adjusted fuel economy. Lower than the test values by about 20 percent, the adjusted figures more closely approximate real-world fuel economy, which tends to be lower due to driver aggressiveness, use of auxiliary systems, and other factors (Mock, German, Bandivadekar, Riemersma, Ligterink, & Lambrecht, 2013).

1.4.5. Growth Rate Assumptions

The fleet model's main purpose is to project total fleet fuel consumption into the future in order to make informed comparisons about the impacts of changes in technology or vehicle characteristics. In order to make these projections, the fleet model must contain assumptions about growth rates in several areas that affect fuel consumption. Though available estimates vary quite widely, the fleet model calculations for this study rely on forecasts and growth rates derived largely from the EIA's *Annual Energy Outlook 2014* for several reasons. First, the EIA is both a credible and impartial source of energy information. Second, the fleet model will be used to compare vehicle sales mix scenarios and the EIA provides a forecast of vehicle type market shares through 2040, which can serve as an ideal reference case. These market share projections may not be entirely realistic – their relative stability contrasts sharply with the volatility that characterizes the last forty years of vehicle sales – but they provide a basis for comparison as well as a means of validating the model. This ability to use EIA data to calibrate the model is the final reason for its selection, as the EIA not only provides projected growth rates, but also its own forecast for light duty vehicle fuel consumption, allowing the model's outputs to be validated against forecasts that rely on the same growth rate values.

Growth rates incorporated into the model include the following:

- Annual Growth in Travel per New Vehicle per Year: 0.1%
- Annual Fuel Economy Improvements: 3% through 2025; 0.5% through 2040
- Annual New Vehicle Sales Growth: 0.64%
- Vehicle Segment Market Shares: See Figure 2

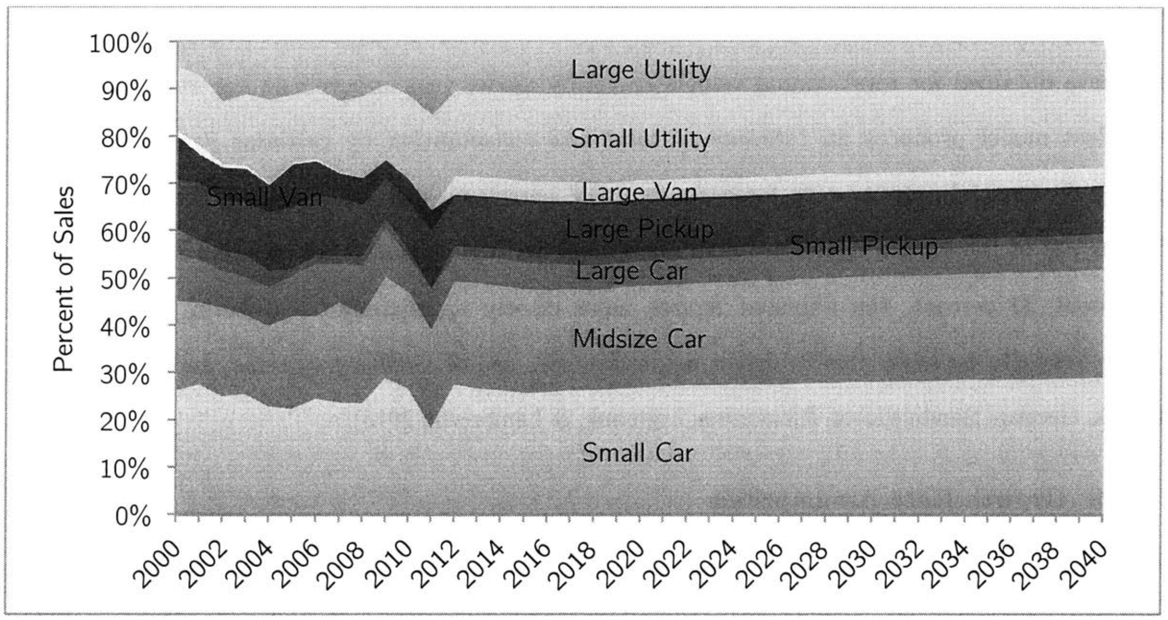

Figure 2: Light duty vehicle segment market shares, 2000 through 2012, with projections through 2040 (Source: U.S. Environmental Protection Agency (2014) and U.S. Energy Information Administration (2014))

1.4.6. Fleet Model Validation

Though the primary purpose of the fleet model is to make comparisons between the impacts of hypothetical scenarios, it is important to validate its outputs in order to justify their relevance outside of the model. As the EIA provides growth rates for key model parameters as well as forecasts of fuel consumption from light duty vehicles, validating fleet model outputs against EIA values was straightforward. Fleet model outputs were also compared to historical fuel consumption data from the TEDB to ensure relative continuity between known historical values and future projections. The results of the fleet model validation are illustrated in Figure 3. The output of the fleet model is generally consistent with the EIA projections.

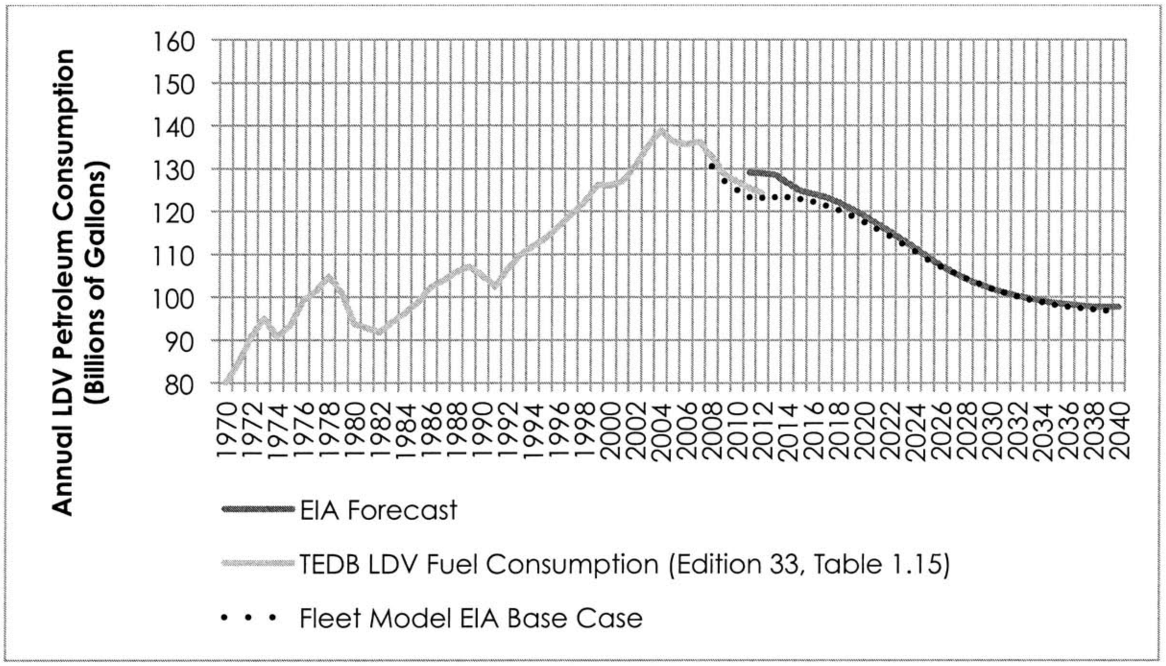

Figure 3: Fleet model validation results (Data Sources: Davis, Diegel, & Boundy, (2014) and U.S. Energy Information Administration (2014))

Both sources suggest that total petroleum consumption will stop declining by about 2040, reflecting the assumptions that (1) new fuel economy regulations will not be passed to replace the current standards, which stop increasing in 2025, but (2) vehicle sales, total fleet size, and per-vehicle travel will continue to increase at a modest rate. Though these assumptions may ultimately prove incorrect, the fleet model's greatest value for the analysis contained in this paper is as a means of comparing the outcomes of potential scenarios rather than predicting future fuel consumption values. Therefore, the intent of validation is to ensure that, given the same assumptions, the fleet model's outputs match those generated by other credible sources, in this case the U.S. Department of Energy.

2. Shifting Vehicle Types and Segments

2.1. Overview

Much previous research has focused on the impact of powertrain technologies on fuel consumption, both at the vehicle and fleet levels, but comparatively little research has focused on the impact of vehicle types and segments on fleet fuel consumption. Though manufacturers must account for the popularity of different vehicle types in ensuring that they meet sales-weighted fuel economy targets, the U.S. has rarely implemented policies intended to directly influence the sales of particular vehicle types in the interest of fuel consumption and emissions.

This section will discuss how new vehicle types – particularly sport utility vehicles (SUVs) – have emerged over the last thirty years and then examine how changes in the market shares of available vehicle segments over the next thirty years could impact fleet-wide fuel consumption. Section 3 will then consider the potential impact of new vehicle segments emerging to represent a significant portion of the new light duty vehicle market.

2.2. Vehicle Segment Definitions

Light duty vehicles – generally considered by the EPA as passenger vehicles weighing less than 8,500 pounds (lbs.) fully loaded with passengers, cargo, and fuel – are classified into segments in different ways depending on the intended use of the definitions. For the purposes of this study, it was important to select a single set of vehicle segment definitions for the sake of consistency. As a preliminary step, the author reviewed several sets of segment definitions to identify the most suitable for this research. WardsAuto tracks vehicle sales using detailed segmentation criteria that reflect characteristics important to consumers, including price, size, body style, performance characteristics, and capabilities (see Table 2). The other relevant set of definitions considered are maintained by the EPA for use in reporting LDV fuel economy and emissions data in its annual *Trends* report. The EPA divides vehicles into five primary segments: cars, car SUVs (otherwise referred to as crossover utility vehicles or CUVs), pickup trucks, vans, and truck SUVs (or simply SUVs). For model years 1975 through 2011, the EPA also subdivided these segments by size using interior volume for the car categories and wheelbase for the pickup truck, van, truck SUV, and car SUV segments (see Table 1). Moreover, instead of using functional characteristics like towing capacity and off-road ability to distinguish between SUVs and CUVs, the EPA definitions differentiate between these two types of vehicles on the basis of four-wheel-drive and weight. The EPA generally considers vehicles with wagon-style bodies and two-wheel-drive, weighing less than 6,000 lbs. to be car SUVs or CUVs. The agency classifies as truck SUVs or SUVs any vehicle with a wagon-like body that either has four-wheel-drive or weighs more than 6,000 lbs. and has characteristics making it suitable for off-road use (e.g., low approach and departure angles allowing for ascent and descent of steep slopes). Finally, with its focus on characteristics that affect fuel economy, the EPA does not distinguish between luxury and regular variants of vehicle segments.

Table 1: EPA LDV size classification criteria (Source: U.S. Environmental Protection Agency (2014))

	Car Interior Volume (cubic feet)	Wagon Interior Volume (cubic feet)	Car SUV Wheelbase (inches)	Truck SUV Wheelbase (inches)	Pickup Truck Wheelbase (inches)	Van/Minivan Wheelbase (inches)
Small	≤109	≤129	<100	<100	<105	<109
Midsize	110-119	130-159	100-110	100-110	105-115	109-124
Large	≥120	≥160	>110	>110	>115	>124

Both sets of vehicle segment definitions have merits for the purposes of this effort. The WardsAuto definitions are far more representative of the attributes and characteristics that consumers use to differentiate between types of vehicles, drawing distinctions between vehicles that seem, overall, less arbitrary than those made by the EPA, which may classify the two-wheel-drive and four-wheel-drive variants of a single model as a CUV and SUV, respectively. For example, the EPA classifies as CUVs the two-wheel-drive Ford Escape, Honda CR-V, and Nissan Murano, but lists the same vehicles as SUVs if equipped with four-wheel-drive (Davis, Diegel, & Boundy, 2014). However, despite certain ambiguities, the EPA definitions have a significant strength that makes them ideally suited for this project. Not only has the EPA maintained a thorough dataset on vehicle attributes for all model years beginning with 1975, but the agency has also propagated changes to its vehicle classification schemes through all model years so that the data are consistent and comparisons between years are valid. Therefore, most of the analysis contained in this thesis will refer to the EPA definitions unless otherwise noted.

Table 2: WardsAuto Light Duty Vehicle Segment Definitions (Source: WardsAuto (2014))

Segment	Typical Price Range	Typical Length	Other Factors
Lower Small Car	Under $14,000	Under 170 in.	4- or 5-door dominant body style
Upper Small Car	$14,500 to $19,500	Under 180 in.	4- or 5-door dominant body style
Small Specialty Car	Under $25,000	Under 180 in.	Predominantly 2-door, 4-passenger or 2+2 seating
Lower Middle Car	$18,500 to $20,500	180 to 190 in.	4- or 5-door dominant body style
Upper Middle Car	$20,501 to $29,500	185 to 200 in.	4- or 5-door dominant body style
Middle Specialty Car	$20,500 to $32,500	Under 200 in.	2-door, 4-passenger or 2+2 seating only
Large Car	$23,000 to $32,500	195 in. plus	Large sedans that are higher in price, or have overall dimensions bigger than typical Upper Middle vehicle
Lower Luxury Car	$29,000 to $43,500	-	4- or 5-door dominant body style
Middle Luxury Car	$43,501 to $64,500	-	4- or 5-door dominant body style
Upper Luxury Car	Over $64,500	-	4- or 5-door dominant body style
Luxury Specialty Car	Over $32,200	-	2-door, 4-passenger or 2+2 seating only
Small Cross/Utility Vehicle	Under $20,500	Under 175 in.	Truck or wagon body style typically with unibody construction, front- or all-wheel-drive and passenger vehicle qualities the dominant characteristic
Middle Cross/Utility Vehicle	$20,500 to $32,500	Under 193 in.	Same as above
Middle Luxury Cross/Utility Vehicle	Over $32,500	Under 193 in.	Same as above
Large Cross/Utility Vehicle	Under $37,500	190 in. plus	Same as above; third-row seats usually standard
Large Luxury Cross/Utility Vehicle	$37,500 plus	190 in. plus	Same as above
Small Sport Utility Vehicle	$23,800	Under 180 in.	Off-road, cargo hauling and towing capabilities a strong characteristic, usually with body-on-frame construction and rear- or 4-wheel-drive
Middle Sport Utility Vehicle	$20,800 to $33,000	Under 195 in.	Same as above
Middle Luxury Sport Utility Vehicle	$33,000 plus	Under 195 in.	Same as above
Large Sport Utility Vehicle	Under $48,800	195 in. plus	Same as above; third-row seats usually standard
Large Luxury Sport Utility Vehicle	$48,800 plus	195 in. plus	Same as above; third-row seats usually standard
Small Van	Under $32,000	Under 210 in.	-
Large Van	$26,000 plus	210 in. plus	-
Small Pickup	-	Under 200 in.	-
Large Pickup	-	200 in. plus	-

2.3. Historical Examples of Vehicle Segments Shifts

2.3.1. Early Evolution of U.S. Vehicle Segments and Characteristics

Light duty vehicles have evolved constantly across many dimensions since their emergence in the late nineteenth century. In their early history, several fuel sources competed for dominance, including steam, electricity, and gasoline. With the success of Ford's Model T between 1908 and 1927, growing availability of gas stations, and the introduction of the electric starter, gasoline became the dominant fuel source, driving steam and electric power out of the market altogether by the 1920s.

Regardless of fuel source, early automobiles resembled little more than modified versions of the horse-drawn carriages from which they evolved. By the 1910s, though, diverse automobile "types" began to emerge, ranging from basic sedans and pickup trucks to opulent touring cars. As the first affordable automobile, the Model T was representative of this diversification, with nine variants available directly from Ford over its twenty-year production run, as well as additional versions built by custom coachbuilders (Ford Motor Company, 2012). Though only produced for five years, the Model T's successor, the Model A, offered even more body styles. Automobile variants became more standardized through the 1940s, by which time most American manufacturers offered two-door coupe, two-door convertible, four-door sedan, wagon, and pickup truck variants of their cars. By the 1950s, American manufacturers had diverged their car and pickup truck lines entirely to be based on different chassis configurations, enabling higher levels of performance and comfort from cars and greater utility from trucks. Between the 1920s and 1950s, American manufacturers also shifted engine options from predominantly four and six cylinders to the eight-cylinder engines that would commonly power American cars into the 1970s; engine power subsequently rose during the 1950s and 1960s.[1] During the 1960s, truck sales grew to represent a larger portion of the American market, from 15 percent in 1965 to 30 percent in 1978 (see Figure 4). American manufacturers also began to segment their lineups by size beginning in the 1960s, introducing compact cars that were up to two feet shorter in length than available full-size models (Rubenstein, 2001, p. 222).

[1] Though detailed data are not available to substantiate this claim prior to 1975, the American automobile market in the 1950s and 1960s was characterized by the availability of increasingly powerful engines (McKraw, 1998, p. 291)

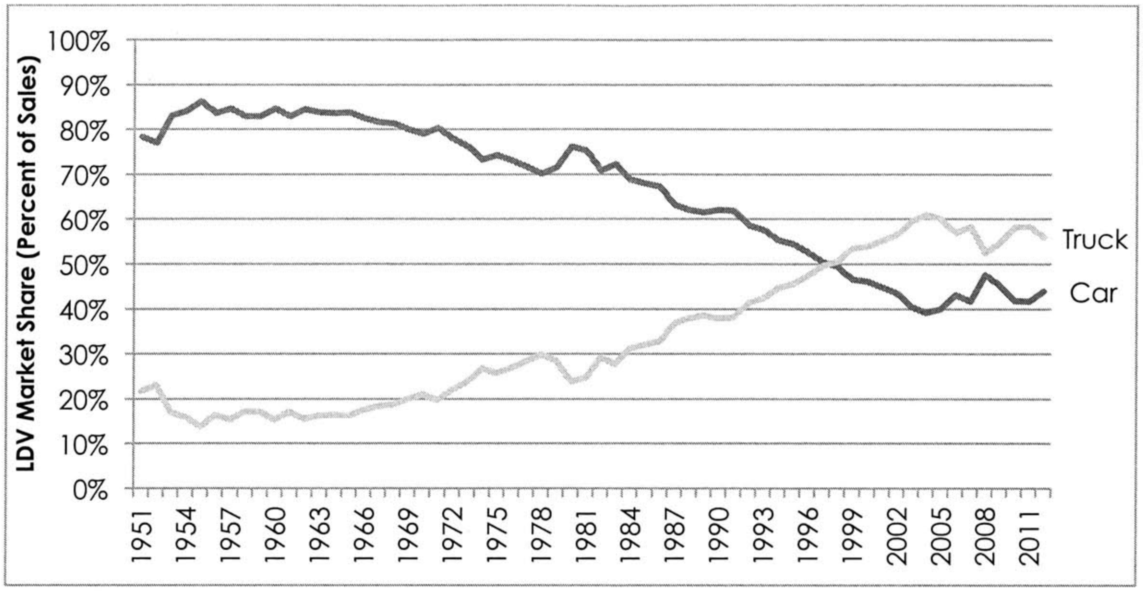

Figure 4: U.S. market share of cars and trucks (Data Source: WardsAuto)

The 1970s represented a significant turning point for the American automobile industry, with the introduction of environmental and safety regulation. For the purposes of this study, the 1970s are also notable in the availability of detailed data regarding automobile characteristics starting in 1975. Several changes have occurred in vehicle characteristics since 1975. Such changes included decreases in average weight into the 1980s and subsequent increases in weight with the addition of new safety features and amenities; substantial increases in engine power, which offset (and then some) weight gains (see Figure 5); and improvements to quality. Vehicles also shifted away from the rear-wheel drive powertrain configurations that were dominant into the 1970s, toward front-wheel drive to achieve better fuel economy and, to a much lesser extent, four-wheel drive (see Figure 6).

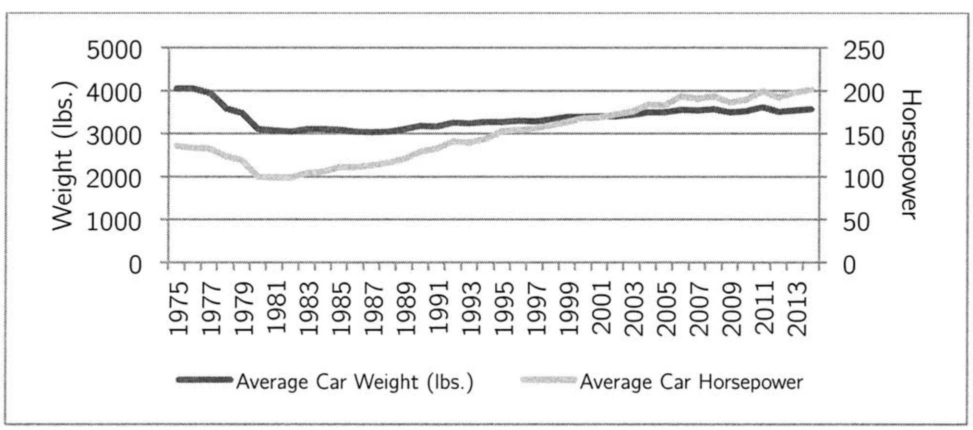

Figure 5: Production-weighted curb weight of new cars sold, 1975 through 2013 (U.S. Environmental Protection Agency, 2014)

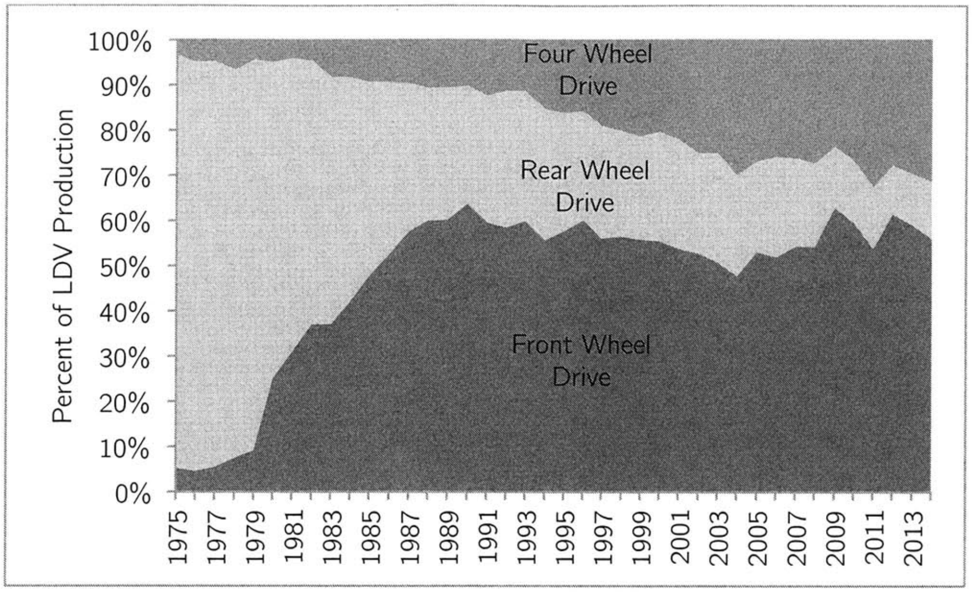

Figure 6: Drive configuration production shares for all LDVs (U.S. Environmental Protection Agency, 2014)

These changes were significant but remained largely transparent to consumers or occurred simply as the result of gradual technology improvements. Previous studies have examined changes along single dimensions like horsepower and performance (MacKenzie D. , 2013), weight (MacKenzie, Zoepf, & Heywood, 2014), and fuel economy (Knittel, 2011). Fewer studies have examined evolution in vehicle design across characteristics, beginning with vehicle types rather than technical features or capabilities. Bonilla, Schmitz, & Akisawa (2012) used a fleet-based model of gasoline demand to assess the relative impacts of projected sales of different vehicle size categories in Japan, finding that vehicle mix, both at the sales and fleet levels, is as important a determinant of gasoline demand as vehicle-specific fuel economy and vehicle travel. Davis & Truett (2000) looked specifically at the impact of SUVs in the United States but restricted their analysis to historic trends and did not anticipate the impact of future potential market share scenarios. The following sections will extend their investigation, focusing particularly on the policy-based factors that contributed to the significant rise in popularity of SUVs over passenger cars.

2.3.2. The Rise of SUVs

The shift away from conventional car "types" represents one of the most significant changes in the American automobile market over the last 30 years. In 1975, cars (by the EPA's definition) represented 80 percent of light duty automobile sales. Their share of sales increased to nearly 85 percent in 1980 only to fall precipitously for the next 25 years. Between 1980 and 1990, two relatively new vehicle types emerged to replace sales of conventional cars. First, vans gained in popularity in the early 1980s, growing as a segment with the help of the first modern minivan, introduced by Chrysler in 1984 (Chrysler, 2015). Though only two percent of annual sales in 1980, the van segment grew to ten percent by 1990, by which time General Motors and Ford had also introduced their own models to compete with Chrysler. The van segment, however, peaked in 1996 at about 11 percent, the same year in which it was overtaken by the similarly new SUV segment.

Like minivans, SUVs offered buyers extra space but, instead of the car-derived front-wheel drive platforms underpinning most minivans, SUVs generally shared their underpinnings with pickup trucks. The platform-sharing approach made them relatively inexpensive to build, yet their high levels of utility and equipment allowed manufacturers to sell them for considerably more than pickup trucks or cars. Ford's Expedition full-size SUV, built on the same chassis as the F-150 pickup truck, reportedly cost $24,000 to build but carried a base price of $36,000 when it was introduced in 1996. The profitability of competing vehicles was not far behind, with Chrysler's Dodge Durango and Jeep Grand Cherokee models earning $8,000 and $9,000, respectively, compared to less than $3,000 on subcompact car models (Rubenstein, 2001, p. 241). Like the trucks on which they were based, SUVs offered a raised driving position, four-wheel drive, and significant towing capacity. Unfortunately, SUVs also suffered from similarly poor fuel economy, emissions, and safety performance.

The American Motors Corporation introduced the first modern SUV, the Jeep Cherokee, at about the same time Chrysler introduced the first minivan, and sales were strong enough to convince Ford and General Motors to introduce four-door competitors, the Explorer and the Blazer, in 1991 (Bradsher, 2002, pp. 48-49). Over the next ten years, SUVs continued to gain in market share as nearly every major manufacturer introduced an SUV model – and many introducing several – by the early 2000s. By the EPA's vehicle segment definitions, a notable milestone occurred in 2004: the conventional car's market share sank below 50 percent for the first time since the agency began tracking such data and SUVs exceeded one quarter of the LDV market (U.S. Environmental Protection Agency, 2014).

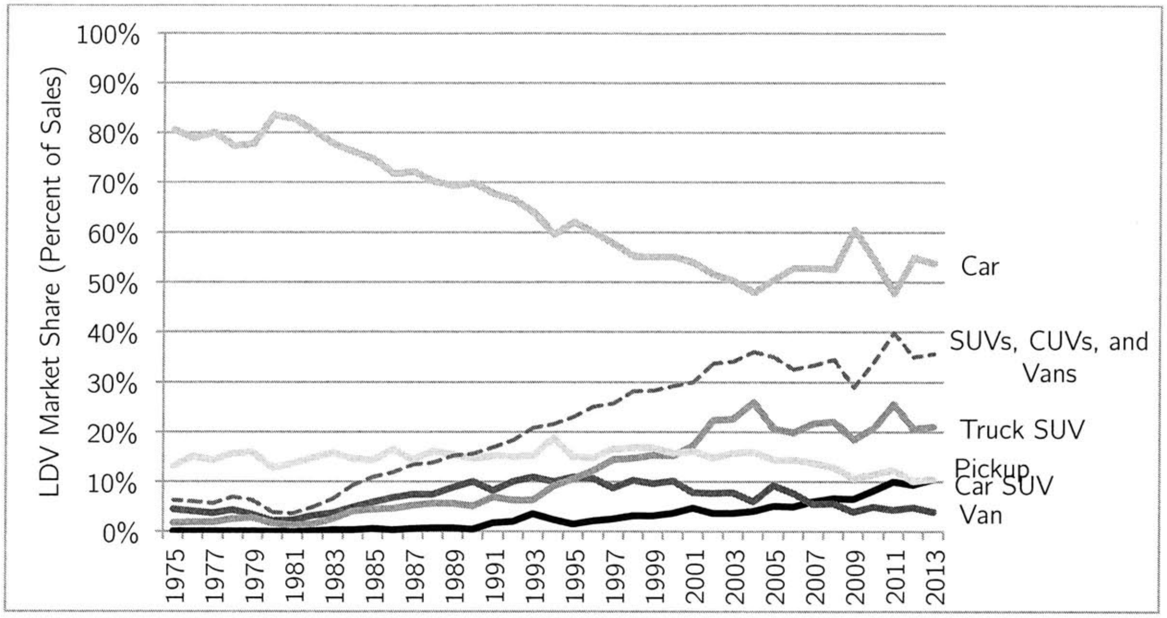

Figure 7: Light duty vehicle market shares, 1975-2013 (Source: U.S. Environmental Protection Agency (2014))

Beginning in the late 1990s, another new type of vehicle began to emerge that would also take a significant portion of the LDV market away from conventional cars. Car SUVs in the EPA's terminology, crossovers, or CUVs combine many attractive features of cars and SUVs. They retain the high driving position, ground clearance, cargo capacity, and four-wheel-drive availability of SUVs, but share many engineering characteristics with cars. For example, while most SUVs shared their body-on-frame structures with pickup trucks into the early 2000s – where the vehicle's body is mounted to a separate frame, to which the engine and suspension are also affixed – CUVs generally use unibody construction, where the body and frame are integrated into a single structure. This type of design sacrifices some strength, reducing towing and hauling capacity, but also reduces weight relative to body-on-frame (MacKenzie, Zoepf, & Heywood, 2014).

The market share of traditional cars has recovered somewhat since the peak of SUVs and CUVs, but has settled at just 55 percent, relinquishing more than one third of the LDV market to alternative types of passenger vehicles.[2] The transition away from vehicle production dominated by traditional cars towards a

[2] The 2009 and 2011 model years experienced anomalous conditions that make them less representative of recent trends. In 2009, the economic recession, combined with high gasoline prices and the Car Allowance Rebate System – more commonly known as "Cash for Clunkers" – contributed to a boost in the market share of small cars. Conversely, the significant earthquake and tsunami that struck Japan in 2011 had a lasting effect on

more heterogeneous mix of vehicle types represents a significant shift that does not appear to be short term in nature. Given the magnitude of this shift – the production share of cars fell by more than 40 percent between 1980 and 2004 – a single, clean explanation seems unlikely. Instead, the nature of this change appears rooted in a combination of government policies, factors affecting consumer demand, and incentives among manufacturers (Sperling & Gordon, 2009, pp. 21-22). Pressure from any one of these influences would have been unlikely to produce the same effect – or an effect of the same magnitude – independent of the others. Moreover, several factors were likely at work within each of the categories to produce a cumulative effect. The following sections outline several of the most prominent influences that played a role in expanding the adoption of vans and SUVs over conventional cars.

Government Policy – Fuel Economy

The U.S. Congress introduced Corporate Average Fuel Economy (CAFE) standards in 1975 as part of the Energy Conservation and Policy Act, largely in response to the 1973 energy crisis. The crisis imposed significant restrictions on oil imports into the United States, leading to gasoline shortages and rationing schemes, and required drastic measures to decrease fuel consumption, including the introduction of a nation-wide 55 mile-per-hour (mph) speed limit. Oil imports were restored in 1974 but at prices that were triple their pre-oil embargo levels. The CAFE standards were set at a sales-weighted average of 18 mpg for cars in 1978 and rose to 27.5 mpg for model years 1985 and later. Light trucks were required to meet a less stringent standard of 20 mpg by 1985. These standards remained in place through model year 2004. At the time of CAFE's introduction, American manufacturers were ill-prepared to meet them with small, fuel-efficient cars. They previously held less than 15 percent of the market for compact and subcompact cars while nearly the market shares of foreign competitors were heavily concentrated in the subcompact segment (Rubenstein, 2001, p. 224). Though they initially opposed the new CAFE regulations, American manufacturers instead decided for legal and publicity reasons to downsize and redesign their vehicles to achieve the fuel efficiency required to meet the CAFE targets. However, doing so required a drastic shift, as fleet-wide fuel economy was just 12 mpg in 1975, with the sales-weighted average for new cars sold by Ford, General Motors, and Chrysler not much higher at 13 mpg (Rubenstein, 2001, pp. 229-231) (Kurylko, 1996). Then president of General Motors, Pete Estes, admitted, "We didn't know how to meet the 27.5

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the Japanese automotive industry. With Japan supplying the US market with a disproportionate share of small cars, the small car market share fell relative to adjacent model years.

mpg fuel economy average for 1985 except by building 92 percent Chevettes. That was the case at the time, and in saying so, I didn't mean that we were not working to do better" (Kurylko, 1996).

Ford and particularly General Motors and Chrysler initially approached the problem by downsizing their models and substituting plastic and aluminum for steel. These strategies were not only expensive, but they also reduced perceived quality and created confusion around model differentiation strategies that had previously emphasized vehicle size (Rubenstein, 2001, p. 232). Japanese manufacturers, already adept at building small, fuel-efficient cars for their domestic market, took full advantage of American manufacturers' difficulties in meeting the new fuel economy standards (Bradsher, 2002, p. 37). Foreign manufacturers quickly increased their market share by ten percent following the 1978 introduction of the passenger car CAFE standard (see Figure 8).

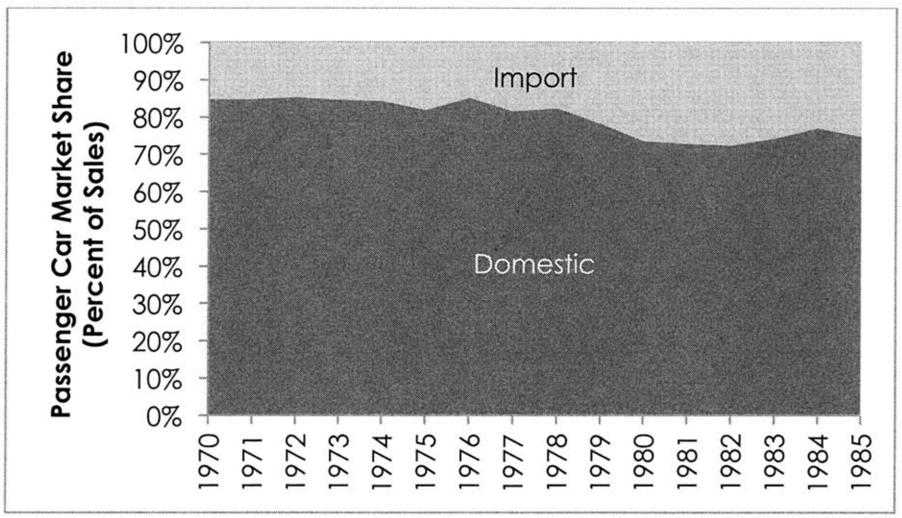

Figure 8: Domestic and import passenger car market shares (Data Source: TEDB)

The CAFE standards, as set in 1975, introduced several incentives that would have a strong influence on the introduction of SUVs about a decade later (Sperling & Gordon, 2009, p. 53). First and quite obviously, manufacturers could much more easily meet the less stringent standard for light trucks. In 1975, cars and pickup trucks were similarly inefficient; the sales-weighted average fuel economy was just 1.6 miles per gallon higher for cars than it was for pickup trucks (see Figure 9). Manufacturers needed to sell smaller, lighter cars to meet the 27.5-mpg standard by 1985 but faced a much less significant challenge to meet the light truck standard. Illustrative of this incentive was Chrysler's interest in having its original minivans classified as trucks rather than cars, despite the fact that they shared most drivetrain and chassis components with cars (Rubenstein, 2001, p. 242).

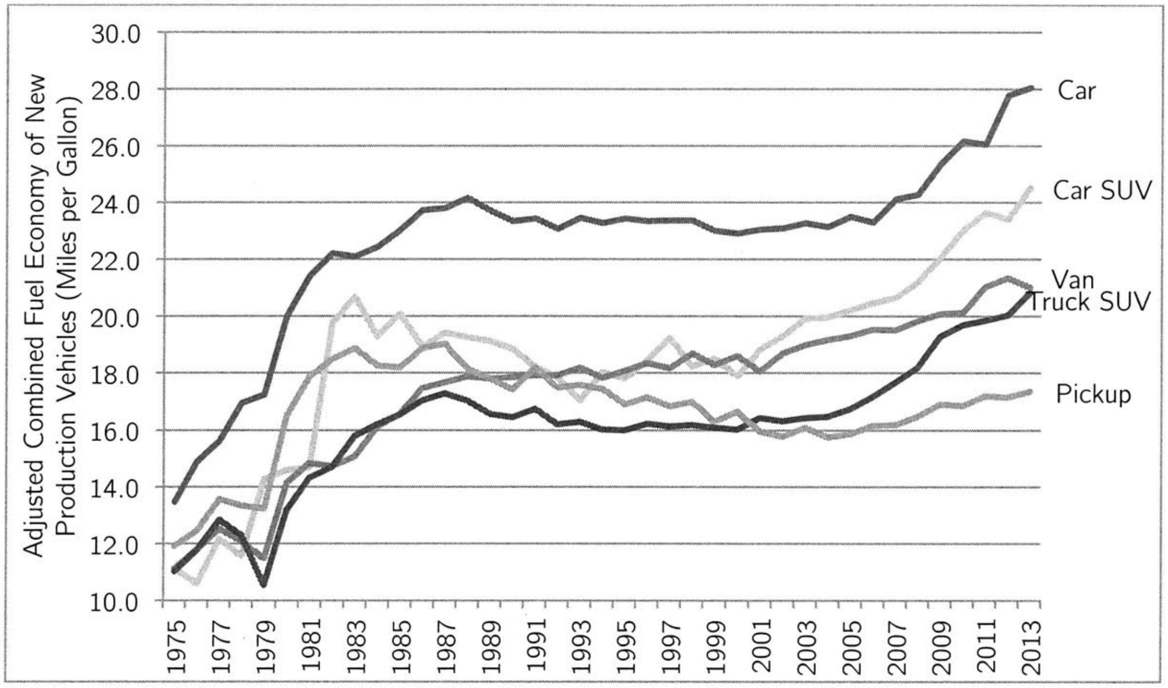

Figure 9: Production-weighted adjusted fuel economy of new production vehicles by type (miles per gallon) (*Source: EPA*)

Perhaps less obviously though, the different means of establishing the car and light truck CAFE standards made the light truck standards far more susceptible to regulatory capture. The car standards were established legislatively, set directly by Congress. Changing them, therefore, would require another act of Congress. When the CAFE standards were passed, light trucks were largely owned and driven by small businesses with legitimate needs for their towing and hauling capabilities. In order to avoid setting unreasonable standards for trucks that would decrease their capabilities and increase their price, thereby hurting small businesses, Congress directed DOT to set a fuel economy standard for light trucks and review it every one to two years. This approach introduced significant flexibility and created opportunities for industry influence in reviewing the standard. In fact, when the DOT considered increasing the light truck standard in 1994, the automotive industry lobbied Congress to insert a "freeze rider" into the Department's funding bill prohibiting it from doing so. That rider remained in place for ten years (United States Public Interest Research Group, 1999).

Government Policy – Import Taxes

The introduction of fuel economy standards for cars and light trucks in 1975 was instrumental in encouraging the sale of light trucks as replacements for passenger cars, but it seems unlikely that it would have produced such a significant shift in the absence of other incentives. In fact, such incentives were introduced inadvertently over a decade before the establishment of CAFE standards in response to, of all things, poultry exports to Europe. In 1962, facing steep price competition from the United States, the European Economic Community (a predecessor to the European Union) imposed a steep import tax on chicken. In an effort to retaliate in a manner that was nominally nondiscriminatory yet targeted to western Europe, President Lyndon Johnson imposed import taxes on four products: potato starch, brandy, dextrine, and light trucks (Johnson, 1963). Responsible for 90 percent of trucks imported to the United States at the time, West Germany's Volkswagen was the obvious target of the 25 percent truck import tax (Rubenstein, 2001, p. 237). This specificity was intentional, as West Germany was the strongest supporter of the tax on imported poultry. The so-called "chicken tax" on light trucks was relatively inconsequential following its introduction. Volkswagen stopped exporting its small pickup trucks to the United States, just as American farmers stopped exporting chicken to Europe. The tax, however, remained in place and played a critical role in enticing domestic manufacturers to sell SUVs and minivans as replacements for conventional passenger cars (Bradsher, 2002, pp. 11-13).

When the CAFE standards entered force in 1978, foreign manufacturers, particularly those from Japan, were in a far better position to meet them than domestic manufacturers. Companies like Toyota and Honda had emerged from post-war Japan to supply their domestic market with small, basic, frugal vehicles (Section 2.3.3 will examine this trend in greater detail). Such vehicles made little sense in the United States in the 1950s and 1960s when fuel was inexpensive and requirements for fuel economy nonexistent. However, energy crises and fuel economy standards in the 1970s and 1980s spurred demand for smaller, more efficient vehicles that American manufacturers were not yet prepared to build. Imported vehicles began to erode the near-monopoly that domestic manufacturers had maintained since the Model T, beginning with the 1973 oil crisis and accelerating with the introduction of CAFE standards. By comparison, relatively lax fuel economy standards, combined with the chicken tax, created a clear opportunity for American manufacturers in the light truck market.

Figure 10 illustrates the declining market share General Motors, Chrysler, and Ford (collectively and colloquially known as the "Big 3") in the U.S. passenger car market, attributed in no small part to the introduction of CAFE standards and the inability of U.S. manufacturers to meet them with competitive products. The figure also illustrates the ability of the Big 3 to retain their high market share in the light truck market, due in part to the protectionism provided by the "chicken tax." The Big 3's light truck market share did begin to decline in the mid 1990s after foreign manufacturers started assembling trucks in the United States to avoid the "chicken tax" (see Figure 11), but by this point the SUV market had already become fairly well established and the American manufacturers had begun to sell competitive passenger cars capable of meeting the CAFE standards.

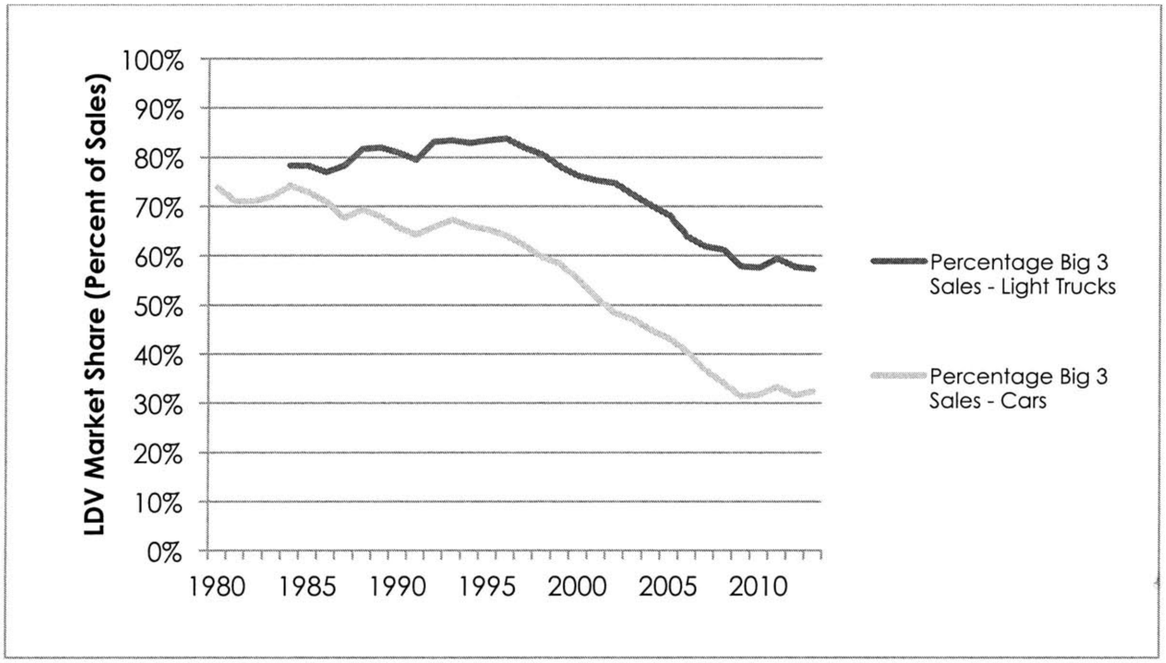

Figure 10: Car and light truck market share of General Motors, Chrysler, and Ford (collectively referred to as the "Big 3") (Source: Davis, Diegel, & Boundy, 2014)

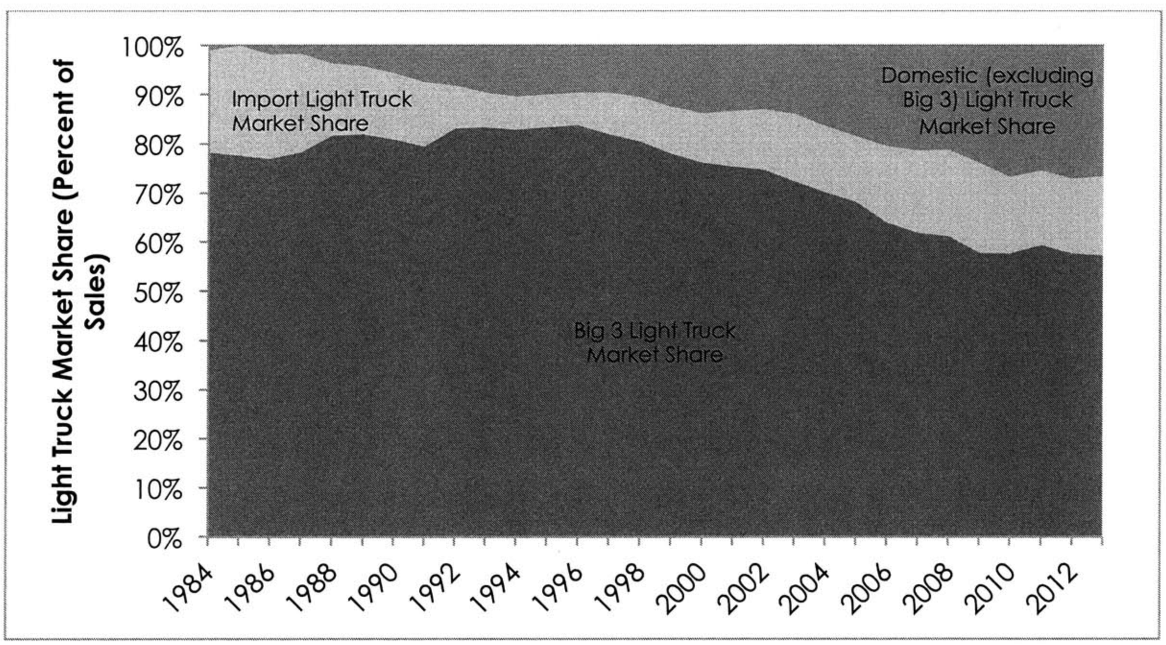

Figure 11: Light truck market shares of imported trucks, the Big 3, and domestically produced foreign brand trucks (Source: Davis, Diegel, & Boundy, 2014)

Market Forces

Though government policies played a large role in spurring the popularity of SUVs, their misalignment with prevailing market conditions was equally significant. Perhaps most noticeable was the sharp drop in fuel prices the same year in which the passenger car CAFE standard reached its maximum level. Fuel prices returned to record low levels in 1985, just as the CAFE standards reached their full extent, and continued to decline for more than a decade (see Figure 12). Household income had also recovered to levels seen prior to the recessions that began in 1980 and 1981 (see Figure 13). With passenger car CAFE standards limiting the extent to which manufacturers could sell large, extravagant cars, American manufacturers found a loophole. Not only did truck-based SUVs have to meet lower fuel economy standards, but they were also subject to the 25 percent "chicken tax" imposed on imported light trucks. SUVs, therefore, represented the ideal vehicle for American manufacturers to sell as formidable foreign competition dominated the small car market.

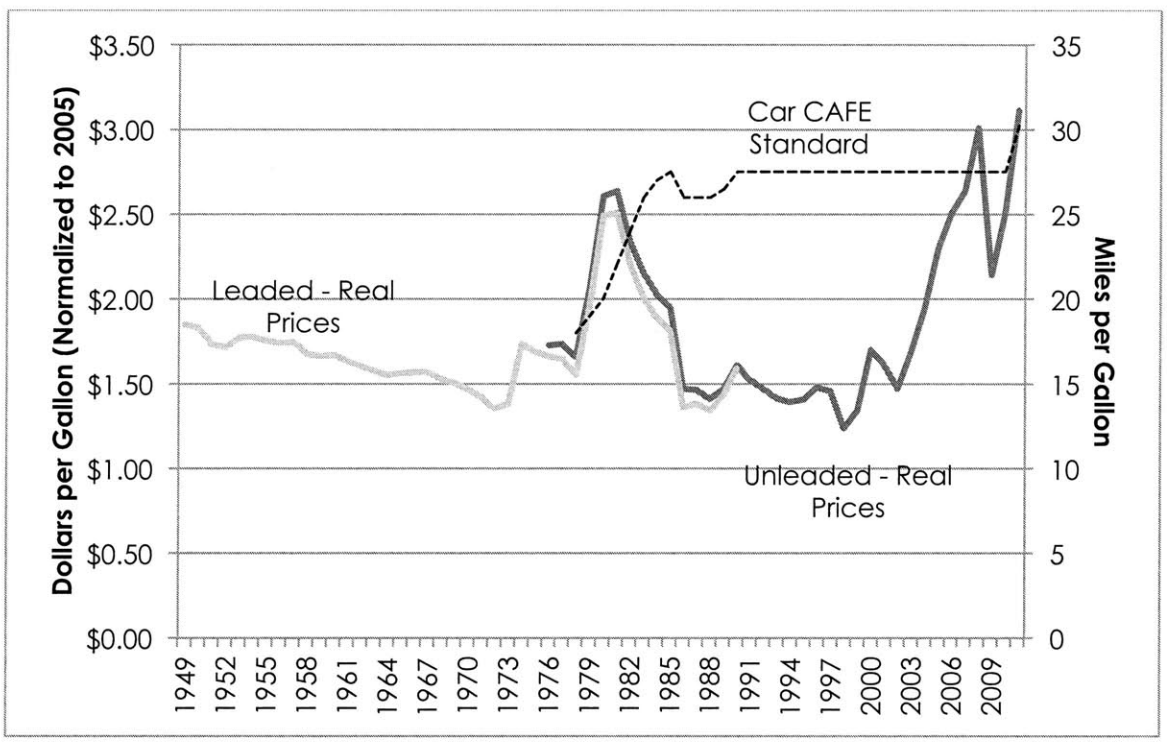

Figure 12: Historic retail gasoline prices (normalized to 2005 dollars; left scale) and CAFE standards for cars (right scale) (Source: Department of Energy and NHTSA)

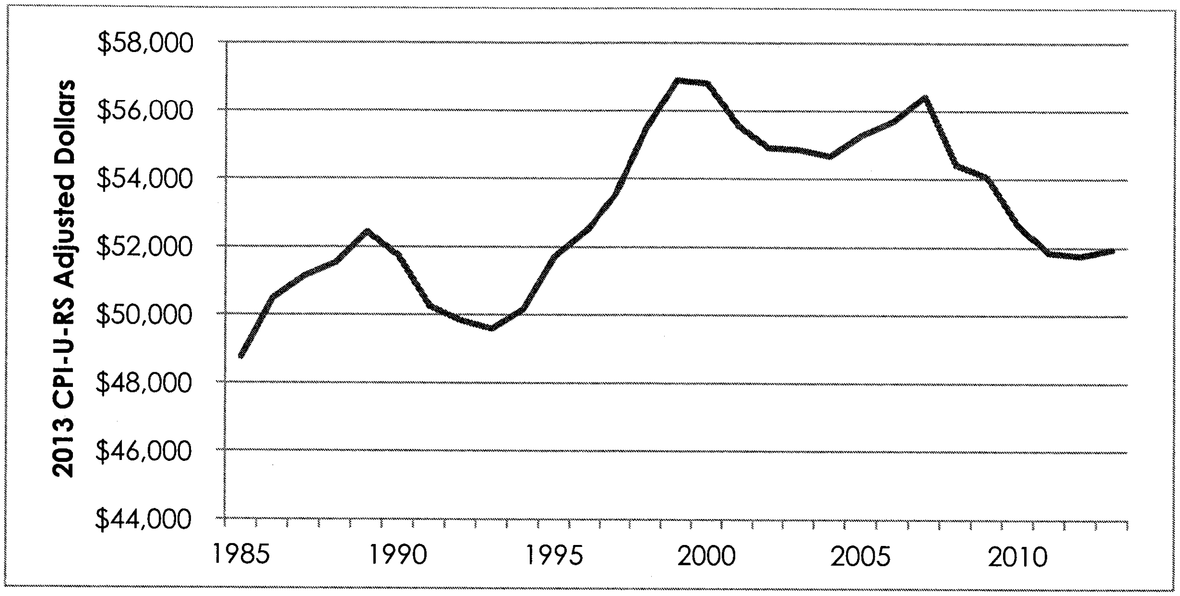

Figure 13: Real median household income (Source: Federal Reserve Bank of St. Louis)

Implications

The SUV boom continued until about 2004 when two abrupt changes occurred. First, fuel prices spiked from their all-time low levels in the late 1990s to an all-time high by 2008 due to record-high demand and constraints in both supply and refining capacity (Kreil, 2007). This rapid increase left average fuel prices at higher than $3.00 per gallon, where they have generally remained until recent falls due to reduced demand and increased domestic supply. Second, in 2003, the administration of President George W. Bush raised the CAFE standard for light trucks for the first time in nearly 20 years[3] so that they would have to achieve a sales-weighted average of more than 24 mpg by model year 2011 (National Highway Traffic Safety Administration, 2003). Though environmental groups criticized the new standards for doing too little, scoffing at the anticipated savings of 10 billion gallons of fuel, they effectively curbed the increasing market share of SUVs, particularly those based on truck chassis (Pressler, 2005).

Given both the actual and perceived inefficiency of SUVs as replacements for passenger cars, it is worth considering and evaluating their true impact. The fleet model introduced earlier provides a means of understanding the extent to which SUVs actually increased fleet-wide fuel consumption, though with some limitations. In particular, limited data are available for LDV sales prior to 1975 and are, therefore, not included in the model. However, the maximum lifetime of a vehicle is assumed to be nearly 25 years

[3] The light truck CAFE standard fluctuated between 20 and 20.7 mpg between 1986 and 1996 due to USDOT reviews.

so the model cannot produce an accurate representation of the fleet – and therefore, it's annual fuel consumption – until calendar year 2000. One workaround is to evaluate fuel consumption by model year – that is, the total lifetime fuel consumption of vehicles sold in a given model year – instead of fuel consumption by calendar year.

In order to determine the impact of SUVs using this metric, a hypothetical sales scenario must be developed in which SUVs do not replace passenger car sales in significant numbers. Figure 14 illustrates the "baseline" scenario, or the actual sales of cars, SUVs and CUVs, and other light trucks for the period from 1986 to 2008. Figure **15** depicts a hypothetical sales scenario in which total sales remain unchanged from their actual values, but the relative market shares of cars, SUVs and CUVs, and other light trucks are held constant at their 1985 values. Therefore, SUVs and CUVs grow to no more than five percent of the LDV market, whereas their actual market share reached a peak of one third in 2004.

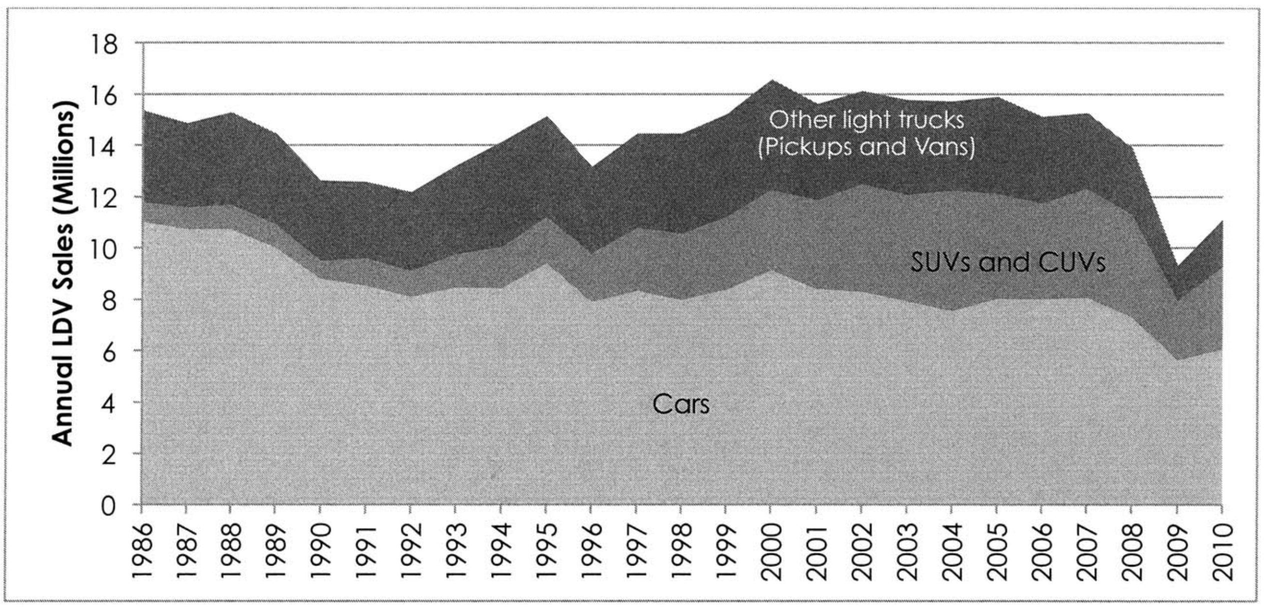

Figure 14: Annual LDV sales, 1986 to 2008; actual market shares (Source: EPA)

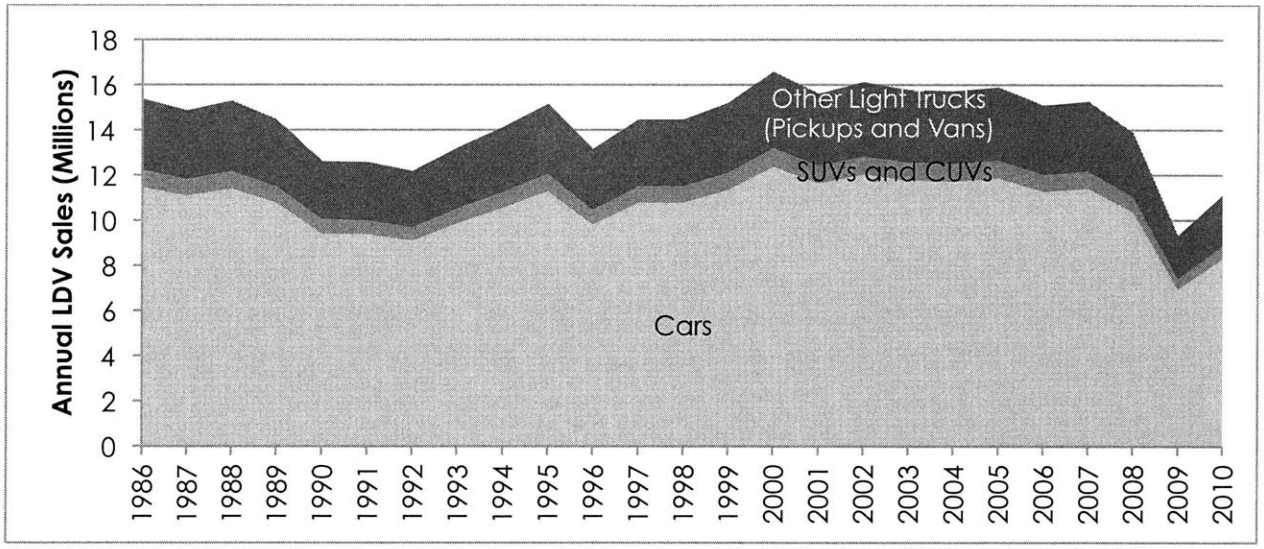

Figure 15: Annual LDV sales, 1986 to 2008; market shares held to 1985 values (Source: EPA)

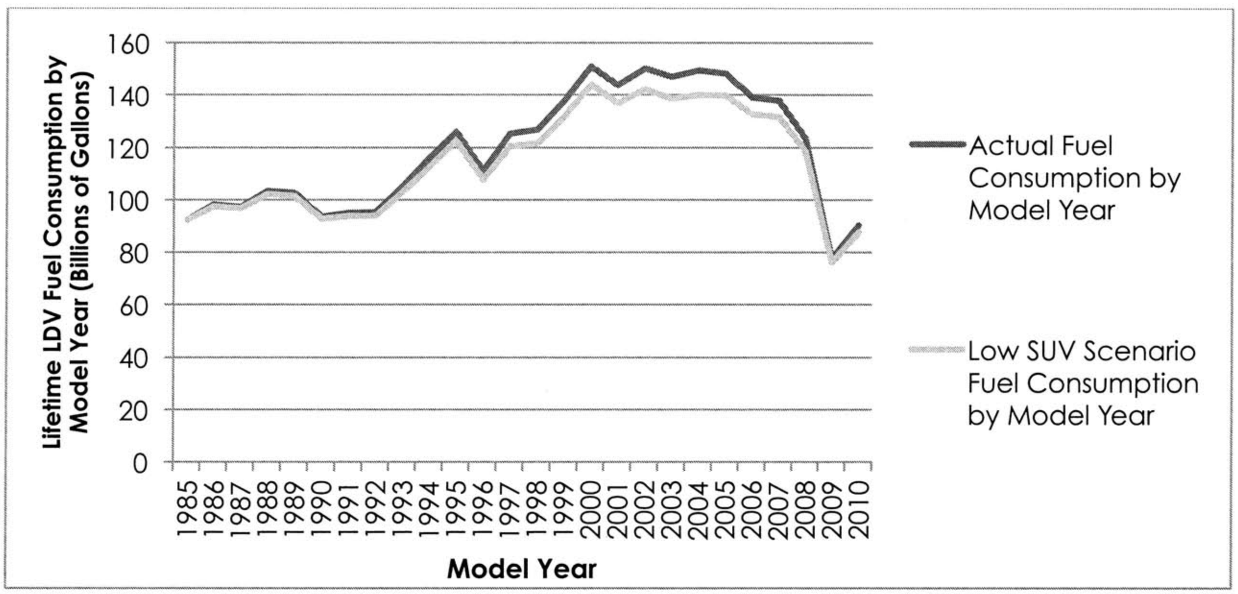

Figure 16 illustrates the difference in lifetime fuel consumption by model year produced under each scenario. Though they are quite close during the 1980s, the results diverge during the 1990s as the popularity of SUVs increases in the actual scenario, but remains constant in the hypothetical low SUV sales scenario. Fuel consumption plummets for both scenarios in 2008 and 2009, as vehicles become more fuel efficient and sales slump with the economic recession. Figure 17 illustrates the cumulative impact of the shift to SUVs covered in this section and the results are significant. In total, passenger vehicles sold between 1985 and 2010 will consume, over their lifetime, more than 100 billion gallons of fuel *more* than if 1985 market shares had prevailed for those model years. For perspective, this is not much lower than current levels of annual of petroleum consumed in the United States by LDVs (see Figure 18).

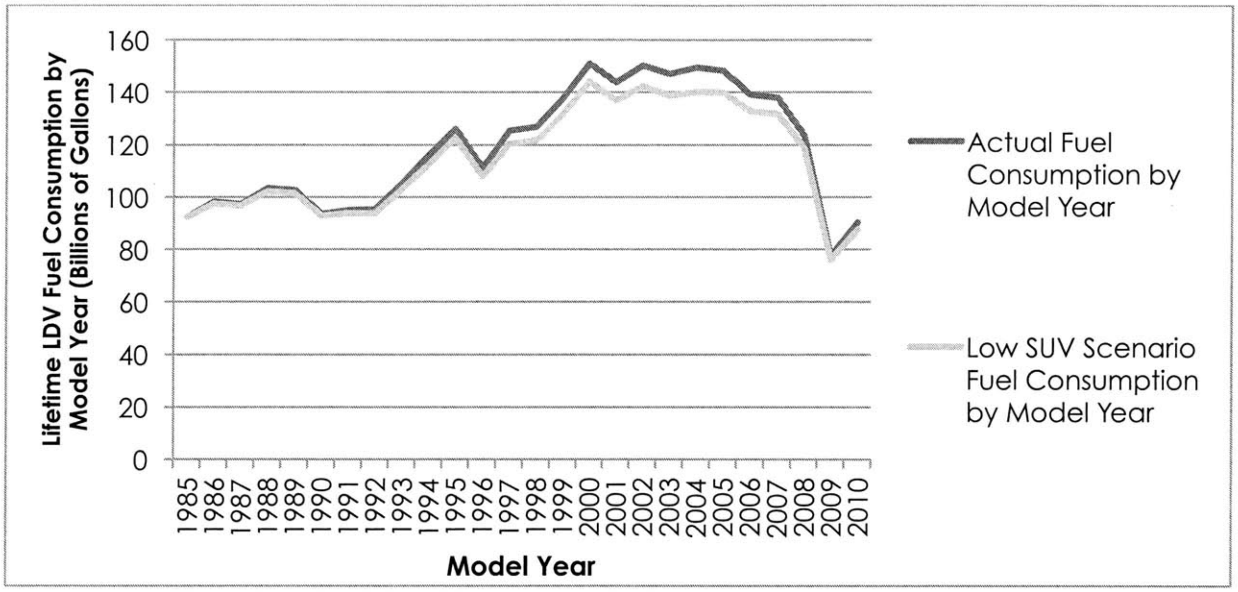

Figure 16: Comparison of actual sales versus a low SUV sales scenario in terms of lifetime fuel consumption by vehicles sold in each model year

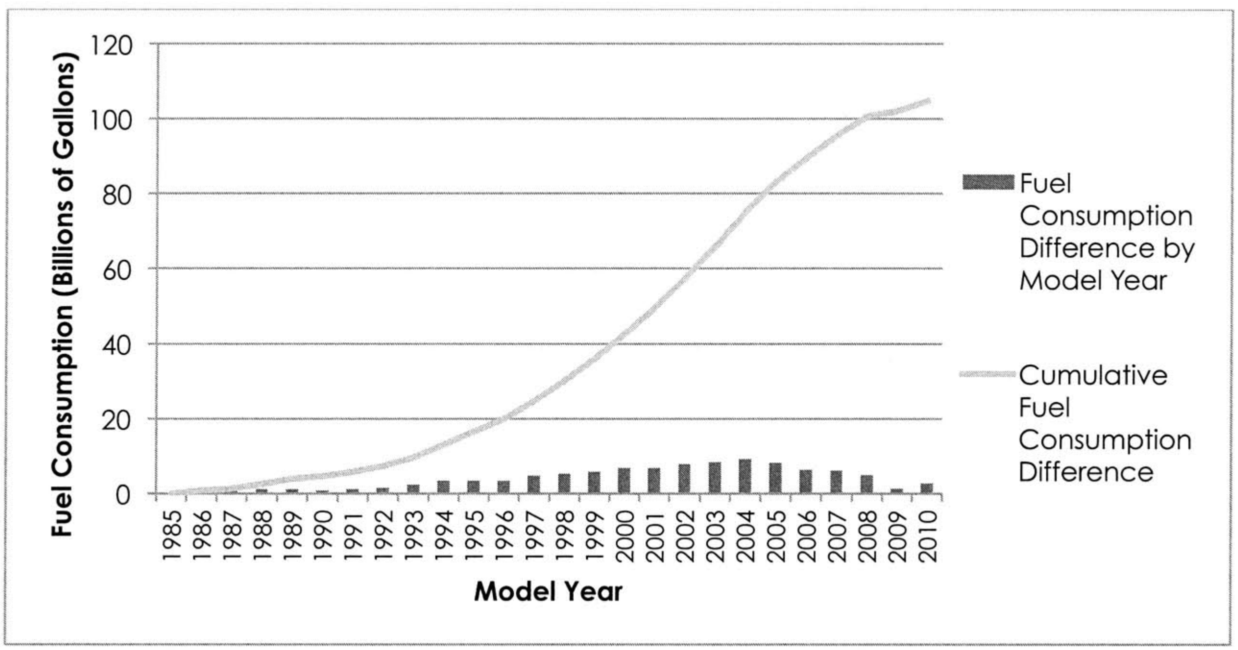

Figure 17: Year-to-year difference in fuel consumption between actual sales and low SUV sales scenario; cumulative difference in fuel consumption between scenarios

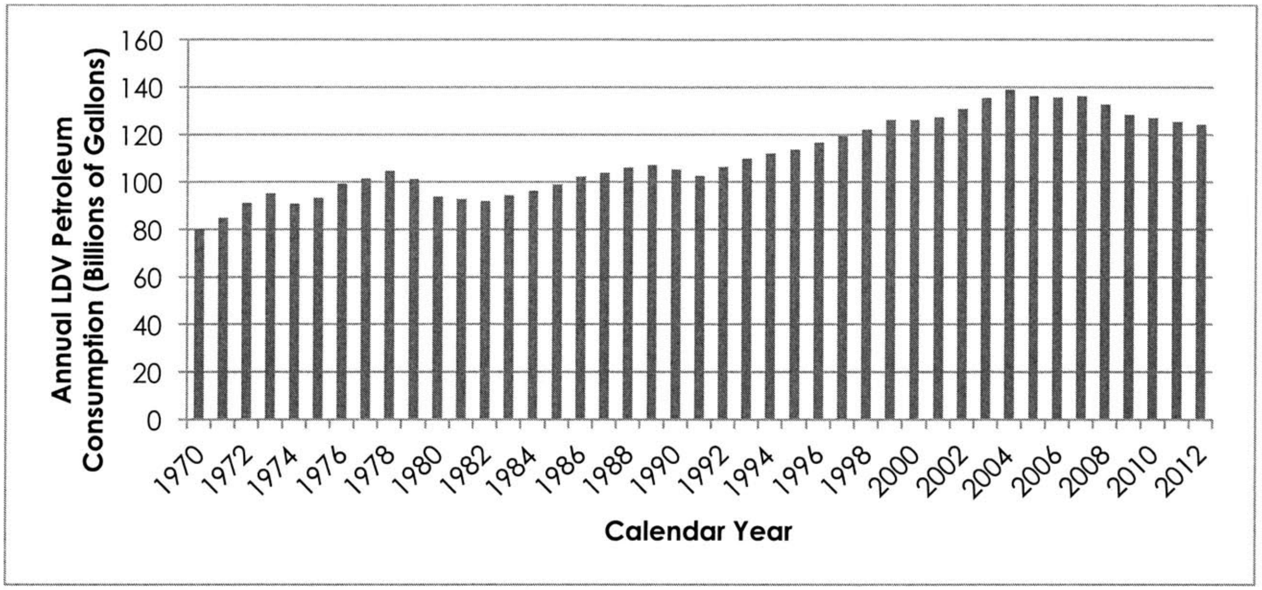

Figure 18: Annual LDV petroleum consumption (Source: Transportation Energy Data Book 2014)

2.3.3. Segment Shifts in Japan

At about the same time that SUVs were gaining in popularity in the United States, Japan experienced its own significant vehicle market shift at the opposite end of the size spectrum. Though the polar opposite of the SUVs that became wildly popular in the United States, Japanese kei jidōsha (literal translation: "light automobile"), or kei cars, grew out of similar policy conditions. These policies were intended to incentivize the production and sale of diminutive and efficient cars, whereas SUVs represented more of an unintended consequence of regulating fuel economy.

Kei cars (interchangeably referred to as mini cars and light cars) are an official classification of cars in the Japanese market that fit within specific size and engine capacity limitations. The maximum allowable engine size has increased over the last few decades but currently stands at 660 cubic centimeters (cc); for reference, the average engine capacity for vehicle sold in the United States is about three liters, or 3,000 cc (Bonilla, Schmitz, & Akisawa, 2012) (U.S. Environmental Protection Agency, 2014). Body dimensions are also capped at 3.4 meters long, 1.5 meters wide, and 2 meters tall (Ingram, 2013).

The significant growth in popularity of kei cars as part of the Japanese automotive market has been particularly notable given their diminutive size. Like SUVs in the United States, kei cars once represented a niche market but have since become a significant portion of sales. In just two decades, their market share has doubled, following much the same trajectory as SUVs (see Figure 19). Exploring the policy basis for this trend further strengthens the parallels between these two cases.

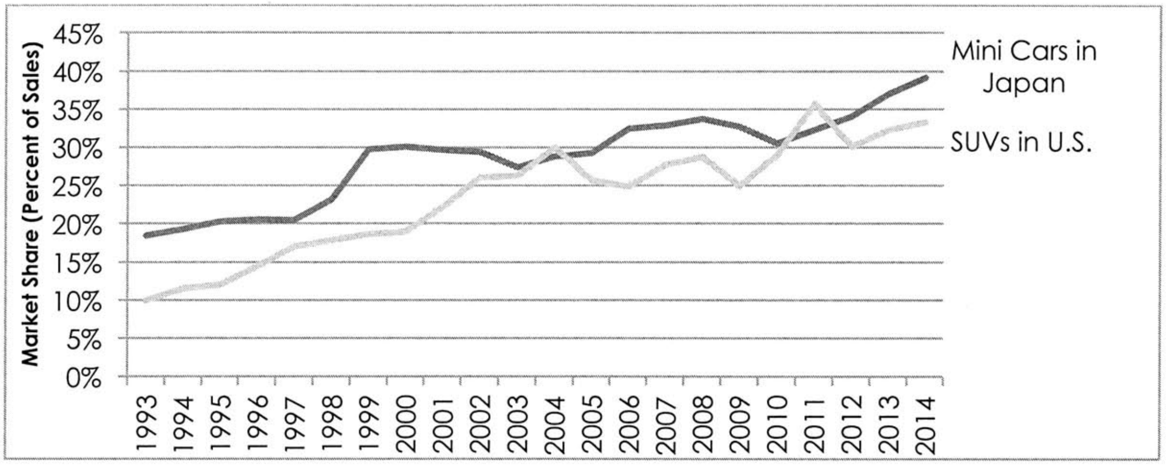

Figure 19: Market shares of kei cars in Japan (Data Source: JAMA) and SUVs in the United States (Data Source: EPA)

Kei Car Origins

Though kei car sales have experienced significant growth over the past few decades, they have been available on the Japanese market since the recovery of the Japanese auto industry following World War II. In 1950, fewer than 43,000 passenger cars were registered in Japan, less even than the fleet size just prior to the war (Townsend, 2013). The period from 1955 to 1973 saw unprecedented growth in the Japanese automotive market, and the kei car played a significant role in this growth in no small part due to favorable government policies. Definitions of a mini car category appeared in regulations as early as 1949, restricting length to 1.8 meters and engine size to just 150 cc. By 1954, maximum length had been increased to 3 meters and engine capacity was capped at 360 cc, a standard that would remain in effect for more than two decades (Kashima & Koshi, 1984). Vehicles conforming to this standard enjoyed many advantages compared larger vehicles, making them extremely popular first cars for many Japanese households. Kei car owners were not required to house their car in a dedicated garage space, an expensive proposition for owners of cars falling into larger size classes. Kei cars were also taxed at one-third the rate of standard-sized cars and still significantly less than small cars. These policies spurred production of kei cars to a peak of nearly 750,000 units, or more than 20 percent of the market, in 1970 (see Figure 20). Declining prices for small cars and increasing incomes caused sales of kei cars to plummet to just 160,000 units and less than five percent of production five years later (Townsend, 2013).

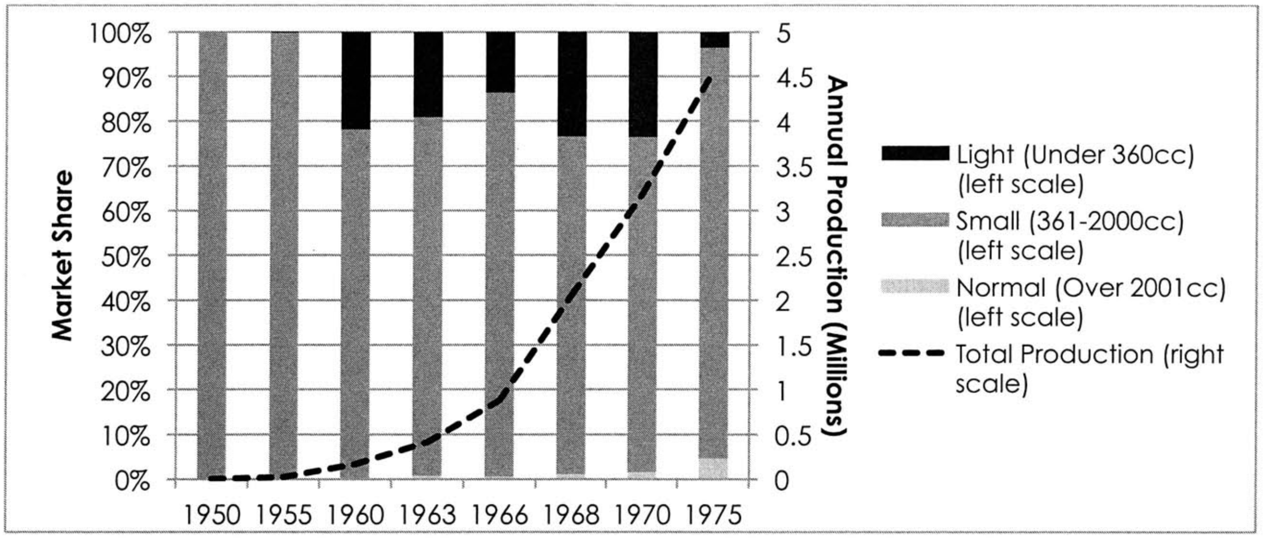

Figure 20: Annual passenger car sales and market share by vehicle segment in Japan (Source: Townsend (2013))

Current Trends in Kei Car Sales

More recently, kei car popularity has resurged due to similar policy incentives to those in place during the 1960s, combined with – just as with SUVs in the United States – favorable economic conditions. Though taxation and other policies incentivizing the sale of kei cars remained in place during the 1970s and 1980s, Japan's economy was experiencing significant growth, as well as cultural shifts. Household incomes grew significantly while new production and manufacturing approaches drastically reduced the cost of new vehicles of all sizes. Just during the 1960s, the average price of a 1,500 cc car fell from nearly three times the average household income, to just over half of the average household's income (Townsend, 2013). Therefore, most new registrations during this period of economic growth were small cars, with engines between 361 and 2,000 cc in size.

However, the 1990s represent a turning point in the Japanese economy, as stagnation replaced expansion. The 1990s are commonly cited as Japan's "lost decade", during which growth in gross domestic product (GDP) and GDP per capita, slowed significantly (see Figure 21). As a result, annual new registrations steadily declined from their 1990 peak and became significantly more heterogeneous, eventually becoming evenly split between mini, small, and standard-sized cars (see Figure 22).

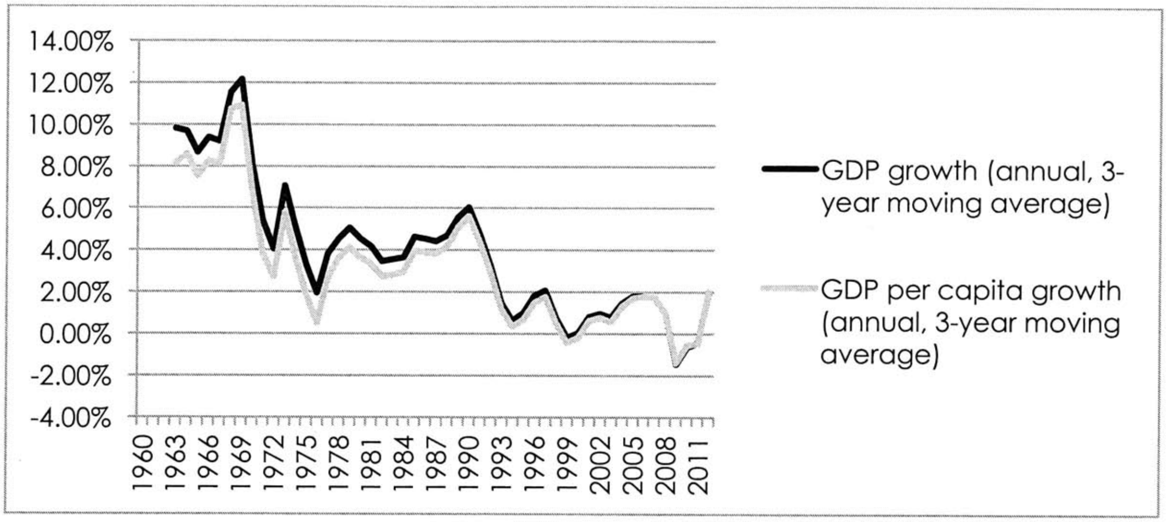

Figure 21: Economic indicators (GDP growth and GDP per capita growth for Japan, 1960 to 2012 (Source: World Bank)

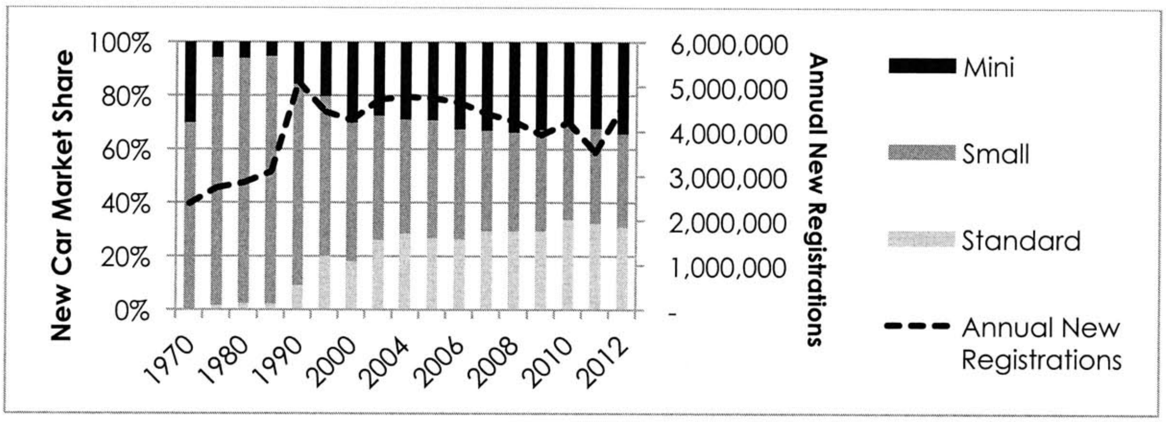

Figure 22: Annual new car registrations in Japan, total and market share by vehicle category (Source: JAMA)

In a limited-growth economy, such as Japan experienced during the 1990s, it is not difficult to see why kei cars became so popular. Wages stagnated during Japan's "lost decade" and, as a result, total household consumption declined as did the growth rate of household consumption per capita (see Figure 23). Therefore, the government-imposed costs of automobile ownership in Japan took on new significance. Where vehicle owners in a rapidly growing economy might be content to pay a premium to drive a small or standard car, the economic stagnation of the 1990s likely emphasized the savings that could be derived from driving a kei car. First, kei car buyers must pay a three percent acquisition tax compared to five percent for standard vehicles; kei cars also cost considerably less than standard cars, often starting around the equivalent of $10,000. More significant, however, is the disparity in annual taxes between kei cars and standard cars. The Japanese government levies an annual engine capacity-based tax on automobiles ranging from ¥29,500 (about $240) per year for engines below 1,000 cc to ¥111,000 (about $915) for engines larger than 6,000 cc. In contrast, the tax for kei cars is just ¥7,200 (about $60), though it was increased to ¥10,800 (about $90) for 2015 (Higgins, 2014). Moreover, vehicle owners are also assessed a tonnage tax of ¥2,500 per 500 kilograms (Kaikan, 2013). Therefore, the average annual taxes incurred to own a kei car are one quarter as high as even the smallest standard car.

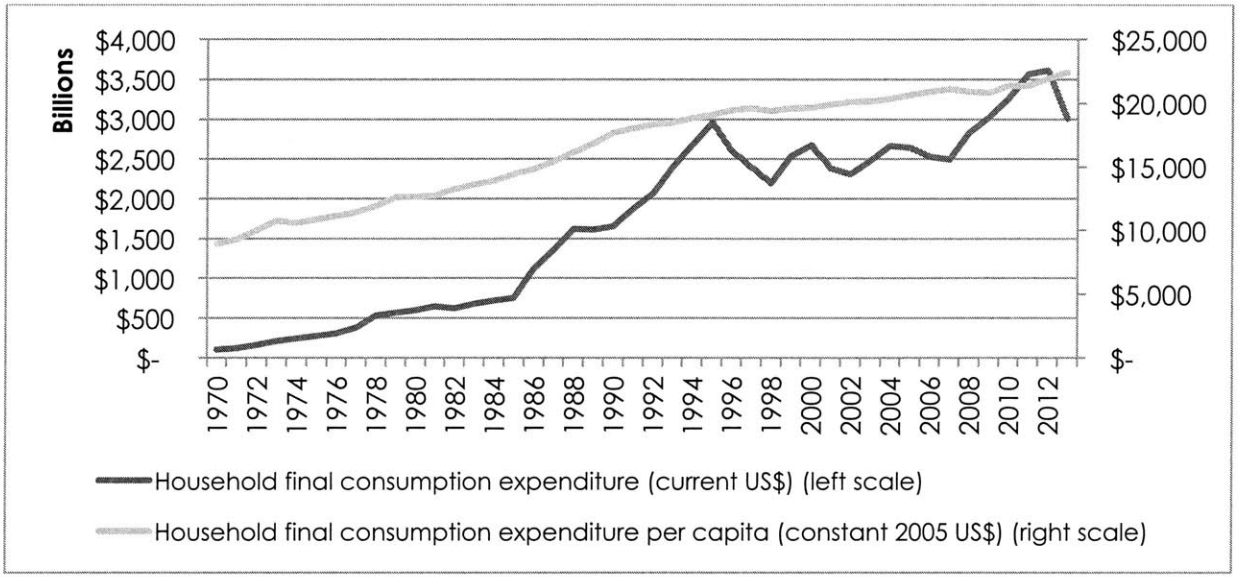

Figure 23: Total household consumption and household consumption per capita in Japan, 1970 to 2012 (Source: World Bank)

A less obvious factor in the kei car's success over the last two decades has been the aging of Japan's population. Partially responsible for the country's slow GDP growth in the 1990s, Japan's birth rate declined sharply in the 1970s, leaving its population age profile with two distinct "baby booms" in the late 1940s and early 1970s, with a shrinking share of the population represented by young and middle-aged citizens (Aoki, 2013). In 1980, just nine percent of the population was over the age of 65 but now more than one quarter of Japanese citizens fall into that age group (Statistics Japan, 2014). Meanwhile, the share of the population under age 40 dropped during the same time period from 62 percent to 42 percent (Japan Ministry of Health, Labour, and Welfare, 2013). Kei cars have taken full advantage of an aging population that is increasingly dependent upon personal vehicle ownership but also interested in frugality. Kei cars have appealed to Japan's large, older population; the average kei car buyer is 50 years old and more than one quarter of kei car buyers are over 60 (Takahashi, 2012). Kei cars are also purchased predominantly by women (up to 65 percent, according to the Japan Automobile Manufacturers Association) and represent a strong majority of new vehicle sales in many rural areas, where lack of transit makes personal vehicle ownership a necessity (Tabuchi, 2014).

Much like the case of SUV sales growth in the United States, the rise in popularity of kei cars over the last two decades was the result of a very specific combination of government policy incentives, economic conditions, favorable demographics, and a receptive populace. The influence of policy incentives are clear but kei car sales during the 1970s and 1980s suggest that the economic conditions were vital as well. Similar incentives existed during this period yet kei car sales slumped, as strong economic growth gave consumers fewer incentives to save money by buying such small vehicles compared to the period of slow and negative economic growth in the 1990s.

The future of the kei car is uncertain, as it faces several threats. First, just as in the United States, Japan's younger generation has demonstrated less interest in vehicle ownership than their parents' and grandparents' generations and, therefore, account for a disproportionately low share of vehicle sales overall, and kei car sales in particular (Associated Press, 2008). Moreover, the aging demographics of kei car buyers – the average age of a kei car buyer increased by eight years over the course of 12 years – suggest that manufacturers may soon run out of older customers (Takahashi, 2012). One commentator on the situation glibly wrote, "The bulk of consumers [in Japan] are likely buying their last car" (Kreindler, 2013). Increasing tax rates represent the second threat to the kei car's success, as the Japanese government recently increased the annual automobile tax levied on them from ¥7,200 to ¥10,800. Though the higher tax is still one third of that for even the smallest standard car, industry representatives are concerned that it will still discourage their sales. In response to the tax increase, 20 percent of kei car owners surveyed by JAMA indicated that they would consider giving up their car while ten percent indicated that they would consider switching to a larger model, given the reduced cost gap (Tabuchi, 2014).

Perhaps the largest threat to the kei car, however, is from the automotive industry and the Japanese government. Recently, Japanese manufacturers have expressed concerns about the extent to which they have had to invest in the development of kei cars whose sales are largely limited to the Japanese market. Whereas larger models can be sold with few changes in other large markets like Europe and North America, little demand exists for kei cars outside of Japan. Some companies, like Suzuki, argue that their research and development efforts for kei cars can be transferred to models sold in other markets (Tabuchi, 2014). Others compare the Japanese automobile market to the Galapagos Islands, suggesting that successful models in Japan are difficult to market in the rest of the world. Even the Vice Chairman of Nissan, Japan's fourth largest manufacturer, questioned whether it makes sense for manufacturers to continue building models that only sell domestically (Takahashi, 2013). Given the importance of the automotive industry to Japan's economy, the government echoes the industry's concern over kei car production, worrying that manufacturers cannot afford to produce models for a single market (Tabuchi, 2014).

2.4. Summary and Implications

The parallel examples of kei cars and SUVs presented above highlight the pace with which the market share of particular types of vehicles can change in response to favorable policy, market, and demographic conditions. The policies present in both examples affected taxes, ownership costs, and incentives to industry but spurred significant growth in vehicle segments at opposite ends of the size spectrum. In the United States, the phase-in of separate fuel economy standards for passenger cars and light trucks, combined with a severe drop in fuel prices, favorable tax conditions for domestic manufacturers of light trucks, and increased competition from foreign competitors in producing fuel-efficient passenger cars created ideal conditions in which SUV sales could flourish. In this case, the policy drivers were unintentional, but no less effective, than the tax policies introduced in Japan to incentivize kei car sales.

These two cases provide motivation for considering potential sales scenarios for the next 25 years and their implications for fleet-wide fuel consumption. Though the scenarios presented in the next section are not accompanied by indications of likelihood, they are all intended to be plausible given the pace of change exhibited in these cases as well as projected trends affecting automobile sales. Finally, the policy factors identified in the preceding cases will inform discussion of what policies might be used to influence scenarios that produce desirable results.

3. Exploring Future Shifts in Vehicle Segments

The preceding section illustrated the extent to which the relative market shares of certain vehicle types can expand over a relatively short time period. This section will build upon those findings by proposing several plausible scenarios for the evolution of the U.S. light duty vehicle market through 2040. Characterizing scenarios as plausible suggests that, short of assigning a probability or likelihood of their coming to fruition, they *could* occur given the current state of the vehicle market and projections about factors that affect vehicle demand. Each scenario assumes the same projection for total LDV demand, with 0.64 percent sales growth per year, consistent with the EIA assumptions discussed in Section 1.4.5. In order to evaluate conditions parametrically, each scenario focuses on the potential for the market share of a different type of vehicle to grow significantly. This is not to say that several vehicle segment market shares could not grow simultaneously, but is rather a compromise made in the interest of analytical clarity. Scenarios also hold the technical characteristics of vehicles constant, save for the assumption adopted from EIA projections that fuel economy will improve by three percent per year.

In the following sections, the justification for considering each scenario will be summarized along with a general description of the shift in vehicle types being considered. Finally, results of the fleet model analysis conducted for each scenario will be presented. The section will conclude with a discussion of the policies that could be implemented to encourage the scenarios that are most desirable given the fleet model results.

3.1. City Cars

3.1.1. Overview and Justification

The kei car case presented in the previous section provides some evidence to suggest that, given the right set of incentives, consumers may be willing to forgo size and power in making a vehicle purchase. Though kei cars took engine and vehicle downsizing to an extreme, the underlying principle of smaller vehicles and smaller engines has merit, even in the U.S. where consumers have generally valued size and power. BMW's Mini division and Fiat have both had modest success selling cars a fraction of the size of even compact offerings from other companies. Even Daimler's Smart ForTwo, the closest vehicle in size and spirit to Japan's kei cars, has sold in surprising numbers, with *Automotive News* referring to their first-year sales figures of 25,000 units in 2008 as an "improbable success" (Smart aims to repeat 25,000 in U.S. sales in this year, 2009).

Evidence has also emerged in recent years suggesting that, as young Americans become less interested in cars, size, power, and performance will become less important sales drivers than efficiency and technology content. Moreover, younger Americans are moving into urban areas in greater numbers than previous generations (Miller, 2014). Even if many of them will commute by transit, those who remain dependent on a personal vehicle are likely to seek compact models that are more appropriate in an urban environment.

Models like the BMW Mini Cooper, Fiat 500, and Smart ForTwo may seem impractical, but travel survey data suggest that the majority of commuting trips (up to 80 percent in some areas) are made alone (McKenzie & Rapino, 2011). Though owning a small vehicle might introduce the need to rent a vehicle periodically – or use a car sharing service – for trips where additional passenger or cargo capacity is necessary, these vehicles also represent a far more efficient means of travel for most trips. These vehicles have experienced modest success on the U.S. market, totaling between 50,000 and 100,000 units per year over the last ten years. Adding slightly larger models like the Ford Fiesta, Mazda 2, Chevrolet Sonic and Spark, and the Toyota Yaris (all with interior volumes around 100 cubic feet) raises the total to a high of about 300,000 units per year in 2012, 2013, and 2014, or about two percent of total LDV sales (Good Car Bad Car; Wards Auto Data Center).

The automotive industry has reason to suspect that this segment of very small, efficient, and affordable vehicles may become a more significant part of the American LDV market over the coming decades. First, research emerged several years ago suggesting that the Millennial Generation and Generation Z (born between 1980 and 2000 and born after 2000, respectively, according to Pew Research) were far less interested in car ownership than previous generations (see Weissman (2012) and Chozick (2012)). Though this trend seems to be turning around, particularly for Millenials[4], industry research also suggests that these two younger generations are following different development timelines, have different values, and, therefore, value different vehicle attributes than their predecessors. Most notably, Millenials are delaying the purchase of a home and waiting longer to have children. Small cars are, therefore, far more appealing to this generation. An AutoTrader study found that Millenials are "big on small" vehicles due to their

[4] TrueCar reported that its population of Millenial buyers increased by nearly 78 percent between 2013 and 2014 and expects sales to Millenials to increase by more than 30 percent from 2014 to 2015 (TrueCar, 2015).

affordability, maneuverability in urban areas, and lower environmental impact (Eisenstein, 2014). A survey of Generation Z members revealed similar car-buying values, with more than half of respondents interested in compact or subcompact models (Martinez, 2015).

With Millenials and Generation Z already a significant part of the LDV customer base, and set to grow in prominence as the dominant Baby Boomer generation begins aging out of the car-buying market, automakers will need to increasingly cater their model offerings to those generations' needs and interests. These generations place higher priority on efficiency and value, are less concerned with utility, are far more interested in living in walkable, multi-use neighborhoods, and are open to the use of car-sharing services if convenient (Deloitte, 2014). Therefore, it seems plausible that they will increasingly turn to models like the city cars discussed above, with interior volumes generally under 100 cubic feet and footprints (defined by the EPA as the area between the wheels, or the track width multiplied by the wheelbase) of less than 40 square feet.

For the purposes of evaluating a scenario in which city cars grow in popularity, it was necessary to conceive of an "average" city car in terms of fuel efficiency. Given the range of models available today, which achieve between 30 and 38 mpg in the EPA's combined test cycle, the hypothetical city car used in the analysis was assigned an average figure of 6.5 liters per 100km, or 36 mpg. Each of the ensuing scenarios introduces city cars as a growing component of annual sales, with their total market share reaching a target figure by 2040 through linear growth. As discussed earlier, total LDV sales remain the same as in the base case, so the increase in city car sales is assumed to reduce the relative market shares of all other passenger car segments in proportion to their total market share.

Figure 24 illustrates the three city car scenarios analyzed that, in short, grow the city car market to three percent, seven percent, and ten percent by 2040. Given the fact that Millenials and Generation Z will account for half of the population and at least 60 percent of potential vehicle buyers by 2040, and that at least 80 percent of Americans will live in urban areas, these values seem plausible.

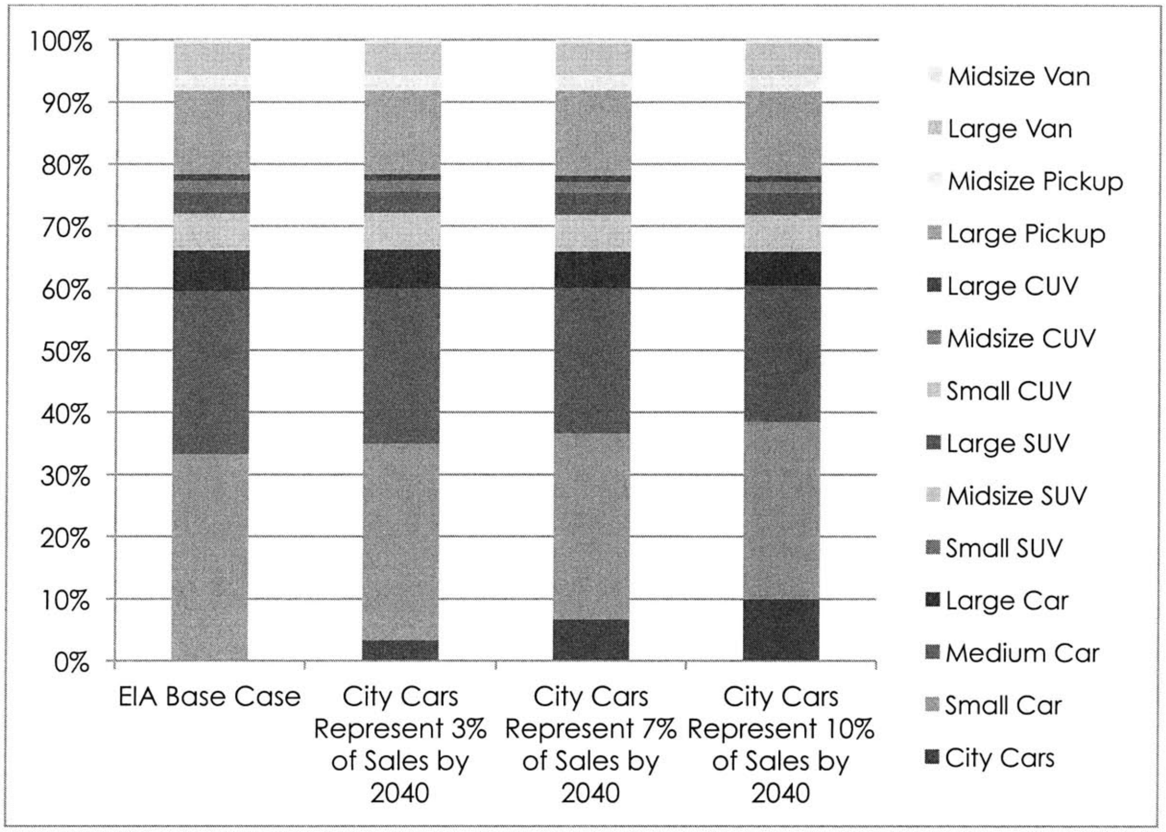

Figure 24: Summary of 2040 LDV market shares for three city car scenarios plus EIA base case

3.1.2. City Car Scenario Results

The results of the scenario analysis suggest that the introduction of city cars in increasingly significant numbers can provide a modest benefit in terms of fleet-wide fuel savings. The three percent scenario corresponds to sales of nearly 575,000 units annually by 2040 while the seven and ten percent scenarios correspond to 1.34 million and 1.92 million units respectively. The final case may be extreme, but it also represents an attractive situation in terms of benefits. The scenarios show little difference through about 2025, reflecting the inertia of the in-use fleet in responding to changes in sales mix, but diverge thereafter. At 2040, the most conservative scenario yields a two percent decrease in LDV petroleum consumption while the seven and ten percent cases yield five and seven percent decreases, respectively (see Figure 26). Moreover, where fleet-wide fuel demand begins to level off by 2040 in the reference case, suggesting a rise in annual LDV petroleum consumption beyond 2040, all three alternative scenarios show LDV petroleum consumption continuing to decrease at a moderate rate.

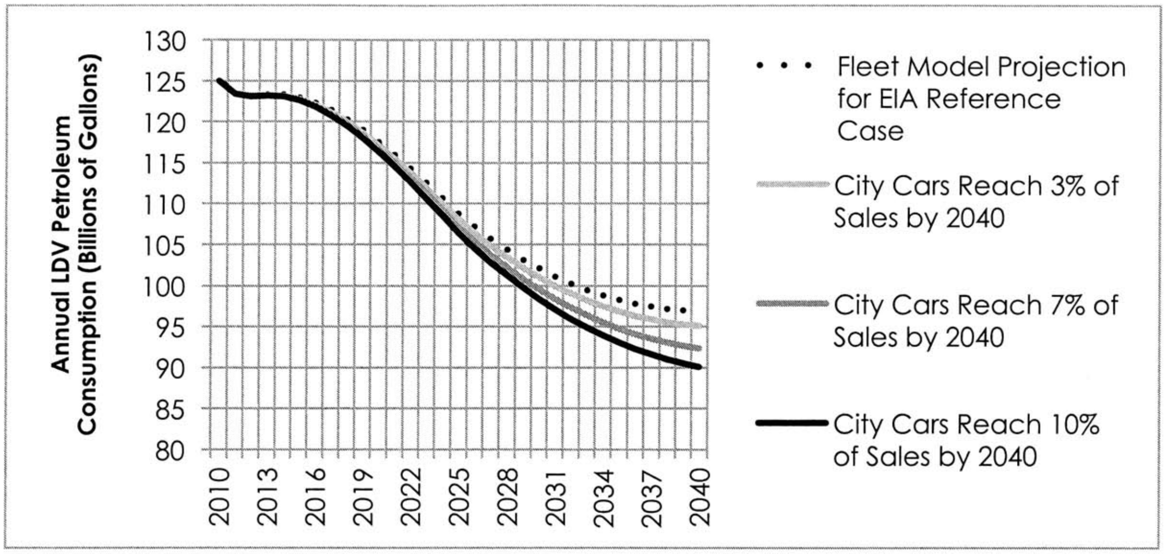

Figure 25: Annual LDV fuel consumption projections for city car scenarios, 2010 through 2040

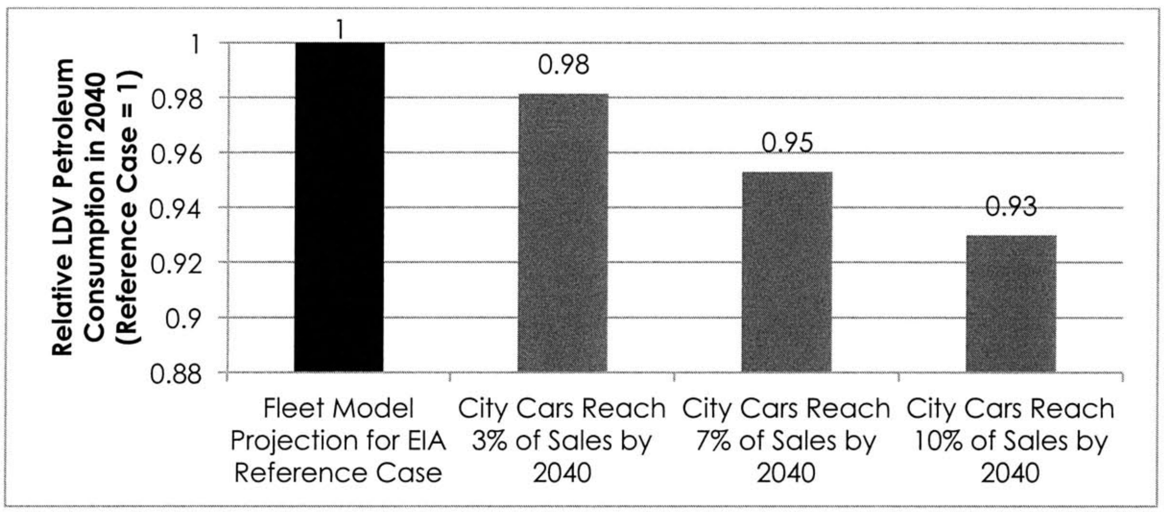

Figure 26: LDV petroleum consumption in 2040 for city car scenarios relative to reference case

3.2. Growth in CUVs

3.2.1. Overview and Justification

The CUV category of the LDV market has been growing since SUV sales peaked in the mid 2000s. Their compromise between utility and relative efficiency made them attractive substitutes for former SUV buyers who had no need for high towing capacity or off-road ability, or former car buyers who hadn't previously been willing to sacrifice efficiency and handling dynamics for additional interior space or four-wheel drive. CUVs represent a best of both worlds vehicle that currently comprises ten percent of the LDV market.[5] It is reasonable to expect that this success will continue.

It is less clear which types of CUVs will grow and to what extent the segment will continue increasing its market share. One path, supported by market research and several prominent model introductions, would be for the small CUV segment to grow, siphoning sales away from small passenger cars as well as other SUV and CUV size categories. The segment is small now, with a two percent market share by WardAuto's definitions and no market share by the EPA's. However, several manufacturers have introduced models recently to compete in this segment, including the Jeep Renegade, Honda HR-V, and Mazda CX-3. These vehicles represent a significant strategy for many manufacturers to produce vehicles that appeal globally. *Automotive News* describes the appeal of this strategy succinctly: "These vehicles are small enough for Europeans, tall enough for Americas, rugged enough for the developing world. They work for budget-minded 20-somethings and empty nesters. They come in luxury packages (Mercedes GLA) or dressed down (Chevy Trax). They can be geared for the trail (Jeep Renegade) or the track (Porsche Macan)" (Colias & Beene, 2015). Even more appealing for manufacturers, *Automotive News* highlights a similarity between SUVs and compact crossovers that make them similarly profitable. Where the most popular SUVs of the 1990s and early 2000s were built on existing pickup truck platforms, compact CUVs can be built using existing compact car platforms. Where the latter sell in large quantities with thin profit margins, compact SUVs can be sold at higher base prices, yielding up to $3,500 in additional profit per vehicle, according to TrueCar president and former Hyundai Motor America CEO John Krafcik (Colias & Beene, 2015).

Several scenarios seem plausible for the compact CUV segment to see success over the next several decades and they vary in two general dimensions. First, the magnitude of their potential market share could range widely. Given that small cars currently account for about one third of the LDV market, and that small and midsize crossovers account for about ten percent, a range of five to 15 percent seems plausible. In the scenarios evaluated, the maximum market share of compact CUVs is limited to 12 percent, in order to avoid exceeding the maximum share of SUVs and CUVs in 2040 provided in the EIA

[5] This market share figure is based on the EPA definition of a CUV, which focuses on lightweight utility vehicles that are not equipped with four-wheel drive. By the WardsAuto vehicle segment definitions, the CUV segment now represents nearly one quarter of the LDV market. By both sets of definitions, the CUV and SUV segments together represent about 30 percent of the LDV market.

reference case. The second variable to consider is the source from which compact CUVs will draw customers. Given that the intent of this analysis is to keep overall sales constant across scenarios, an increase in sales of compact CUVs will necessitate a decrease in market share for other segments. Given their attributes, two general scenarios seem plausible. First, their high profitability relative to the compact passenger cars on which they are based suggests that manufacturers will market them as stylish, exciting, and more capable alternatives to small cars. The other possibility is that their relative fuel efficiency will attract buyers of larger CUVs and SUVs. The analysis that follows will explore scenarios varying in both dimensions.

Just as in the mini car scenarios, it was necessary to introduce a representative compact CUV into the fleet model in terms of fuel efficiency. For the purposes of the analysis, compact CUVs are assumed to consume an average of just over 8 liters per 100 km of travel, or about 30 mpg. This falls roughly in the middle of recently introduced models like the Jeep Renegade, Honda HR-V, and Chevrolet Trax.

Figure 27 illustrates the 2040 LDV market shares for the six compact CUV scenarios considered, alongside the EIA reference case.

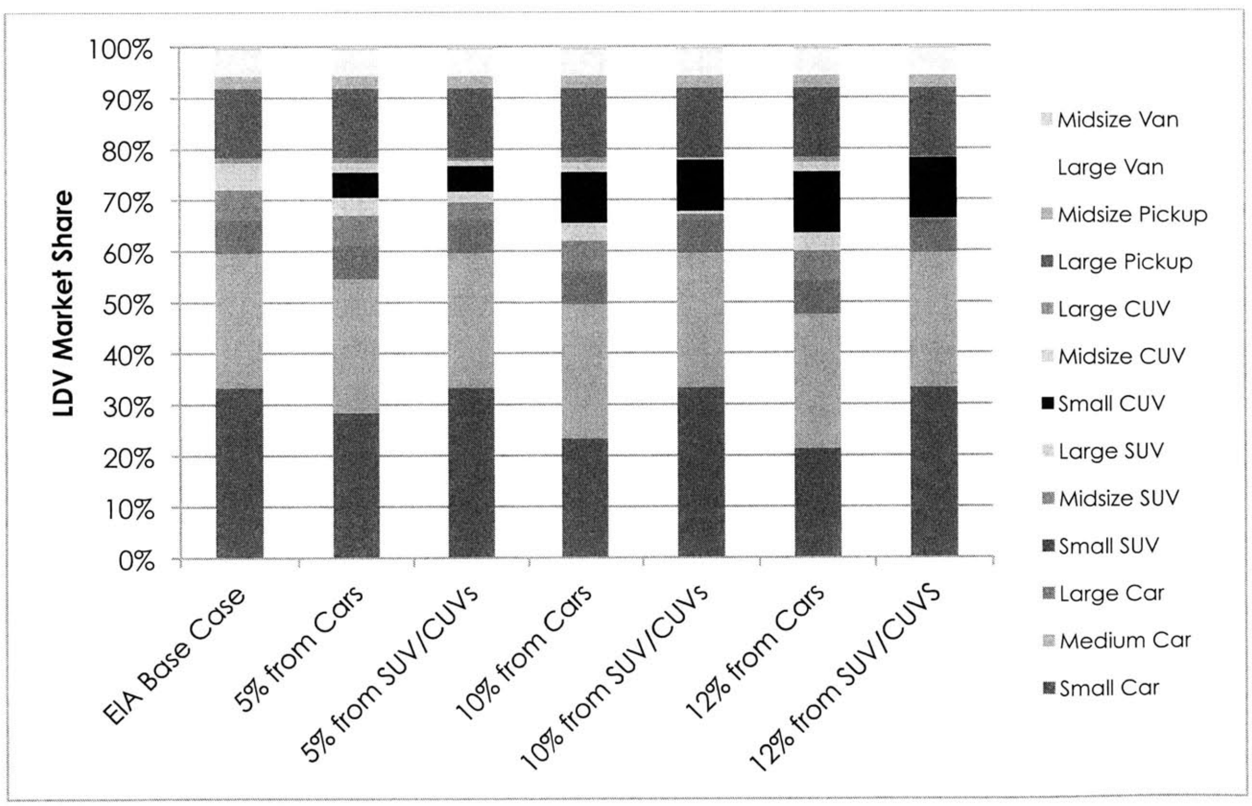

Figure 27: Summary of 2040 LDV market shares for six compact CUV scenarios plus EIA base case

3.2.2. Growth in CUV Sales Scenarios Results

The results of the CUV scenarios are far less significant than those obtained for the city car scenarios explored above. Even with compact CUVs growing to account for 12 percent of total LDV sales, or about 2.3 million units, in 2040, total LDV petroleum consumption changes by just 1.2 percent. The direction in which total fuel consumption shifts is dependent on the segment from which compact CUVs draw customers. As expected, drawing customers from the small passenger car segment increases overall fuel consumption, while drawing them from larger SUV and CUV segments decreases overall fuel consumption. However, in either case, the change is quite minimal. Moreover, it seems likely that growth in the compact CUV segment will draw customers away from both areas of the vehicle market, suggesting that the actual change in annual LDV petroleum consumption will be close to zero.

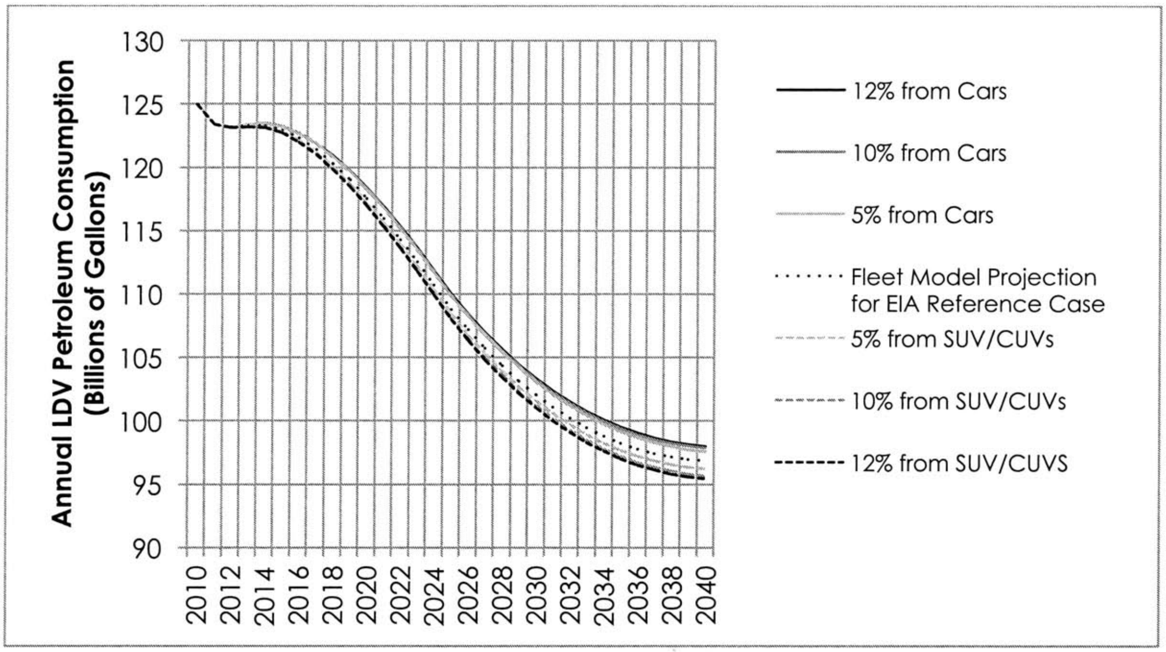

Figure 28: Annual LDV fuel consumption projections for compact CUV scenarios, 2010 through 2040

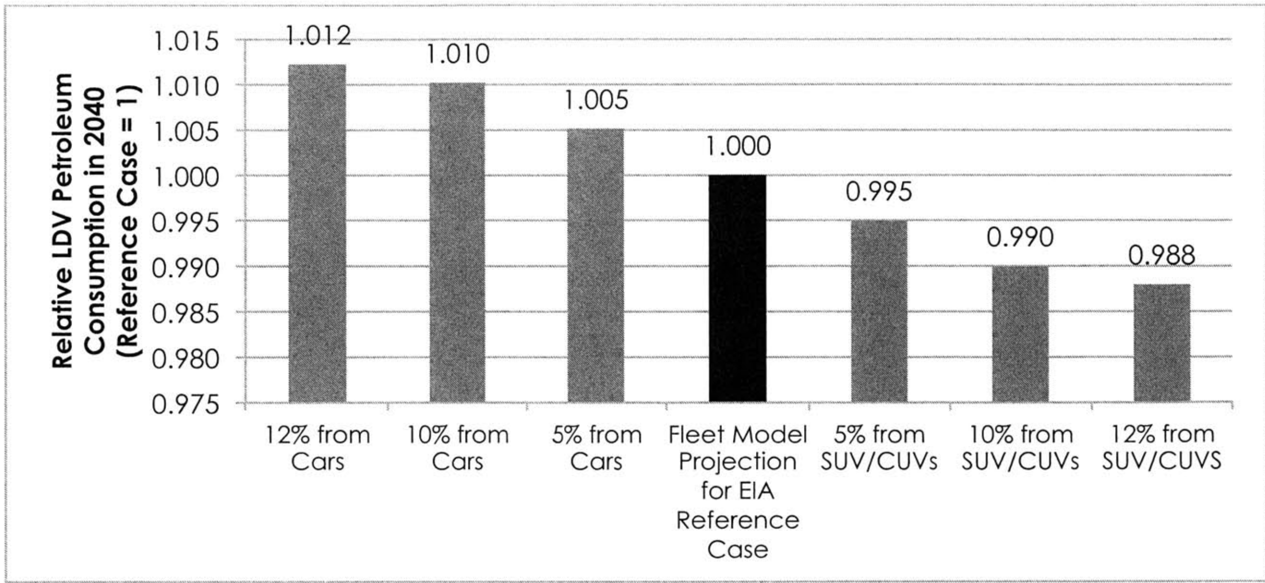

Figure 29: LDV petroleum consumption in 2040 for compact CUV scenarios relative to reference case

3.3. SUV Decline

3.3.1. Overview and Justification

As discussed in Section 2.3.2, SUVs and other alternatives to passenger cars have seen enormous sales growth in the past several decades and, though preferences may be shifting towards smaller, more efficient variations, it does not seem that their popularity will be declining anytime soon. However, given the vehicle attributes valued by younger generations, discussed in Section 3.2.1, and their strong interest in cars over SUVs relative to older generations, a scenario in which market shares return to those seen prior to the SUV sales boom seems plausible (though perhaps the least so of those investigated). Even if it is unlikely, such a scenario also represents an interesting analytical counterpoint to the potential for high SUV sales in the future. Such vehicles are often criticized for poor fuel economy, yet it is important to understand the extent to which their fuel economy deficit actually translates into increased fleet-wide consumption.

3.3.2. SUV Decline Scenario Results

Just as with the city car scenarios, the decreases in fleet-wide fuel consumption relative to the reference case are modest for scenarios in which LDV market shares return to their 1975 levels. However, they are instructive in revealing the extent to which a reversion back to dominant passenger car sales relative to light trucks and CUVs could lead to a reduction in fleet-wide fuel consumption.

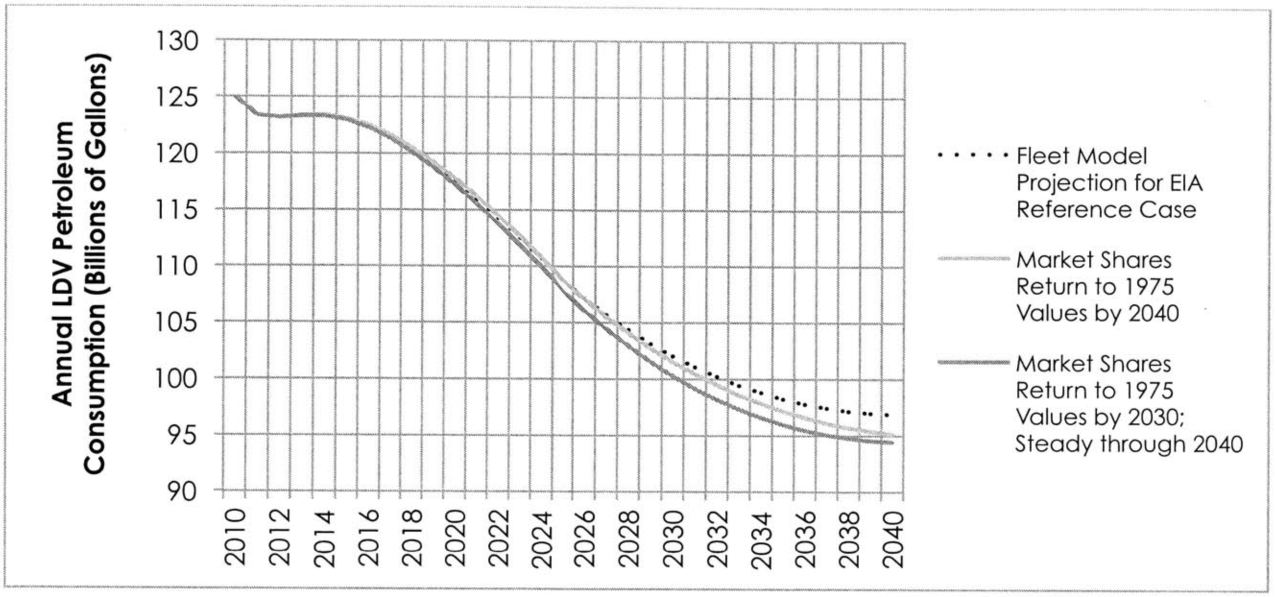

Figure 30: Annual LDV fuel consumption projections for SUV decline scenarios, 2010 through 2040

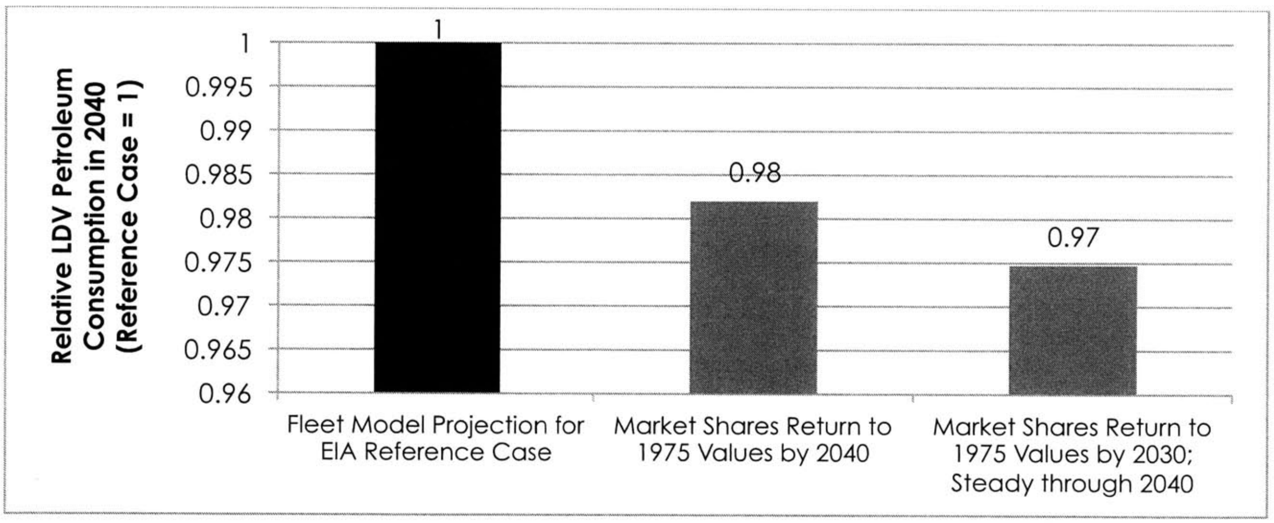

Figure 31: LDV petroleum consumption in 2040 for SUV decline scenarios relative to reference case

3.4. Strong SUV Sales

3.4.1. Overview and Justification

In contrast to the preceding set of scenarios it is illustrative to explore an opposite set of scenarios in which SUV sales remain constant from today, or perhaps even grow. Though the EIA's reference case suggests that the market share of SUVs and CUVs will decline from current levels by nearly two thirds to reach 12 percent in 2040, their current trajectory does not yet hint at this decline. In fact, the combined market share of CUVs and SUVs has continued to climb despite high gas prices and increasingly stringent fuel economy standards for cars and light trucks, albeit at a slower rate than prior to the early 2000s (see Figure 32 for three-year moving average market share). A recent drop in fuel prices has also turned public attention away from fuel savings, at least temporarily (Young, 2015).

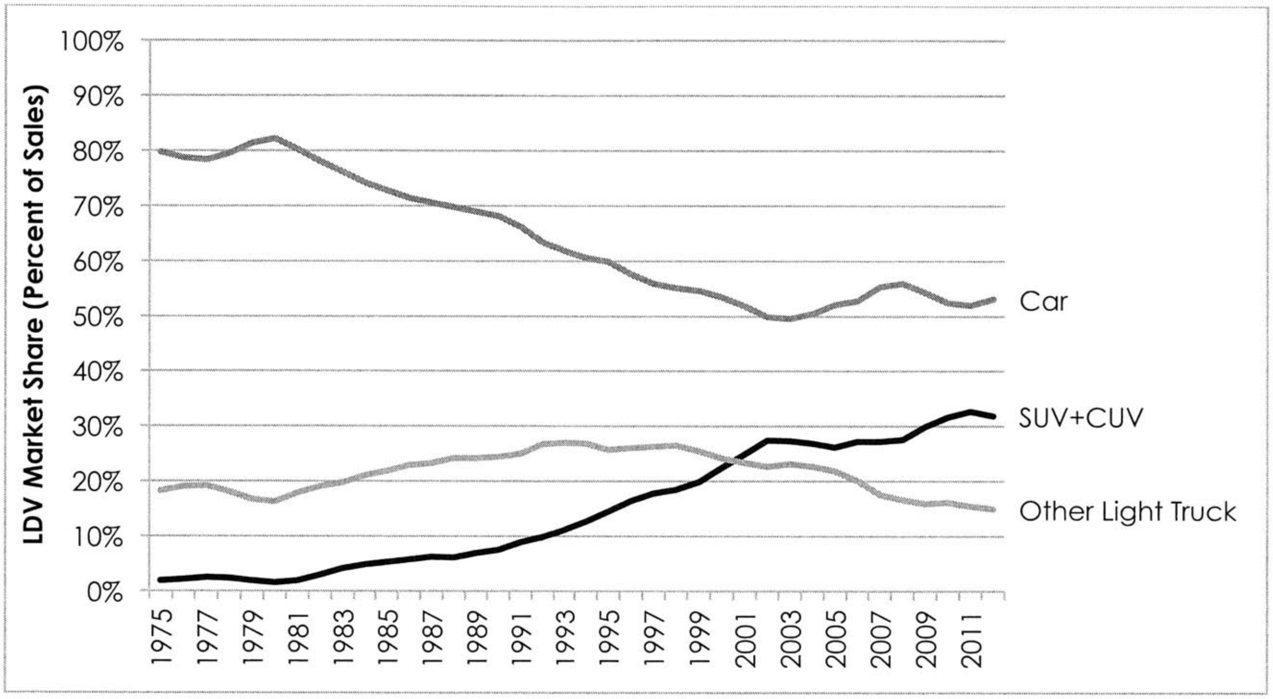

Figure 32: Three-year moving average of LDV market share (percent of sales) (Data Source: EPA)

As manufacturers begin to lobby regulatory decision-makers over reducing the stringency of upcoming CAFE standards, citing renewed demand for SUVs that will interfere with their ability to meet the standards as set, two general scenarios appear worth investigating (Spector & Rogers, 2015). The first would hold the combined market share of SUVs and CUVs at its current level of 31 percent through 2040, compared to 12 percent in the reference case. An alternative scenario worth exploring continues the expansion of the SUV and CUV segments to a combined 45 percent by 2040. This is admittedly an extreme scenario, essentially carrying forward the growth in combined SUV and CUV market share that the segments experienced between 2002 and the present. Given the extreme nature of this scenario, it should be viewed as an upper bound for LDV fuel consumption if consumer preferences gravitate significantly toward larger, less fuel-efficient vehicles.

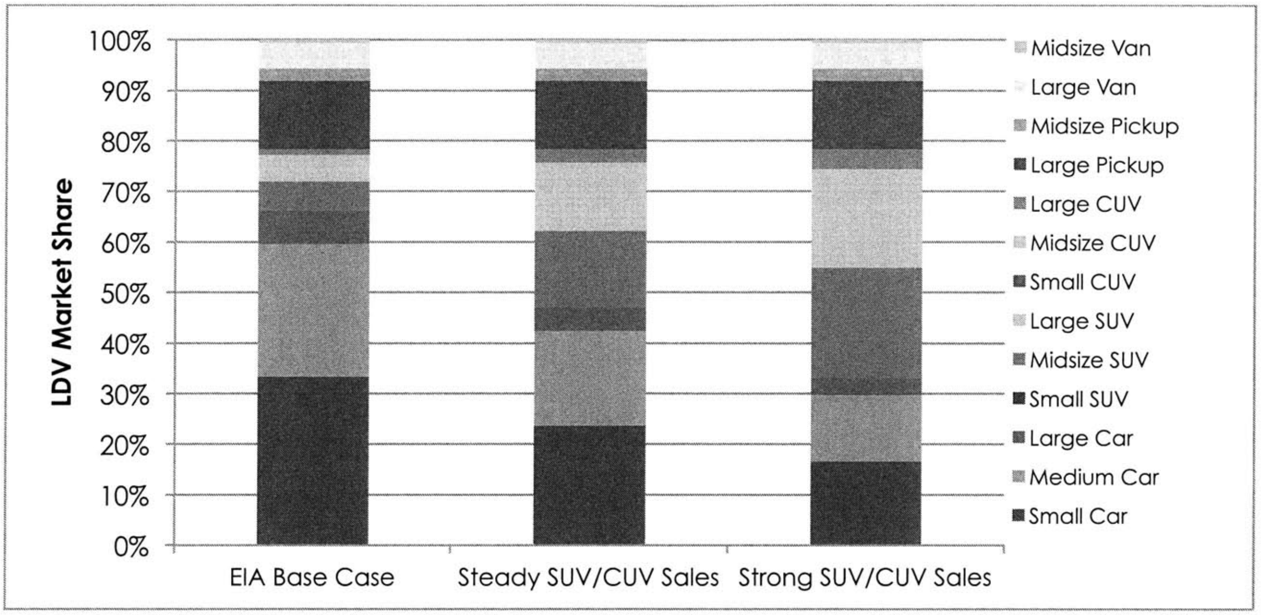

Figure 33: Summary of 2040 LDV market shares for steady and strong SUV/CUV sales scenarios plus EIA base case

3.4.2. Strong SUV/CUV Sales Scenario Results

The results of the strong SUV/CUV sales scenarios illustrate the extent to which fuel consumption potential might be sacrificed in the interest of continued success of passenger car alternatives. Though across-the-board fuel economy improvements in response to the CAFE standards still produce a decrease in fleet-wide fuel consumption relative to current levels, the steady and strong SUV/CUV sales scenarios result in four and five percent higher fuel consumption levels by 2040, respectively, compared to the reference case.

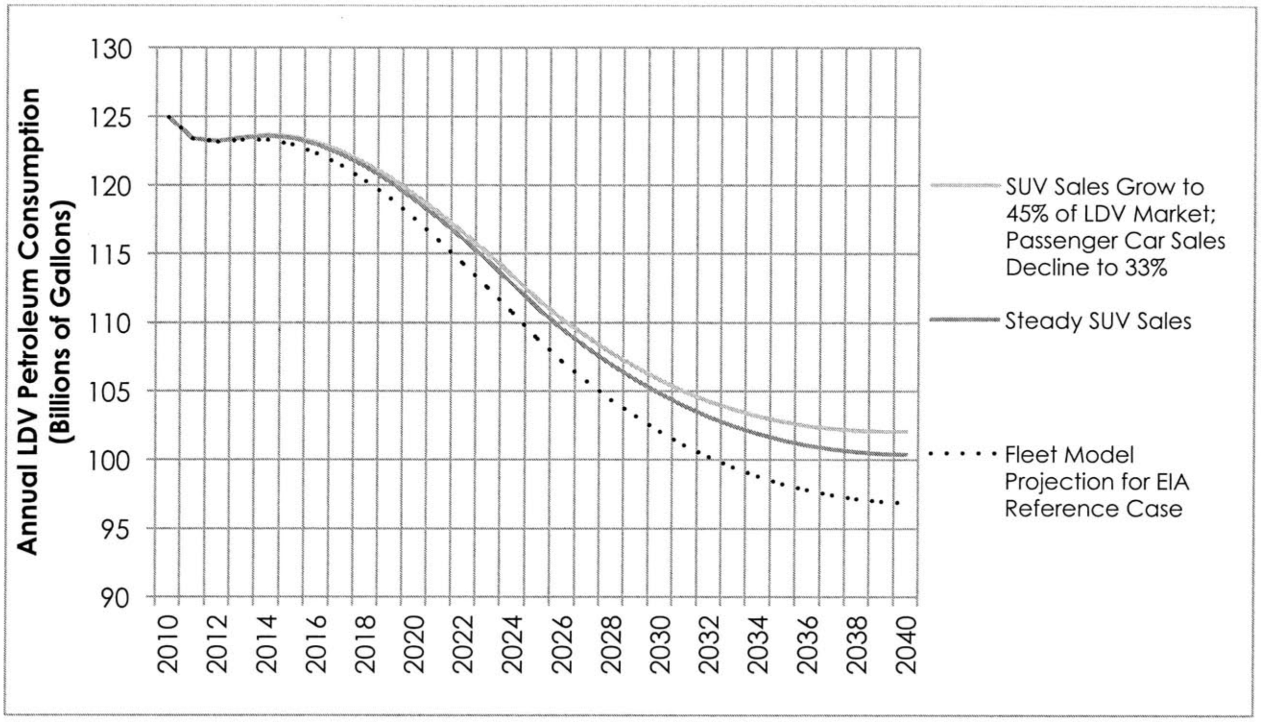

Figure 34: Annual LDV fuel consumption projections for strong SUV sales scenarios, 2010 through 2040

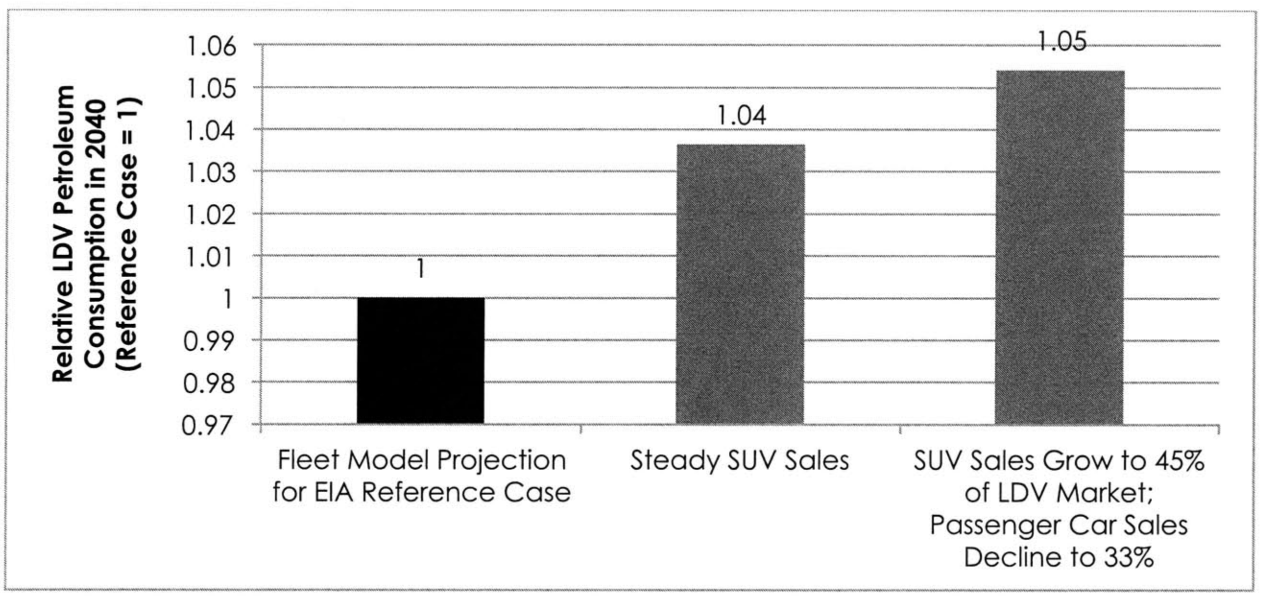

Figure 35: LDV petroleum consumption in 2040 for strong SUV/CUV sales scenarios relative to reference case

3.5. Overall Scenario Results

The scenario results presented above suggest that modest reductions in fleet-wide fuel consumption are possible in response to shifts between the relative market shares of different LDV segments. The most extreme scenarios resulted in total fuel consumption level changes of up to six percent by 2040, relative to the reference case, while the more plausible scenarios generally increased or decreased overall fuel consumption by less than four percent. These values are obviously quite low compared to the expected impact of the current CAFE standards, which are nominally intended to double the fuel economy of the average new passenger car between 2011 and 2025 (though with credits for various fuel-saving features considered, the actual expected improvement is somewhat lower). However, that does not mean that they are insignificant. First and foremost, even though none of the scenarios differ from the reference case by more than six percent, their full range spans more than ten billion gallons of fuel consumption in 2040, considering the difference between the highest and lowest fuel-use scenarios. This range represents more than ten percent of the 2040 fuel consumption values in the reference case and is important to consider, as it reflects both potential benefits and avoided disbenefits. Second, any changes in LDV fuel consumption revealed in the scenarios are exclusive from those required to meet the new CAFE standards, which are reflected in the reference case. Therefore, any of the potential market segment shifts discussed in the preceding sections might be considered as additional strategies to save fuel and reduce emissions in the light duty fleet beyond engine efficiency improvements. The following section discusses several policy options for encouraging these shifts and contrasts them with the strategies traditionally pursued in the United States.

3.6. Policy in the Context of Influencing Vehicle Segments

Federal-level policy in the United States covers many areas of LDV design and engineering. Fuel economy is the most prominent target for policy through the implementation of the CAFE standards, but safety and emissions are also significant focus areas. The following sections will detail each policy area affecting the automotive industry and discuss implications with regard to the scenarios explored above.

3.6.1. Fuel Economy

Prior to the 1970s, fuel economy was unregulated in the United States, leading to an abundance of models available will large engines capable of no more than 20 mpg. Passed in 1975, largely in response to the

1973 Arab Oil Embargo, the Energy Policy and Conservation Act established the Corporate Average Fuel Economy standards, or CAFE, which were intended to double the average fuel economy of a new passenger car by 1985 (new passenger cars averaged just 13.5 mpg in 1975). The basic mechanics of CAFE remained fairly constant from their establishment in 1975 until the present, but saw a significant structural revision in 2011. At their most basic level, the original CAFE standards required the harmonic mean of the fuel economy of all vehicles sold by each manufacturer to reach a designated target. More difficult to achieve than the simple arithmetic mean, the harmonic mean is computed by taking the reciprocal of the arithmetic mean of the reciprocals. More specifically, the harmonic mean fuel economy of a manufacturer's sales composed of i models, each achieving a fuel economy of f_i and selling n_i units would achieve a CAFE value of:

$$\sum_i n_i \Big/ \sum_i \frac{n_i}{f_i}$$

or the sum of total sales divided by each model's sales divided by its respective fuel economy, summed over each available model. Failure by a manufacturer to reach the established standard for a given model year would result in a fine of $5.50 per vehicle for every 0.1 mpg shortfall (U.S. Environmental Protection Agency, 2001). Between 1983 and 2012, NHTSA collected over $873 million in CAFE-related fines (National Highway Traffic Safety Administration, 2014).

In 2011, after two decades of stagnant fuel economy standards (particularly for passenger cars), NHTSA established a revised set of CAFE standards that, instead of issuing blanket targets for all vehicles, introduced standards that are scaled by vehicle footprint (defined as the area between the four wheels, or the track width multiplied by the wheelbase). Where the original CAFE standards created incentives for manufacturers to sell smaller vehicles (and inadvertently to sell trucks as replacements for passenger cars, as discussed earlier), the new footprint-based standards are intended to be neutral with regard to vehicle size, with the stringency of the standard scaled to the footprint of the vehicle. The official rulemaking attributes this change to four factors:

(1) A footprint-based standard has the potential to produce greater fuel savings than a single, industry-wide average because the standard for each manufacturer will be tailored to its sales mix;

(2) A footprint-based standard does not introduce incentives to build smaller vehicles, which would compromise safety;

(3) A footprint-based standard is more equitable to manufacturers, as it does not penalize manufacturers whose success has been based on producing large vehicles; and

(4) A footprint-based standard is more flexible with regard to economic conditions and consumer choice, as it does not create incentives for manufacturers to comply through the production of smaller vehicles, to which consumers may not be receptive (U.S. Department of Transportation, 2012).

Because of this new approach, the standard that each manufacturer is required to meet will be determined by their vehicle sales mix and, therefore, may be far higher or lower than projections made during the rulemaking process. The new CAFE standards are also made significantly less stringent than the nominal figures would suggest by allowances provided for vehicles equipped with particular technologies, including high-efficiency air-conditioning systems, engine stop-start systems, active aerodynamics, and alternative fuel powertrains (U.S. Environmental Protection Agency, 2012).

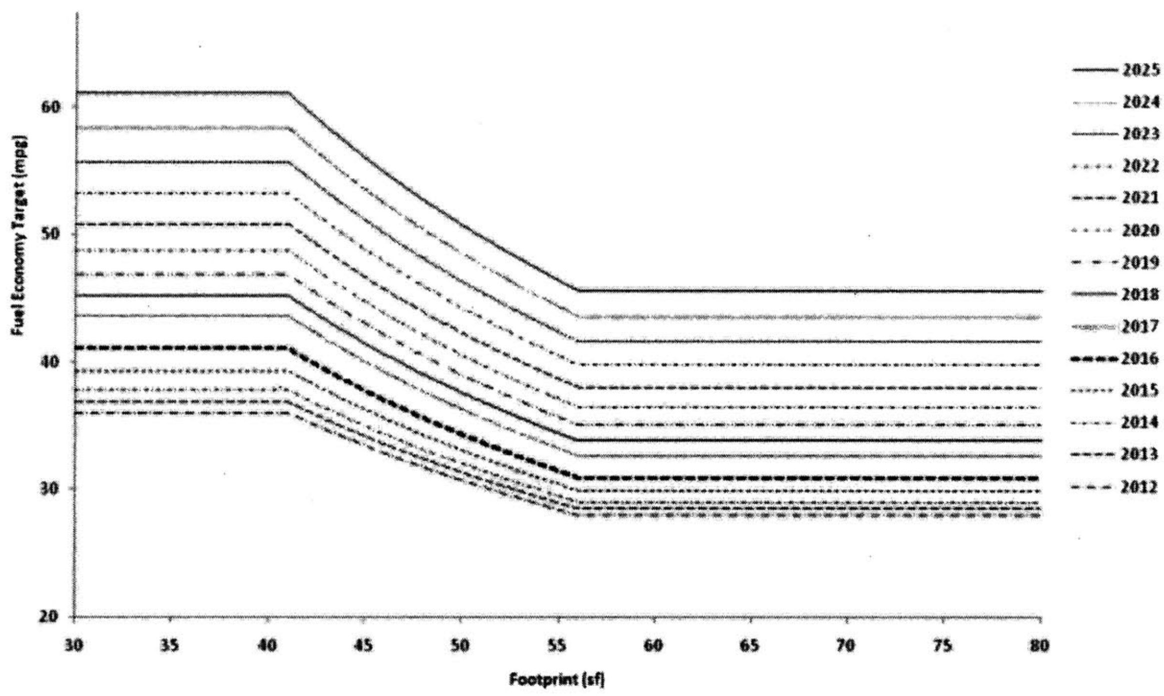

Figure 36: Footprint-based passenger car CAFE targets for model years 2012 through 2025 (Source: NHTSA)

The implications of the revised CAFE standards are mixed for the scenarios explored above. On the one hand, the current CAFE standards are explicitly designed to provide manufacturers with flexibility in meeting them and consumers with a choice between vehicle segments that is minimally affected by the regulations. Unlike the original CAFE standards, which initially pushed manufacturers to sell smaller, more fuel-efficient vehicles, the current standards were designed to avoid an implicit preference for certain types or sizes of vehicle. However, Whitefoot and Skerlos (2012) did find that the footprint-based CAFE standards generally introduced incentives for manufactures to increase vehicle size, except when consumers have a low preference for large vehicles and a high preference for acceleration. They suggest that a flatter relationship between footprint and the fuel economy requirement would lessen this effect. That is, if the difference in the requirement between large- and small-footprint vehicles were smaller, manufactures would have fewer incentives to increase vehicle size. That said, assuming that the footprint-based CAFE standards will have a far less significant impact on vehicle size distributions than the previous standards, they leave open opportunities for additional strategies that encourage the purchase of more fuel-efficient vehicle types in pursuit of the benefits revealed in the fleet analysis.

3.6.2. Pollution Control and Emissions

The U.S. Congress first introduced legislation to control pollution from automobiles with the 1970 Clean Air Act, which created the U.S. EPA and gave the agency authority to regulate motor vehicle pollution. Pollution standards first required the use of catalytic converters in 1975 and introduced even more stringent pollution control standards in the early 1980s (U.S. Environmental Protection Agency, 1994). Pollution standards have been updated multiple time since then, such that standards for LDV emission of carbon monoxide, hydrocarbons, and nitrogen oxides are currently between one and three percent of their uncontrolled levels (Faiz, Weaver, & Walsh, 1996).

More recently, automobile emission control has focused on reducing the release of greenhouse gas (GHG) emissions, mainly carbon dioxide. This new direction in emission control policy stems from a 2007 Supreme Court ruling in *Massachusetts v. EPA*, in which Massachusetts and several other states petitioned the EPA to regulate GHG emissions under the Clean Air Act. The EPA denied the petition but Massachusetts appealed, eventually bringing the matter to the Supreme Court. In a 5-4 decision, the Supreme Court ruled that the Clean Air Act's broad scope did encompass carbon dioxide emissions and that, if the EPA wished to delay in regulating them, it must do so based on evidence concerning whether they contribute to climate change (Massachusetts et. al., Petitioners v. Environmental Protection Agency et al., 2007). Following this ruling, the EPA worked jointly with NHTSA to develop the first program of harmonized fuel economy and carbon dioxide emission standards for LDVs; such harmonization follows that logic that, unlike other pollutants that can be controlled using by improved engine technology, carbon dioxide emissions vary directly with fuel consumption. Therefore, efforts to control carbon dioxide emissions impact fuel economy, and vice versa. Like the corresponding fuel economy rules, these new carbon dioxide emissions rules follow a footprint-based logic based on the same considerations mentioned in the previous section (U.S. Environmental Protection Agency, 2010).

3.6.3. Safety Standards and Requirements

In addition to directly regulating the environmental impacts of light duty vehicles through fuel economy and emissions standards, the third significant means by which federal policy impacts vehicle design is through safety standards. The Federal Motor Vehicle Safety Standards (FMVSS), first made effective in 1967, establish minimum safety performance requirements for a variety of aspects of motor vehicle design. Notable additions to the FMVSSs have included the introduction of seatbelt requirements, airbag requirements, brake master cylinders with redundant brake fluid reservoirs, and collapsible steering columns (Tarbet, 2004).

Though FMVSSs do not directly impact emissions or fuel economy, they are worth noting in the context of this research due to their impact on vehicle weight, and therefore, indirect impact on emissions and fuel economy. NHTSA estimates that the FMVSSs in place through 2001 represented about 125 pounds of the total weight of an average passenger car on sale (Tarbet, 2004). MacKenzie, Zoepf, & Heywood (2014) carry the analysis further, suggesting that, including secondary weight additions, safety features added 220 pounds to the weight of an average passenger car between 1975 and 2012. Secondary weight includes modifications to supporting systems and structures needed to accommodate increases or decreases in primary weight in order to maintain structural integrity and performance. For example, a vehicle with a lightened body architecture will require less robust, and therefore lighter, suspension and braking components, and potentially a smaller and lighter engine. Based on Cheah (2010), MacKenzie, Zoepf, & Heywood (2014) applied a secondary weight coefficient of 80 percent; that is, any primary weight increases or decreases were multiplied by 1.8 to account for the impacts of secondary weight increase or decreases.

Perceived safety has been partially responsible for the shift towards larger vehicles over the past few decades and played a role in the current size-neutral approach to fuel economy regulation, with one of the criterion for adopting a footprint-based standard being the preservation of safety. In fact, the perception of safety of large utility vehicles was generally overblown and undeserved and the impact of larger vehicles, particularly SUVs and CUVs, on overall safety has been mixed (Gladwell, 2004). SUV and CUV occupants are less likely to die in crashes than those in passenger cars, but this tends to be more indicative of crash incompatibility than actual differences in safety performance. Until recently, SUV drivers were more likely to die in single-vehicle crashes than drivers of passenger cars (Insurance Institute for Highway Safety, 2005). Moreover, the increased prevalence of SUVs has actually made smaller passenger cars less safe, leading to an effective "arms race" for larger vehicles that are safer in a crash with another large vehicle (White, 2004). A mutual "de-escalation" could, therefore, reduce fuel consumption and emissions while also maintaining relative safety levels.

3.6.4. Comparison to Other Large Automotive Markets

The American approach to regulating motor vehicles, particularly in the areas of fuel economy and emissions, differs sharply from those found in other major automotive markets, namely Europe and Japan. The U.S. Congress, as well as states, has long avoided implementing policies that would directly impact the ownership cost of relatively inefficient vehicles. One exception has been the gas guzzler tax, introduced in 1978 as a disincentive to the purchase of the least fuel-efficient passenger car models. Since 1991, the gas guzzler tax has ranged from $1,000 for vehicles rated between 21.5 and 22.5 mpg in the EPA's combined driving cycle (55 percent city, 45 percent highway) to $7,700 for passenger cars rated at less than 12.5 mpg (U.S. Environmental Protection Agency, 2012). Due to the fact that gas guzzler tax levels have remained constant for nearly 25 years, as well as the significant improvements to the fuel efficiency of even the least efficient vehicles, critics argue that the gas guzzler tax is largely irrelevant, applying mainly to high-end vehicles with high price tags that generally overwhelm the modest tax. In 2013, the cheapest vehicle to which the gas guzzler tax applied cost $41,000 but more than half cost over $100,000 (Tingwall, 2014).

Where the U.S. charges modest taxes to just a few inefficient models, governments in other major automotive markets take a far more aggressive approach. The United Kingdom, for instance, charges excise tax based on carbon dioxide emissions, with models emitting less than 130 grams per 100 km entirely exempt from the tax in their first year of registration (though only vehicles emitting less than 100 grams of carbon dioxide per 100 km are exempt from the tax in subsequent years). Otherwise, the annual first-year excise tax ranges from £130 for vehicles emitting between 131 and 140 grams of carbon dioxide per 100 km to £1,090 for vehicles emitting more than 255 grams of carbon dioxide per 100 km (European Automobile Manufacturers Association, 2014, p. 266). France takes an even more aggressive approach, taxing high emissions vehicles (emitting more than 250 grams of carbon dioxide per 100 km) purchased in 2014 up to €8,000, while rewarding buyers of hybrid vehicles emitting less than 110 grams of carbon dioxide per 100 km with a €3,300 rebate, and buyers of any vehicle producing less than 60 grams of carbon dioxide per 100 km with a €4,000 rebate (European Automobile Manufacturers Association, 2014, p. 123).

European countries are also far more aggressive in taxing fuel than the United States. At just 18.4 cents per gallon, the federal gasoline tax in the United States has remained constant since 1993. In contrast, most European countries collect several dollars per gallon in taxes, leading to higher total fuel costs and, therefore, stronger incentives for consumers to purchase fuel-efficient vehicles (see Figure 37).

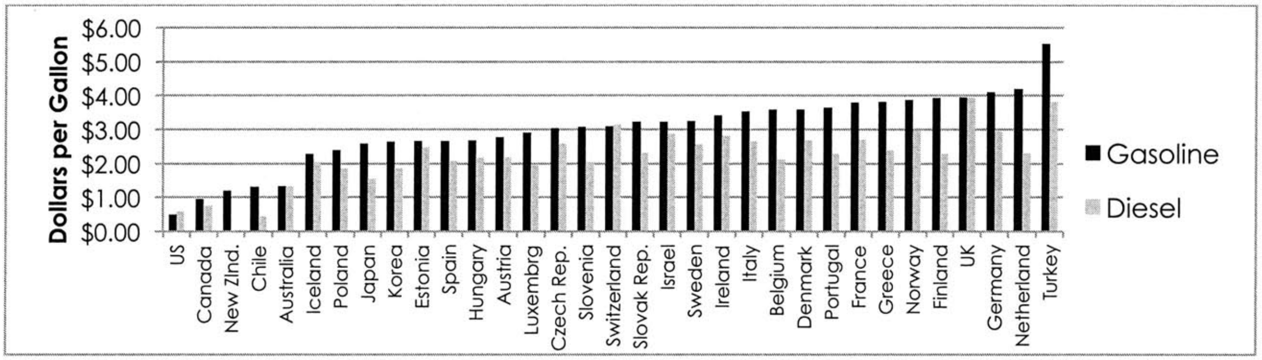

Figure 37: Fuel taxes by country (Source: U.S. Department of Energy Alternative Fuels Data Center)

3.6.5. Discussion and Policy Options

Karplus (2013) suggests that the United States has pursued fuel economy regulation over fuel and vehicle efficiency-based taxes because the costs are indirect – potentially affecting the purchase price of new vehicles, but not explicitly – and incurred infrequently. Fuel and excise taxes, on the other hand, are incurred on a weekly and annual basis, respectively. Regardless of reasons, the U.S. approach to addressing automobile externalities has generally been unsuccessful – whether by design or inadvertently – in influencing the purchase of smaller, more fuel-efficient vehicles and has instead focused intently on improving technology for all vehicles. The original CAFE standards, in their establishment of a single standard for all passenger cars and a separate standard for light trucks, created a path by which consumers could opt for less efficient vehicles and manufacturers could avoid CAFE-related fines. More recently, the switch to footprint-based CAFE standards was explicitly designed to avoid giving preferential treatment to a particular type of vehicle. However, the results of the fleet analysis presented above suggest that this leaves the potential for significant improvement on the table. Moreover, the gains to be made by shifting preferences towards smaller vehicles are additive with the gains already made through the direct regulation of fuel economy and emissions.

As Karplus (2013) suggests, tax schemes that discourage the sale of large, inefficient types of vehicles are unpalatable politically because they place direct economic burden on the public, who feels this burden far more frequently than they do purchasing a new vehicle and encountering slightly higher prices. Feebate systems, however, could provide a publicly acceptable way of encouraging the purchase of smaller types of vehicles. France's rebates for low emissions vehicles provide a good example, where buyers of the most fuel-efficient vehicles not only receive a substantial credit, but also avoid paying taxes. Some incentives are available in the U.S., but are largely limited to one-time credits for the purchase of hybrids and alternative fuel vehicles. Such schemes could potentially be extended to any vehicle achieving high fuel economy.

The U.S.'s Car Allowance Rebate System, or "Cash for Clunkers", provides another example – albeit an ephemeral one – of an incentive scheme designed to lure drivers toward more fuel-efficient vehicles. Participants in the program received a \$3,500 to \$4,500 rebate toward the purchase of a new vehicle achieving at least 22 mpg by retiring a vehicle rated at less than 18 mpg (with the exact rebate amount dependent on the fuel economy difference between the scrapped vehicle and the new vehicle). The results clearly illustrate the power of incentives to shift vehicle type preferences. In just one month, the program led to the sale of nearly 700,000 new vehicles with an average fuel economy rating of just under 25 mpg. Meanwhile, the "clunkers" traded in – the most popular of which were SUVs and pickup trucks – achieved an average of less than 16 mpg (Puzzanghera & Zimmerman, 2009). Critics suggest that this was an expensive way of reducing carbon emissions; Knittel (2009) places the implied cost of carbon under the program at no less than \$237, far more than the \$33 per ton suggested by the Interagency Working Group on the Social Cost of Carbon. That said, Hoekstra, Puller, & West (2014) also suggest that the program was far more successful from an environmental perspective than an economic one, and that the environmental goals likely undermined the economic objectives.

Tax schemes – both for fuel and vehicle operation and ownership – as well as vehicle retirement programs can provide means of incentivizing consumers to adopt vehicle types that are smaller and/or more fuel-efficient (i.e., foregoing tall profiles and four-wheel-drive systems that decrease fuel economy). Where these types of policies, particularly taxes, have been used extensively in Europe as a primary strategy for controlling automobile externalities, they have generally been ignored in the U.S. The scenario analysis presented earlier suggests that implementing such strategies to shift consumer preferences toward more fuel-efficient vehicle segments – or discouraging them from adopting less fuel-efficient options – could produce modest benefits in terms of overall fuel consumption, and by association, carbon dioxide emissions. To say that the benefits are modest should not imply that they be ignored or considered inconsequential. Instead, these strategies may prove desirable as technology improvements reach their maximum potential and new sources of fleet-wide fuel-efficiency improvements become necessary. Alternatively, they might be implemented alongside the current technology-forcing standards to reduce the fleet's environmental impacts sooner. Furthermore, the results cannot simply be considered solely in terms of potential benefits, but also potentially avoided disbenefits. While the most desirable scenario reduces LDV fuel consumption relative to the reference case by six percent in 2040, it is a more than ten percent improvement over the highest fuel consumption scenario explored above.

4. Assessing the Fuel Economy Benefits of Increasingly Automated Vehicles

4.1. Overview

Where section 3 evaluated the extent to which shifts among different segments of light duty vehicles might influence fleet-wide fuel consumption, this section will turn to a far more revolutionary change poised to transform the automobile. Few fundamental characteristics of the automobile have changed in its history since the early twentieth century. Internal combustion engines, typically in the front, have powered the majority of cars since the Ford Model T's introduction. With rare exceptions, cars have had four wheels, compartments for passengers and cargo, and a wheel and pedals as the primary controls. Cars have become more powerful, efficient, and computerized, but trends in vehicle evolution have generally been linear. Even the shift from passenger cars to SUVs and CUVs discussed in section 2 was more the result of product planning decisions, marketing, and design than it was a fundamental engineering change. In the past five years, though, a new element of vehicle design has been undergoing research, development, and testing that has the potential to fundamentally change the nature of the car. Since 2004, teams from universities, the automotive industry, and high-tech companies have been developing the requisite hardware and software systems that would allow a vehicle to navigate without human intervention.[6]

Research teams, most prominently one led by Google, are now testing prototypes on public roads, refining their systems and collecting real-world data on how the vehicles behave and react to typical driving situations. Advocates of automated vehicles suggest that they have the potential to drastically reduce the prevalence of crashes and associated fatalities and injuries that plague America's – and the world's – roads. This section, however, will explore the extent to which the gradual automation of the U.S. LDV fleet might be used as a tool for reducing fuel consumption. Though this is not the primary benefit touted by the technology's developers and advocates, there is reason to believe that automating some or all driving might prove more fuel-efficient than full manual control. Neubauer & Wood (2013) found that

[6] This paper will use the terms automated, autonomous, and self-driving vehicles interchangeably.

aggressive driving behavior, characterized by high average acceleration and speed, could decrease fuel economy by up to 50 percent, while docile driving behavior could increase fuel economy by up to 20 percent. Automated driving systems offer the ability to systematically limit acceleration (and potentially speed), thereby enabling more fuel-efficient driving patterns. Moreover, automated driving features may allow significantly shorter following distances while maintaining safety, reducing fuel consumption even further through platooning.

The following sections will detail the recent development of automated vehicles, highlight the relevant parameters for evaluating the potential of automated vehicles to affect fuel consumption using the fleet model, and present the results of a fleet analysis.

4.2. A Brief History of Automated Vehicles

The current fleet of automated vehicle prototypes largely originated from the 2004 Grand Challenge, a race for unmanned land vehicles sponsored by the Defense Advanced Research Projects Agency (DARPA), a military research organization. In its first year, not a single vehicle finished the 150-mile course; in fact, the most successful vehicle only travelled 7.4 miles (Walton, 2004). DARPA repeated the event the following year and four vehicles finished the 132-mile course within the ten-hour allotted timeframe (Defense Advanced Research Projects Agency, 2005). Two years later, DARPA hosted the Urban Challenge, which introduced more realistic driving elements into the competition, including interactions with other vehicles, traffic laws, and a simulated urban street network. The results were a significant improvement over the Grand Challenge, but the vehicles were still far from ready for real-world use, as suggested by the headline of an *IEEE Spectrum* article about the competition: "Autonomous Vehicles Complete DARPA Urban Challenge: Six of 11 autonomous vehicles finish 90-kilometer course *with no major accidents*" (emphasis added) (Voelcker, 2007).

Automated vehicles continued to advance following the DARPA Urban Challenge and in 2010, Google made a startling announcement: the company's prototypes had travelled 140,000 miles on California's public roads (Google, 2010). Since the technology was considered novel and relatively infeasible at the time, no laws explicitly prohibited or allowed this testing. As a result, Google began lobbying state lawmakers to adopt licensing laws that would allow them to continue testing (Efrati, 2012). Google has successfully convinced Nevada, California, Florida, and the District of Columbia to introduce specific laws to allow the use of automated prototypes and several other states have introduced legislation that follows suit. The company now has a pool of employees who drive a fleet of prototypes equipped with its "Chauffeur" system to work each morning, providing feedback to engineers on any glitches or problems that they encounter.

Google is optimistic about the future of the automated vehicle and is directing its efforts to create a commercially viable product (Bilger, 2013, p. 104). The automotive industry, on the other hand, is divided. Most companies exhibit a healthy skepticism about the technology, investing in its development but proceeding cautiously, fearful that prematurely releasing automated vehicles to the public would expose them to legal liability. Some, like Nissan and Mercedes-Benz, have taken bold stances on the technology, with the latter releasing a truly driverless prototype and the former announcing its intentions to release increasingly automated vehicles over the next decade, eventually leading to a "driverless" model (Mercedes-Benz, 2015) (Renault-Nissan Alliance Team, 2015). Others, like Audi, General Motors, and Ford, have not committed to truly "driverless" vehicle technology and have, instead, committed to releasing features that increasingly automate vehicle controls. Systems to assist with low-speed driving in congested highway traffic are likely to be the first available, with General Motors' Super Cruise representing the first wave of high-speed capable systems for automating highway driving, beginning in the 2017 model year (General Motors, 2014).

4.3. Automated Vehicle Fleet Analysis Considerations

The modern wave of automated vehicle development, underway for more than a decade, is exciting but also quite uncertain in numerous respects. The following sections discuss the various uncertainties and considerations surrounding both the deployment of automated vehicles and estimating their potential impacts.

4.3.1. Automation Level and Deployment Timeline

Initial conversations around automated vehicles, particularly those related to the DARPA Grand and Urban Challenges, focused most intently on "driverless" vehicle technology. More recently, however, both the technology's developers and commentators have employed more nuanced ways of referring to it that convey the range of potential automation levels. NHTSA released a set of definitions referring to the levels of automation in 2013, which have helped to structure discussions around the range of automation capabilities, as well as to cement the notion that vehicle automation is a continuum, not a binary state.

Their 2013 memo defines five levels of automation as follows:

Table 3: NHTSA automation levels and descriptions (National Highway Traffic Safety Administration, 2013)

Automation Level	Description
Level 0: No Automation	The driver is in complete and sole control of the primary vehicle controls – brake, steering, throttle, and motive power – at all times.
Level 1: Function-Specific Automation	Automation at this level involves one or more specific control functions. Examples include electronic stability control or pre-charged brakes, where the vehicle automatically assists with braking to enable the driver to regain control of the vehicle or stop faster than possible by acting alone.
Level 2: Combined Function Automation	This level involves automation of at least two primary control functions designed to work in unison to relieve the driver of control of those functions. An example of combined functions enabling a Level 2 system is adaptive cruise control in combination with lane centering.
Level 3: Limited Self-Driving Automation	Vehicles at this level of automation enable the driver to cede full control of all safety-critical functions under certain traffic or environmental conditions and in those conditions to rely heavily on the vehicle to monitor for changes in those conditions requiring transition back to driver control. The driver is expected to be available for occasional control, but with sufficiently comfortable transition time. The Google car is an example of limited self-driving automation.
Level 4: Full Self-Driving Automation	The vehicle is designed to perform all safety-critical driving functions and monitor roadway conditions for an entire trip. Such a design anticipates that the driver will provide destination or navigation input, but is not expected to be available for control at any time during the trip. This includes both occupied and unoccupied vehicles.

With the NHTSA automation level definitions in mind, several uncertainties exist surrounding the deployment of automated vehicle technology. First, the timeline and expected progression of automated vehicle technology is still ambiguous, particularly when considering higher levels of automation. Though many industry representatives point to the mid 2020s for the initial availability of truly "driverless" cars, they also acknowledge the considerable uncertainty surrounding such predictions (Intelligent Transportation Systems Joint Program Office, 2014, p. 12). The availability of partially-automated systems, reflective of NHTSA Level 2 (and possibly verging on Level 3), is considerably more certain. As mentioned earlier, General Motors has committed to making its Super Cruise highway autopilot feature available in the 2017 model year while Tesla CEO Elon Musk recently announced that his company would be issuing an over-the-air software update to Model S sedans during the summer of 2015 that would enable similar highway-only automated driving functionality (Kessler, 2015). In light of these commitments by major manufacturers, it seems most reasonable to focus on the introduction of highway-only automated driving systems with anticipated introduction within the next few years.

Even if the year of introduction can be anticipated, the rate of adoption is far more difficult to predict. Zoepf (2011) found that the diffusion of new automotive technologies has generally followed a standard logistic form, or S-shaped, curve first discussed widely by Bass (1969). Unfortunately, where Zoepf (2011) reviewed the adoption profiles of several powertrain, safety, and comfort/convenience technologies, none of these technologies reflect the complex adoption challenges that automation systems will face. Zoepf (2011) points out several factors that affect the maximum demand for automotive features, including limited appeal, the imposition of tradeoffs, and competing technologies, all of which will potentially impact the introduction, for example, of a Level 2 highway autopilot system. Given its position on the automation spectrum, adaptive cruise control represents a potential analog in anticipating the adoption of a partial-automation system. However, even though adaptive cruise control has been available on the U.S. market for over 15 years, data on the extent to which it has been adopted in new vehicle purchases only exists for the 2013 model year. Moreover, in 2013, just five percent of new vehicles were equipped with adaptive cruise control according to WardsAuto; IHS predicts that just over seven percent of vehicles globally will be equipped with the feature by 2020 (Wayland, 2015). These figures are insufficient to develop an empirically based adoption curve for a highway automation system. Perhaps the best estimate, then, comes from the consulting industry, where the Boston Consulting Group (BCG) has compiled input from both consumers and industry to estimate the likely adoption path of partially automated vehicles. Where industry representatives suggest widespread introduction of Level 2 systems within the next few model years, consumer survey results indicate strong interest and a relatively high willingness to pay for automated driving features (Boston Consulting Group, 2015). Recognizing the vast limitations of their forecasts (citing, for example, the inherent uncertainty in asking consumers to rate their interest in a product they have never experienced firsthand), BCG's work represents one of the more comprehensive attempts to predict the adoption potential of automated vehicles. BCG's projection assumes a 2015 introduction for partial automation systems, a 25 percent maximum market penetration in 2035, and suggests that the penetration rate will increase most rapidly in 2025. These parameters are sufficient for approximating a logistic adoption curve with the following form:

$$\textit{Percent of New Vehicles Equipped in Year } t = \frac{Limit}{1 + e^{-\alpha(t-t_0)}}$$

where:

Limit = Maximum percent of new vehicles equipped

t = current year

t_0 = year in which percent of new vehicles equipped equals Limit/2

α = regression parameter approximating steepness

Assigning parameters of t_0 = 2025, Limit = 0.25, and α = 0.35 yields a curve approximating that derived by BCG (see Figure 38).

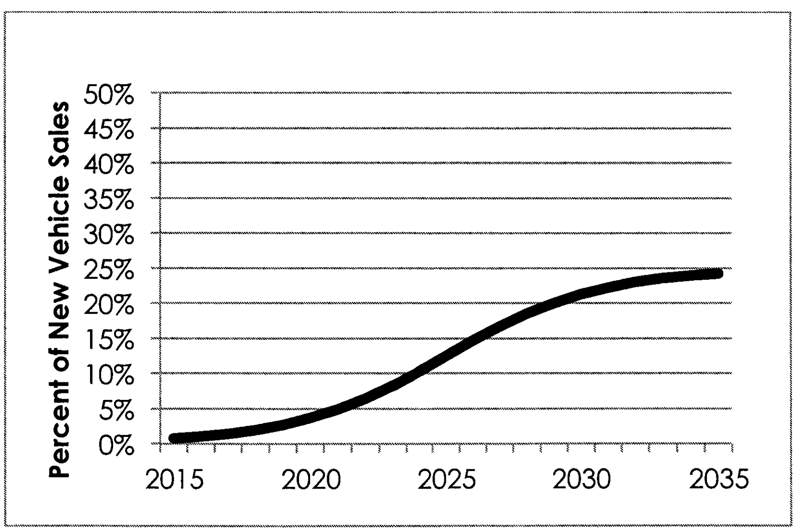

Figure 38: Proposed adoption curve for partially-automated vehicles based on BCG study, with t_0 = 2025, Limit = 0.25, and α = 0.35, compared to BCG adoption curve for partially-automated vehicles

4.3.2. Fuel Economy Benefits

If Level 2 highway-only automation systems are deployed along the timelines anticipated by BCG, the next source of uncertainty to address concerns the specific benefits to fuel economy. Based on several preliminary studies that have evaluated the potential vehicle-level fuel economy benefits that automation could bring, two specific benefit areas from Level 2 automation seem likely. MacKenzie, Wadud, & Leiby (2014) conducted a review of ten potential sources of fuel-savings from vehicle automation and suggest that benefits from platooning and "eco-driving" behavior are most likely with Level 2 automation. Similar research by Brown, Gonder, & Repac (2014) noted the same potential sources of fuel economy benefits.

Both groups suggest that automation, even a Level 2 highway-only system, could enable benefits from platooning, whereby vehicles can follow more closely. Automated vehicles could greatly reduce the need to leave a safe following distance between vehicles because they offer negligible reaction times to changes in the speed of vehicles ahead. Simulation and field experiments have generally measured human reaction times to expected stimuli at an average of about 0.75 seconds while reaction times to unexpected stimuli (such as the sudden braking of a car in front) average about twice as long; the American Association of State Highway and Transportation Officials suggests that transportation engineers assume an average reaction time of 2.5 seconds (Green, 2000). These reaction times require drivers to leave ample distance between vehicles in case of a sudden braking event. Automated systems, on the other hand, can react almost instantaneously, allowing for greatly reduced following distances and aerodynamic drag. Studies reviewed by MacKenzie, Wadud & Leiby and Brown, Gonder, & Repac, attribute 20 to 60 percent reductions in drag to platooning, depending on the types of vehicles and the following distances. Based on Kasseris (2006), MacKenzie, Wadud & Leiby assume that overcoming drag accounts for between 50 and 75 percent of tractive energy. Combined, these figures suggest a potential reduction in fuel consumption during platooning of between ten and 45 percent. Brown, Gonder, & Repac define the potential benefits of platooning more narrowly, but are consistent in establishing the potential for a 20 percent reduction in fuel use by platooning vehicles.

Increased prevalence of "eco-driving" patterns is the second area of potential fuel economy benefits on which MacKenzie, Wadud & Leiby and Brown, Gonder, & Repac agree. The Alliance of Automobile Manufacturers, an industry group representing the 12 largest vehicle manufacturers, defines eco-driving as subtle driving habits intended to save fuel (Alliance of Automobile Manufacturers, 2008). These include avoiding rapid starts and stops and maintaining a constant speed to the greatest extent possible, instead of constantly varying speed. Automated vehicle systems present opportunities to consistently implement eco-driving habits, as a human driver would not control acceleration profiles when they are in use. Instead, system designers can dictate maximum acceleration rates as well as following distance buffers that allow automated vehicles to adjust their speed gradually in response to surrounding traffic, rather than abruptly as many human drivers do. MacKenzie, Wadud & Leiby reviewed available studies on the benefits of such eco-driving techniques and generally found that they can lead to up to a 20 percent reduction in fuel consumption. The sources reviewed by Brown, Gonder, & Repac indicate a 20 to 30 percent reduction for aggressive drivers, but suggest an upper bound of 15 percent compared to the habits of average drivers. Combined with the benefits of platooning, a vehicle equipped with a Level 2 highway-only automation system could achieve between a ten and 25 percent reduction in fuel consumption while being driven in automated mode.

One dynamic that neither MacKenzie, Wadud & Leiby nor Brown, Gonder, & Repac discuss is the impact of network effects on the benefits derived from automation. Network effects refer to the dependence of individual benefits on the behavior of others (Easley & Kleinberg, 2010, p. 509). Telephone ownership exhibits an oft-cited example of network effects. A single telephone provides its owner with few benefits if no one else owns a telephone, but its utility increases dramatically as the number of telephones in use grows. Network effects will likely affect even the limited benefits of partial automation discussed above. For example, a single vehicle with a Level 2 highway automation system will find few opportunities to effectively platoon if no other vehicles on the road are equipped with a comparable system. Similarly, a vehicle equipped with the same system will be unable to follow the eco-driving rules of constant speed and smooth acceleration/deceleration profiles if surrounding vehicles are not operating in the same manner. Therefore, it is important to incorporate a network effect in the fleet analysis. Though the fleet model lacks the dynamic nature to rigorously apply a network effect, a simple workaround should offer an approximation. Instead of applying the full fuel economy benefits discussed above from the introduction year, the fuel economy benefits will be scaled based on the percentage of vehicles *in use* (as opposed to percent of sales) that are equipped with automated features. More specifically, the benefits will be scaled as follows:

$$\begin{aligned}&\textit{Fuel Economy Benefit in Year } i\\ &\quad= \frac{\textit{Maximum Benefit}}{2} + \frac{\textit{Maximum Benefit}}{2} * \frac{\textit{\% of Fleet Equipped with Automation in Year } i}{\textit{Adoption Limit}}\end{aligned}$$

Therefore, the full benefit will only be realized for each vehicle equipped with automation once the percent of vehicles in use equipped with automation equals the maximum penetration rate (as a percentage of annual sales). That said, the equation assumes that half of the maximum benefit is available at the technology's introduction, when no other vehicles are equipped. This reflects the fact that even a vehicle equipped with a highway automation function is likely to experience some fuel economy benefit when operating alone (a single vehicle driving on a deserted road, for example, is likely to still derive some eco-driving-based fuel economy benefits). Figure 39 illustrates a sample application of this scaling approach for the introduction of an automation system that reaches a maximum adoption rate of 25 percent and yields a maximum fuel consumption reduction of 20 percent.

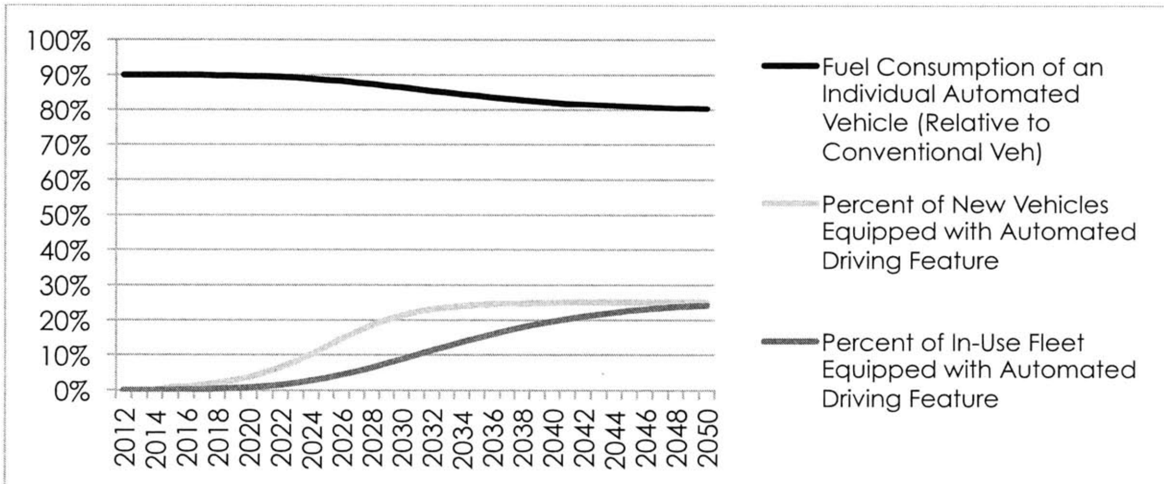

Figure 39: Illustration of fuel consumption reduction scaling to account for network effect; example assumes 25 percent maximum adoption rate of an automation that yields a maximum fuel consumption reduction of 20 percent

4.3.3. Extent of Operation

All of the fuel economy benefits discussed above refer to the benefits of a hypothetical automated vehicle control system when it is in use. However, the earliest systems to be deployed will likely be limited to specific road and traffic conditions and will, therefore, not be used all the time. It is necessary then to scale the benefits to the percent of miles during which such systems will be used. Both MacKenzie, Wadud & Leiby and Brown, Gonder, & Repac cite Federal Highway Administration (FHWA) statistics on the percent of driving miles that take place on highways and scale the benefits to this figure. FHWA defines three general classes of road based on the character of the traffic (i.e., local or long distance) and the extent of access (i.e., limited to distantly spaced ramps versus frequent cross-street access) (Federal Highway Administration, 2012). For the purposes of evaluating the fuel economy benefits of Level 2 automation, this paper adopts the assumptions of MacKenzie, Wadud & Leiby and Brown, Gonder, & Repac that such a system would only operate on roads defined as arterials (highest level of service and lowest degree of access) by FHWA. Figure 40 illustrates the percent of miles travelled on arterials, as measured by FHWA, between 1980 and 2011; the average across this period was 53 percent, which will be considered an upper bound for the number of miles that would be driven in an automated mode with the availability of a Level 2 automation system. The analysis will also consider cases in which fewer miles are automated, as it is unlikely that vehicles equipped with such systems will drive all highway miles in an automated mode.

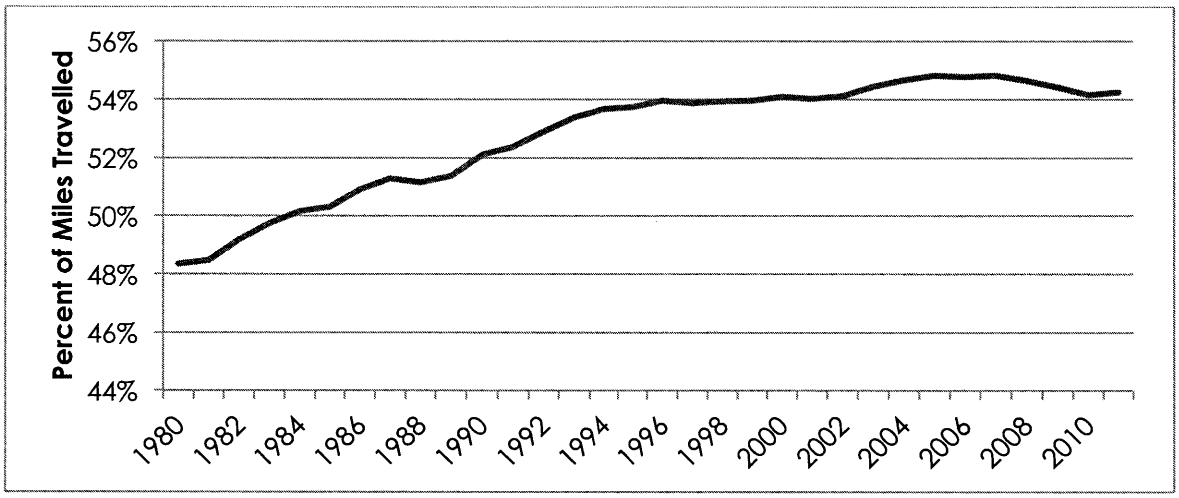

Figure 40: Percent of miles travelled on arterials by year (Source: FHWA Table VM-202)

Related to the percent of miles driven in an automated state is the relevant fuel economy value to adjust based on the benefits discussed in Section 4.3.2 above. The fleet model generally references the adjusted combined fuel economy figures reported by EPA because they reflect the average fuel efficiency of vehicles weighted by their split of urban and highway driving. However, since this analysis is assuming an automation system that is only functional on the highway, the fuel economy benefit must only apply to the adjusted highway fuel economy value, which is typically about 17 percent higher than the adjusted combined value (conversely, adjusted highway fuel *consumption* is 15 percent lower than adjusted combined fuel *consumption*) (U.S. Environmental Protection Agency, 2014).

4.3.4. Summary of Variables Affecting the Fuel Economy Benefits of Automation

Variable	Range of Values
Level of Automation	Level 2: Highway-only partial automation of steering and longitudinal controls; requires vigilant human supervision and ability to regain manual control Limited Function Level 3: Highway-only full automation; requires some human supervision
Year of Deployment	Level 2: 2015 Limited Function Level 3: 2025
Fuel Consumption Reduction	Platooning: Up to 20% during use Eco-Driving: Up to 20% during use
Extent of Operation	Up to 53% of vehicle miles travelled (VMT) for applicable vehicles
Network Effects	Fuel consumption reduction is scaled by the ratio of vehicles in use equipped with automation in the current year to the maximum adoption rate (i.e., the limit in the adoption rate logistic function)

4.4. Vehicle Automation Fleet Analysis Results

With the vehicle-level fuel economy benefits defined by MacKenzie, Wadud & Leiby and Brown, Gonder, & Repac in mind, the author conducted a fleet analysis across the range of variables presented in the previous section. All of the scenarios presented below are based on the EIA reference case discussed in section 1.4.6 in terms of vehicle segment sales mix and assumptions for annual changes in average new vehicle fuel economy, miles of travel per vehicle, and vehicle sales.

In light of the uncertainty surrounding the introduction of vehicles with high levels of automation, the most likely and valid scenario is one that explores the near-term introduction of a Level 2 highway-only automation system, akin to the Super Cruise system to be introduced soon by General Motors or Tesla's recently-announced Autopilot system. Both systems allow extended periods of driving during which the driver does not need to operate the steering, brakes, or throttle, though they are required to pay attention and be ready to take over during certain conditions. Human operators are also assumed to be responsible for overall navigation and lane changes. Such a system falls short of being truly "driverless" so it avoids hypothesized societal and vehicle design changes (e.g., reduced auto ownership, increased mileage from reduced disutility of driving, reduced weight due to less need for crash protection features) and, therefore, simplifies the analysis. However, uncertainty still exists in the variables discussed in the previous section, so the analysis results are intended to explore both the overall impact of introducing a Level 2 highway-only automation system as well as the sensitivity of the results to each variable. Each section below, therefore, presents scenario analysis results based on a plausible range of each specific variable (fuel economy benefit, percent of VMT in which automation is used, and adoption level).

4.4.1. Fuel Economy Benefit

As indicated in Section 4.3.2 above, hypothesized benefits of a Level 2, highway-only automation system range from ten to 25 percent. Considering the array of relevant degrading factors (adoption rate, network effect, percent of automated miles), the impact of such an automation system on fleet-wide fuel consumption is unlikely to approach these levels. The fleet model, therefore, can provide insights into the level of impacts that can be reasonably expected given the range of assumptions outlined above.

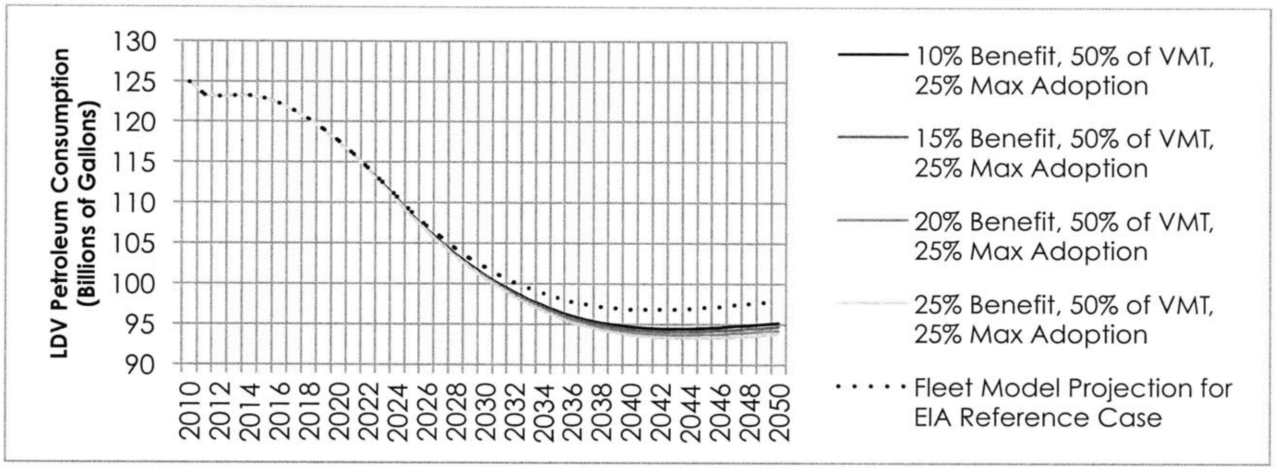

Figure 41: Annual LDV fuel consumption projections for Level 2 automation scenarios with range of fuel consumption benefits, 2010 through 2050

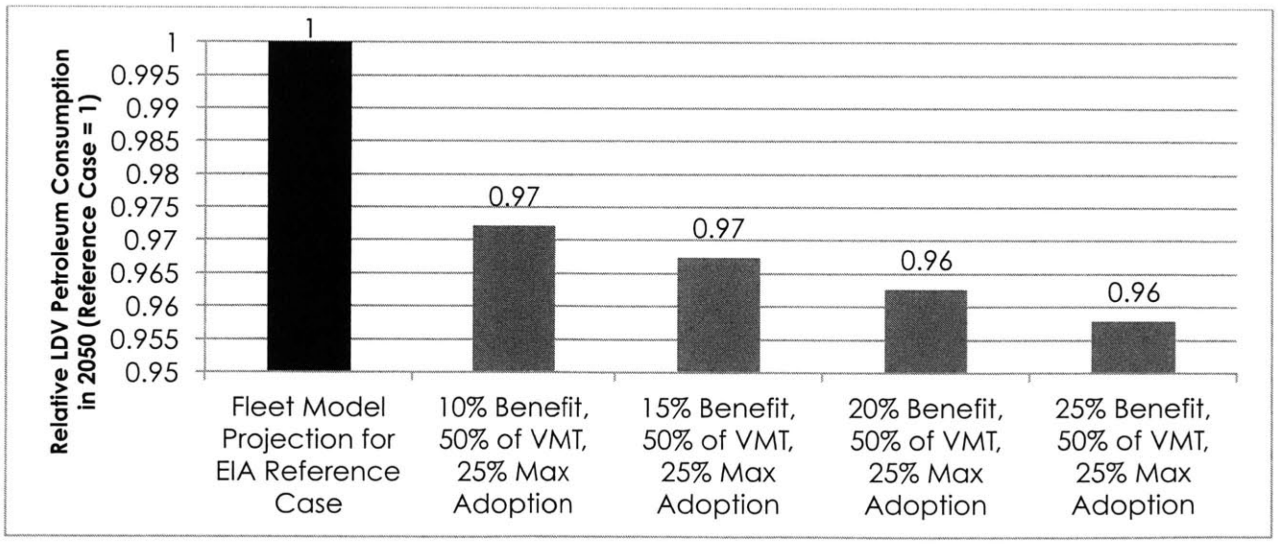

Figure 42: LDV petroleum consumption in 2050 relative to reference case for Level 2 automation scenarios with range of fuel consumption benefits

The results of the fleet analysis suggest that, similar to the vehicle segment shifts explored earlier, modest reductions in fleet-wide fuel consumption are possible with the introduction of a Level 2 automation system used only in highway driving during 50 percent of driving mileage and ultimately adopted by 25 percent of vehicle buyers. Varying the extent of the benefit experienced by vehicles during periods of automated driving has comparatively little effect. All other parameters remaining constant, varying the benefit level between ten and 25 percent yields a change of just one percent in fleet-wide fuel consumption by 2050.

4.4.2. Automated VMT

A Level 2 automated vehicle might operate in an automated mode during up to half of its mileage, or the average annual travel estimated to take place on highways. However, this does not mean that vehicles equipped with such a system will drive all highway miles in an automated mode. Therefore, it is important to understand the extent to which changes in the percent of mileage travelled in an automated state affect the overall impact of fleet-wide fuel consumption.

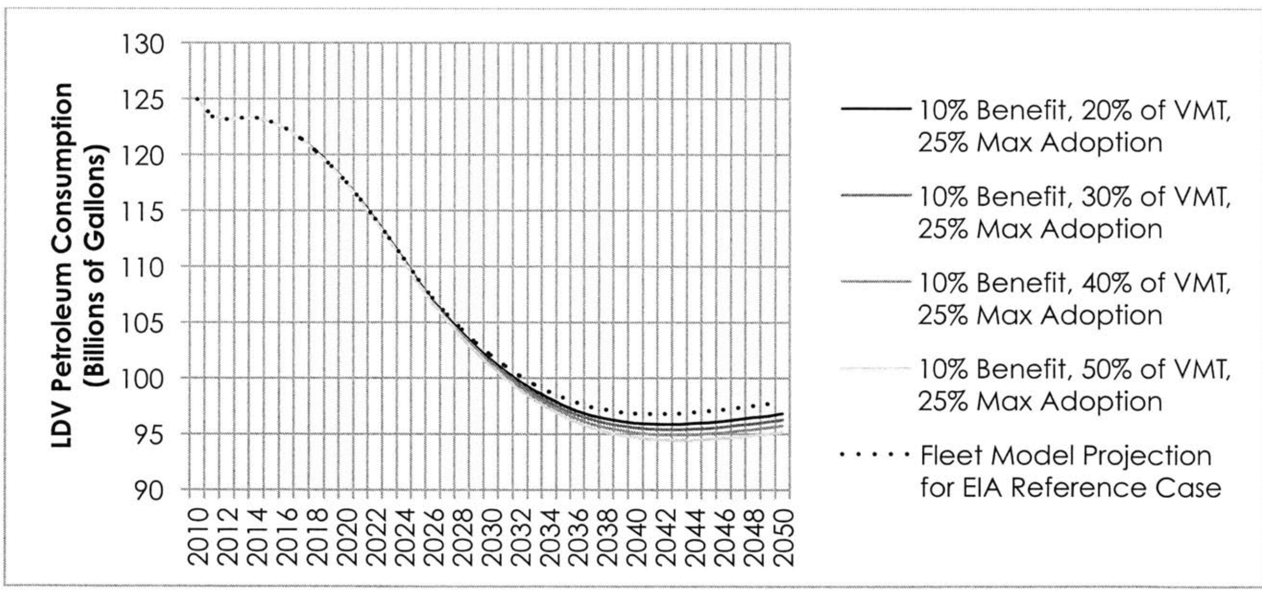

Figure 43: Annual LDV fuel consumption projections for Level 2 automation scenarios with range of automated VMT, 2010 through 2050

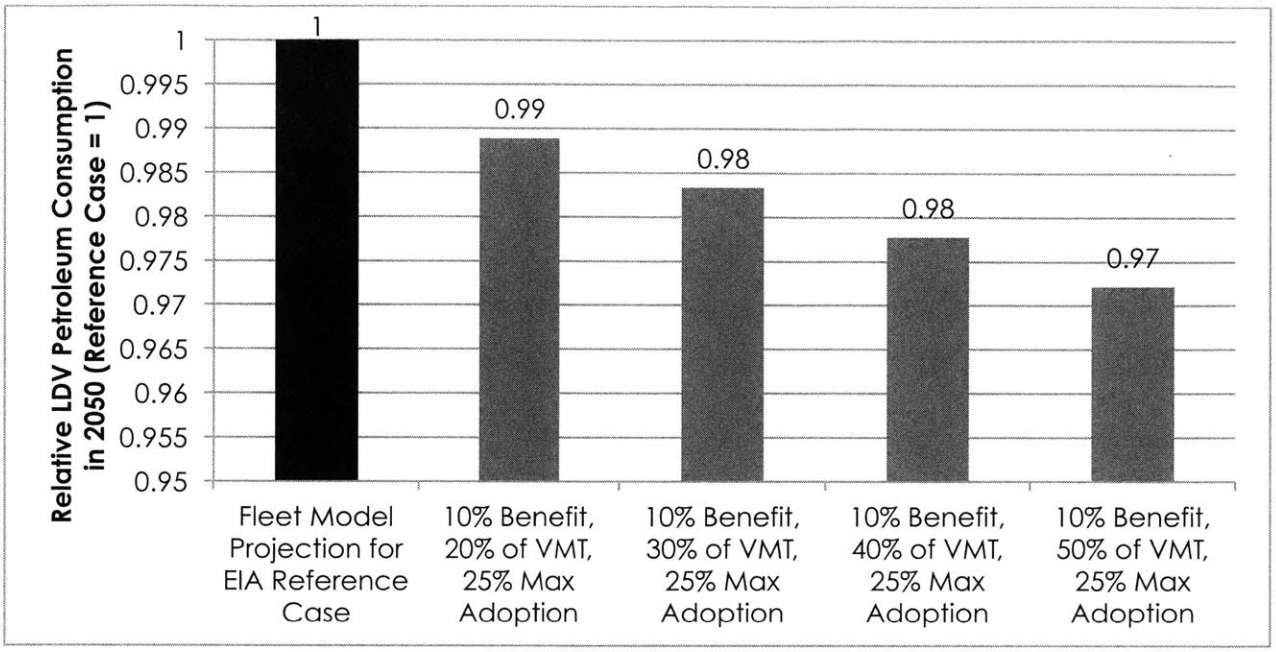

Figure 44: LDV petroleum consumption in 2050 relative to reference case for Level 2 automation scenarios with range of automated VMT

Figure 43 and Figure 44 above suggest that, similar to adjusting the extent of vehicle-level fuel consumption benefits, adjusting the percent of VMT travelled in an automated state in ten percentage point increments shifts fleet-wide fuel consumption by just one percent in 2050.

4.4.3. Adoption Rate

Though BCG suggests a maximum adoption rate for partial automation systems of 25 percent, actual adoption could differ significantly from this forecast. Therefore, it is helpful to understand how different adoption levels might impact fleet-wide fuel consumption. For the sake of simplifying the analysis, each scenario holds all adoption parameters constant, except for the adoption limit. Therefore, adoption (as a percent of sales) is assumed to approach its maximum around 2040, regardless of the level of maximum adoption.

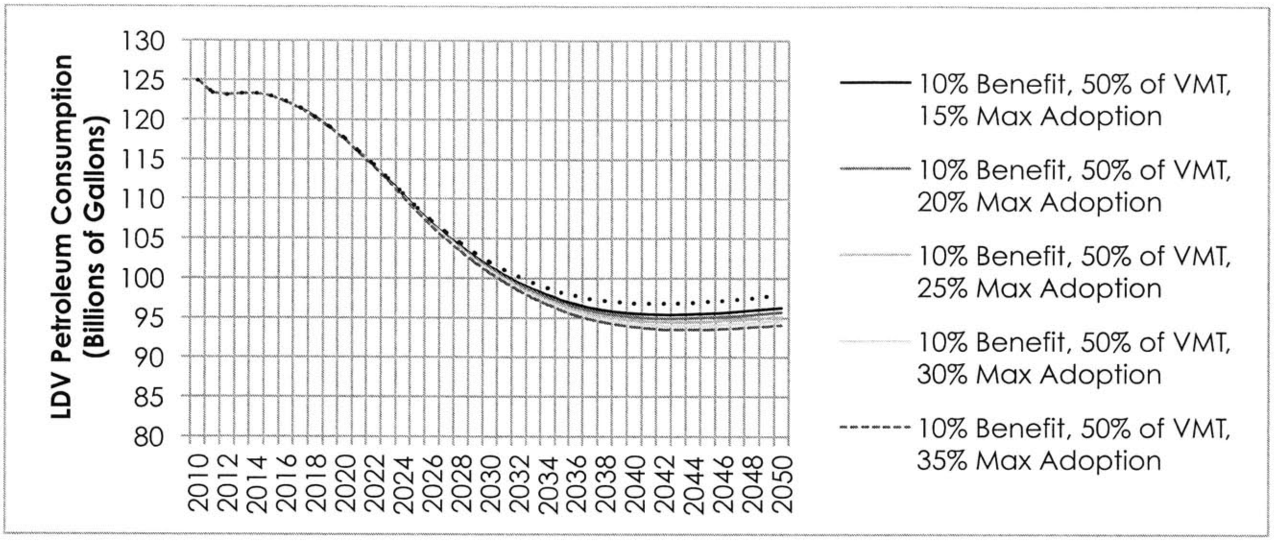

Figure 45: Annual LDV fuel consumption projections for Level 2 automation scenarios with range of adoption rates, 2010 through 2050

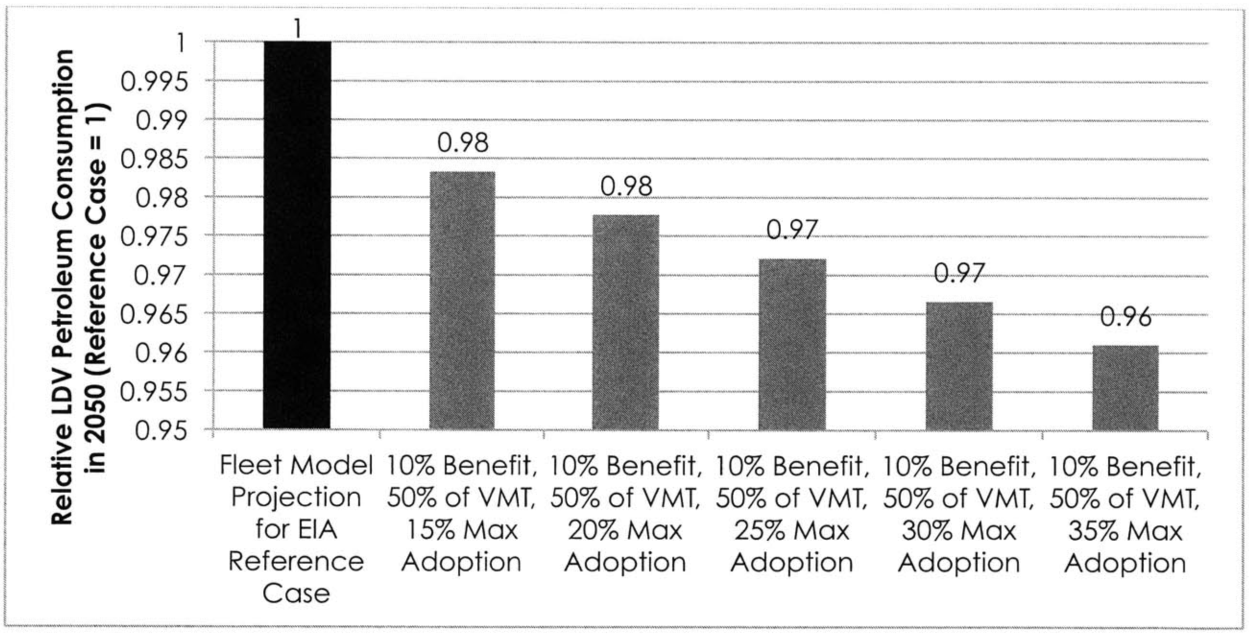

Figure 46: LDV petroleum consumption in 2050 relative to reference case for Level 2 automation scenarios with range of adoption rates

Once again, the results above suggest that ten percentage point changes in maximum adoption of Level 2 automation result in a one percent change in fleet-wide fuel consumption by 2050. It is worth noting that higher levels of adoption may take longer to achieve, in contrast to the scenario parameters, which hold adoption timeline constant while varying the maximum adoption rate. Since the fuel consumption reductions, even in this simplified (and somewhat optimistic) case, are relatively modest, delayed adoption would simply push off these benefits to a more distant horizon year.

4.5. Discussion

The results presented above suggest that modest results are possible from the introduction of a Level 2, highway-only automation system. In the most optimistic case (maximizing all of the variables discussed above), whereby adoption reaches 35 percent of new vehicle sales by 2040; vehicles equipped with such a system can expect a 25 percent reduction in fuel consumption while the system is in use; and equipped vehicles operate in automated mode during half of miles driven, a six percent reduction in fleet-wide fuel consumption can be realized by 2050. However, such a scenario seems unlikely and assumes a perfect confluence of factors affecting both technology adoption and the operating conditions that determine the extent to which vehicles can drive in an automated mode and realize maximum fuel economy benefits. A more moderate case representing the mid-range values for each of the variables (20 percent adoption, 15 percent fuel consumption reduction, and 35 percent of miles driven in automated mode) yields fleet-wide fuel consumption reduction of just over two percent by 2050. Finally, a skeptical scenario that limits each variable to the lower end of their hypothesized range (15 percent adoption, ten percent fuel consumption reduction, and 20 percent of miles driven in automated mode) reduces fleet-wide fuel consumption by less than one percent by 2050.

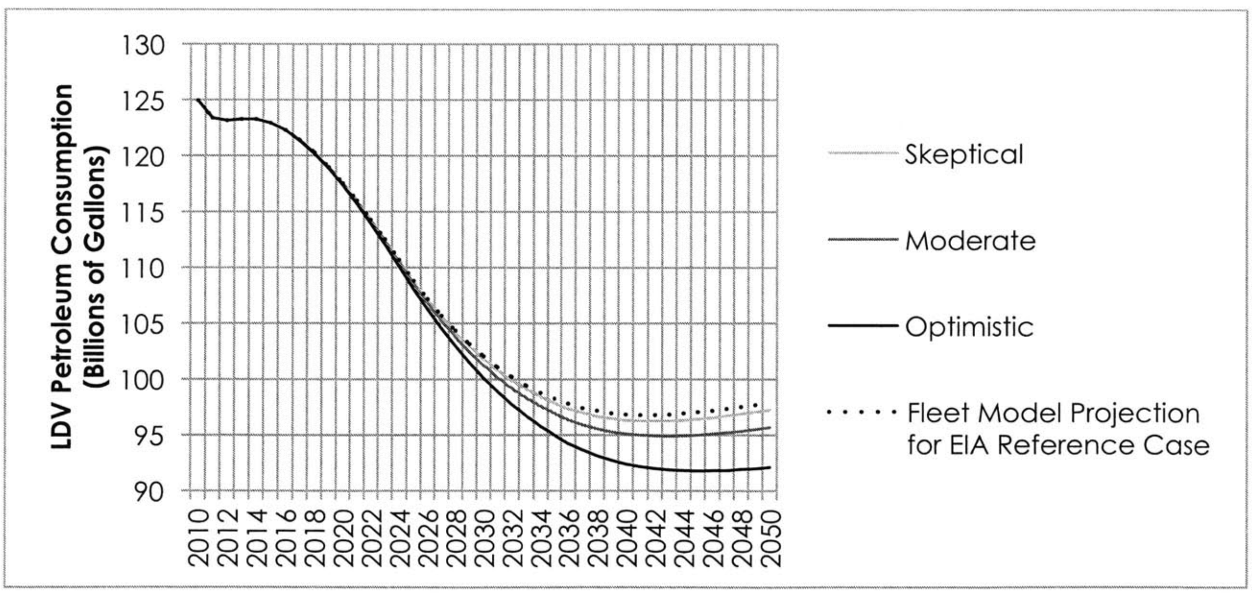

Figure 47: Annual LDV fuel consumption projections for optimistic, moderate, and skeptical Level 2 automation adoption and operation scenarios, 2010 through 2050

The relatively modest reductions in fleet-wide fuel consumptions stemming from relatively substantial per-vehicle fuel economy benefits stems from several degrading factors reflected in the dynamics of the fleet model. The benefits are assumed to only impact a fraction of the miles driven by a fraction of vehicles in the fleet. The latter degrading factor is exacerbated by the assumed network effect, which effectively delays the application of full fuel economy benefits until a significant portion of the fleet is equipped with a highway automation feature. The combination of logistic adoption and the network effect are largely responsible for the delay in realizing any benefits in terms of fleet-wide fuel consumption; the automation scenario results depicted in Figure 47 differ very little from the reference case until about 2030, at which point enough of the fleet is capable of automated highway operation to yield some reduction in fleet-wide fuel consumption.

This is not to suggest that the potential fuel consumption reductions revealed in the scenarios presented above are negligible. In fact, their timing may prove valuable in the quest to reduce LDV fuel consumption. As suggested by the reference case scenario, LDV fuel consumption is likely to decline significantly through about 2040 in response to the current CAFE standards (and perhaps further, depending on whether the standards are tightened beyond the 2025 targets currently in place). However, further reductions may need to be pulled from sources beyond additional engine technology improvements, as manufacturers reach the limits of engine efficiency or political considerations prevent further increases in fuel economy standards. Even the modest benefits from low levels of automation represent an attractive source of fuel savings for several reasons. First, automation is currently viewed primarily as a technology for promoting transportation safety and, therefore, is less likely to be opposed on political grounds (though questions do still exist around appropriately regulating automated vehicles). Its potential for improving fuel economy is a secondary benefit that can be realized once automated technologies are sold on the basis of safety. Second, while the delay in realizing fuel-saving benefits of automation may seem disappointing, it comes at a convenient time relative to other sources of fuel economy improvements. Though immediate benefits are desirable, the delay observed in the scenarios explored above causes benefits to start accruing just after the current CAFE standards reach their highest levels.

It should be noted that the scenarios explored in this section reflect a fairly optimistic adoption timeline, with sales of automation-equipped vehicles reaching half of the market adoption maximum in just ten years. Though supported by market research, such an adoption profile is considerably more aggressive than that experienced by other radical automotive technologies. After 15 years on the U.S. market, hybrids have reached just 4 percent of sales (U.S. Department of Energy, 2014). Adaptive cruise control systems, a predecessor technology to partial and full automation, have been available for the same amount of time and are equipped on roughly the same percentage of new vehicles currently (WardsAuto, 2014, pp. 236-272). One explanation is that these technologies experienced a period of "production prototype" status, whereby they were available publicly but still under development based on feedback from early adopters. On the one hand, given the radical nature of a highway-only automation system, it seems reasonable to expect a similarly progressive rollout. However, unlike hybrid drivetrains and adaptive cruise control, which involved fundamentally new applications of technology when they were introduced, the limited-capability automation system considered in the scenarios above represents an incrementally more complicated application of existing technology. The basic technological foundations for a highway autopilot system are already equipped on many production vehicles in the form of adaptive cruise control and lane departure prevention systems for longitudinal and lateral control, respectively. Therefore, mass adoption may require a significantly shorter "production prototype" phase compared to the introduction of features that were more technologically novel.

5. Summary, Discussion, and Conclusion

Motor vehicles have clearly experienced significant change over the last several decades, reflecting shifting consumer preferences and priorities, improvements in technology, and a focus on mitigating their impact on the environment and contribution to global climate change. Future changes to motor vehicles are likely to be at least as significant, if not more so, and understanding the extent to which these changes will affect fleet-wide impacts has been the main focus of this thesis. In particular, this thesis examined the potential for two fundamentally different changes to the motor vehicle, beyond changes to drivetrain technologies, to affect fleet-wide petroleum consumption. Section 3 outlined several plausible scenarios for the evolution of the LDV market in terms of the shares of various vehicle segments. Though shifts along these lines are not radical to the same extent as hybridization, alternative fuels, or other technology-based changes that might be expected over the next few decades, they nonetheless represent a potential source of fuel savings assuming a shift to smaller and more fuel-efficient vehicle categories. Conversely, shifts to larger and less fuel-efficient vehicle segments carry the potential to increase fleet-wide fuel consumption, despite improvements to technology. Section 2 explored how changes along these lines have occurred over the last three decades in response to the interactions between policy and consumer preferences reflecting prevailing market conditions.

The second change explored in this thesis reflects a fundamentally more radical technological change that has the potential to indirectly impact LDV fuel consumption. The possibility of automating motor vehicle operation has been treated with extreme enthusiasm in the popular press and with increasing, yet cautious, optimism within the automotive industry over the last five years. With traditional manufacturers poised to introduce limited-use automation features to production models within a year, Section 4 explored the potential of a highway-only automation system to reduce fleet-wide fuel consumption. The example system considered falls short of making cars truly "driverless", but is also far closer to production and fraught with far fewer uncertainties than the more radical "autonomous" vehicle concepts popularized by Google, among others. That said, the analysis considers the influence of several variables in degrading the contribution of automation to reducing fuel consumption, including: the extent of automation and relevant potential fuel economy benefits; percent of travel that might be driven in an automated mode; adoption profile and maximum; and a network effect.

Compared to a reference case, which reflects a forecast by the Energy Information Administration, the scenarios explored in both analysis sections have the potential to increase or decrease annual LDV petroleum consumption by up to seven percent in 2050, though the more moderate cases suggest a change of between one and three percent. On the one hand, such a change seems quite modest, particularly in the context of current fuel economy standards that are framed as having the potential to double average new car fuel economy by 2025. However, these modest improvements could play a significant role in reducing the impacts of motor vehicles in the long term. First, they both represent decreases to LDV fuel consumption that extend beyond those made possible by CAFE-motivated improvements to engine efficiency and reductions in vehicle weight. They are also independent of one another; that is, a future LDV fleet could realize the benefits of *both* shifting market segments and automation. Second, both sets of scenarios but particularly the automation scenarios diverge most significantly from the reference case beyond 2030. Therefore, benefits are likely to start accruing at a convenient time, as manufacturers begin to reach the limits of technological improvements and as (potentially) alternative fuel vehicles enter the fleet in significant numbers (up to 40 percent by 2050, according to Bastani, Heywood, & Hope (2012)).

Vehicle automation does not necessarily need a push from policy to spur adoption, as the safety and convenience benefits represent attractive selling points. Moreover, no federal-level policy avenues exist currently for spurring automation adoption short of requiring automated driver assistance features through the current FMVSS regulations. That said, companies wishing to test automated vehicle technology on public roads have faced potential regulatory hurdles at the state level, requiring extensive lobbying efforts to introduce laws intended to remove barriers to testing and, ultimately, commercial deployment. Further effort in this area will likely be required as manufacturers wish to introduce even partially automated systems. Tesla's proposed introduction of a highway autopilot feature in summer 2015 may run afoul of California's driving laws, which currently only cover the operation of an automated vehicle by trained drivers employed by its manufacturer, not by members of the public (Ramsey, 2015). California regulators indicate that they are revising their driving rules in light of the systems that Tesla and others plan to offer in the near future. However, other states may need to follow suit in order to fully remove the barriers to automated driving feature adoption and, therefore, to realizing the benefits revealed through the analysis presented above.

More significant policy incentives may need to be introduced to encourage shifts to more fuel-efficient vehicle segments, or discourage shifts to less fuel-efficient segments, as discussed in Section 3. Most

European countries have LDV fleets composed of significantly smaller vehicles due to, among other factors, high fuel taxes and vehicle purchase and ownership taxes that increase steeply with engine size, emissions, and fuel economy. Like the U.S., they also offer tax rebates for alternative fuel vehicles, though certain countries also extend tax benefits to conventional vehicles that are extremely fuel-efficient or produce minimal greenhouse gas emissions. Tax schemes intended to increase the ownership cost of large, inefficient types of vehicles are unlikely to be politically palatable in the U.S., if the debate over raising the federal gas tax by less than 20 cents is any indication. Karplus (2013) suggests that this is because consumers (i.e., voters) experience the increased cost of gasoline or vehicle ownership taxes on a weekly and annual basis, respectively. Conversely, they purchase a vehicle far less frequently and are, therefore, unlikely to notice the cost added by requirements for manufacturers to meet increasingly stringent fuel economy standards. Vehicle rebates or scrappage schemes may be more palatable to the public, but require significant funding, which can be a challenge politically. Moreover, Knittel (2009) suggests that scrappage schemes can be a highly inefficient way of reducing carbon dioxide emissions. On a bright note, current market research indicates that incentives to shift toward more efficient classes of vehicle may become less necessary as members of Generation Z become a larger percentage of the new vehicle market. Recent survey research indicates that they value efficiency and technology over size and performance and are far more interested in cars than SUVs and CUVs, compared to older generations (Martinez, 2015).

Implicit in the findings from this research on spurring reductions in LDV fuel consumption are the dynamics of an accounting-based fleet model and its value in understanding how vehicle-level changes translate into fleet-wide impacts. Such a model has limitations but also offers valuable insights into the delays associated with translating changes in new vehicle characteristics into fleet-wide changes and impacts. While the dynamic interactions found in a system dynamics or econometric approach may be lacking, the fleet model's core value rests in its detail and its accessibility. Such a bottom-up approach to estimating fleet-wide impacts allow for detailed accounting of vehicle characteristics and their relative contribution to, in this case, LDV fuel demand. Moreover, such an approach serves as an effective scenario comparison tool, though its capabilities as a true forecasting tool are limited by the robustness of underlying assumptions about fleet turnover, technological improvements, and travel demand.

Applying the fleet model to understanding the fuel demand implications of vehicle automation provides further insights into its value and the dynamics of the diffusion of fuel-saving technology. Previous applications of the model have focused on the deployment of technologies that are always in operation (e.g., technological improvements to internal combustion engines or alternative fuels) but the example of a highway-only automation feature introduces further degrading factors. Not only is the application of such a feature limited to a subset of the miles travelled by equipped vehicles, but also the consideration of a network effect degrades the fuel-saving benefits even more by making full benefits contingent upon adoption by others.

In sum, this research has found that, relative to the EIA's reference case for LDV fuel demand, modest reductions – up to seven percent but more likely in the range of two to three percent – are possible to achieve by 2050 through plausible shifts in the demand for more fuel-efficient segments of passenger vehicles. Conversely, increases in fuel demand of a similar magnitude are possible if SUVs maintain a significant share of sales or increase in popularity. Finally, the imminent introduction of a part-time, highway-only automation function could reduce LDV fuel demand by up to six percent but as little as one percent, depending on adoption rate, extent of use, and extent of per-vehicle fuel economy benefits. However, significant uncertainty exists in understanding the dynamics of how the automation of vehicle control, even at low levels, will affect travel demand and traffic patterns. Therefore, vehicle automation represents an attractive potential source of fuel savings, but a true estimation of the benefits at this point must be viewed as speculative.

The United States is entering its second century of mass automobile adoption with much greater awareness of its impacts. After more than two decades of stagnant fuel economy standards, CAFE targets are once again rising and although on-road average fuel economy may not actually double, as advertised by the 54.5 mpg standard for 2025, improvements are likely to be substantial. However, by not explicitly targeting other fuel-saving changes to vehicle characteristics, such as encouraging consumers to adopt smaller vehicles, the U.S. is potentially forfeiting further reductions in fuel consumption. They may be modest, but in the interest of mitigating the automobile's impact on the natural environment and human health, every opportunity must be considered.

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