Climate and Energy Policy for U.S. Passenger Vehicles: A Technology-Rich Economic Modeling and Policy Analysis

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Abstract

Climate and energy security concerns have prompted policy action in the United States and abroad to reduce petroleum use and greenhouse gas (GHG) emissions from passenger vehicles. Policy affects the decisions of firms and households, which inevitably react to changing constraints and incentives. Developing and applying models that capture the technological and behavioral richness of the policy response, and combining model insights with analysis of political feasibility, are important agendas for both research and policy. This work makes four distinct contributions to these agendas, focusing on the case of climate and energy policy for passenger vehicles in the United States.

First, this work contributes to econometric studies of the household response to gasoline prices by investigating whether or not U.S. households alter their reliance on higher fuel economy vehicles in response to gasoline price changes. Using micro-level household vehicle usage data collected during a period of gasoline price fluctuations in 2008 to 2009, the econometric analysis shows that this short-run vehicle switching response, while modest, is more pronounced for low income than high income households, and occurs on both a total distance and per trip basis.

Second, this work makes a methodological contribution that advances the state of empirical modeling of passenger vehicle transport in economy-wide macroeconomic models. The model developments include introducing an empirically-based relationship between income growth and travel demand, turnover of the vehicle stock, and cost-driven investment both in reduction of internal combustion engine (ICE) vehicle fuel consumption as well as in adoption of alternative fuel vehicles and fuels. These developments offer a parsimonious way of capturing important physical detail and allow for analysis of technology-specific policies such as a fuel economy standard (FES) and renewable fuel standard (RFS), implemented individually or in combination with an economy-wide cap-and-trade (CAT) policy. The new developments within the model structure are essential to capturing physical system constraints, interactions among policies, and unintended effects on non-covered sectors.

Third, the model was applied to identify cost-effective policy approaches in terms of both energy and climate goals. The RFS and FES policies were shown to be at least six to fourteen times as costly as a gasoline tax on a discounted basis in achieving a 20% reduction in cumulative motor gasoline use. Each of these policies was shown to have only a modest effect on economy-wide carbon dioxide emissions. Combining a fuel economy standard and a renewable fuel standard produced a gasoline reduction around 20% lower than the sum of forecasted reductions under each of the policies individually. Under an economy-wide CAT policy that targets GHG emissions reduction at least cost, obtaining additional reductions in passenger vehicle gasoline use with RFS or FES policy increases the total policy cost, and does not result in additional reductions in GHG emissions. The analysis shows the importance of integrated assessments of multiple policies that act on separate parts of a system to achieve a single goal, or on the same system to achieve distinct goals.

Fourth, a political analysis shows how, in the case of climate and energy policy for passenger vehicles, sharp trade-offs exist between economic efficiency and political feasibility. These tensions are shown to exist at the level of policy justification, policy type, and design choices within policies. The pervasiveness of these tensions suggests that economically-preferred policies will face the greatest barriers to implementation.

This work concludes by integrating the findings from each of the individual parts to make recommendations for policy. Recognizing the heterogeneity of household responses, the prescriptions of the economic analysis, and the tensions between these prescriptions and politics, policy options should be evaluated not only based on cost effectiveness, but also on their ability to serve as stepping stones toward desirable end states by providing incentives to revisit and increase policy cost effectiveness over time.

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"…es sprechen viele Anzeichen dafür, daß die Zukunft in solcher Weise in uns eintritt, um sich in uns zu verwandeln, lange bevor sie geschieht."

Rainer Maria Rilke (1904)

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Valerie Jean Karplus

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Figures

Tables

Acronyms

ADAGE	Applied Dynamic Analysis of the Global Economy (model)
BEA	Bureau of Economic Analysis
BLS	Bureau of Labor Statistics
CAFE	Corporate Average Fuel Economy (Standards)
CAT	Cap-and-trade
CGE	Computable general equilibrium
CNGV	Compressed natural gas vehicle
CO_2	Carbon dioxide
EIA	United States Energy Information Administration
EPA	United States Environmental Protection Agency
EPPA	Emissions Prediction and Policy Analysis (model)
EPPA5-HTRN	EPPA model version 5 with household transportation detail
EU	European Union
EV	Electric vehicle
FCEV	Fuel cell electric vehicle
FES	Fuel Economy Standard
FFV	Flex-fuel vehicle
GAMS	General Algebraic Modeling System
GHGs	Greenhouse gases
GTAP	Global Trade Analysis Project
ICE	Internal combustion engine
IEA	International Energy Agency
LCFS	Low Carbon Fuel Standard
LES	Linear Expenditure System
MPSGE	Mathematical Programming System for General Equilibrium Analysis
NHTS	National Household Transportation Survey
NHTSA	National Highway Traffic Safety Administration
PHEV	Plug-in hybrid electric vehicle
RECS	Residential Energy Consumption Survey
RFS	Renewable Fuel Standard
SAL	Sloan Automotive Laboratory
TCD	Turbo charging and downsizing
U.S.	United States
VMT	Vehicle-miles traveled

Table of Contents

Chapter 1: Introduction

"The civilized man has built a coach, but has lost the use of his feet."

Ralph Waldo Emerson[1]

This chapter introduces the main topic of this thesis—how should policymakers address the growing contribution of passenger vehicles to petroleum use and greenhouse gas emissions in the United States? After providing brief background on the issue, this chapter discusses the methodologies applied to analyze several important considerations for policy design, including cost effectiveness, the distribution of impacts, and political feasibility. The methodologies include econometric techniques to measure the effects of fuel price changes on micro-level household decisions, a technology-rich modeling approach to compare the cost-effectiveness of alternative passenger vehicle policy designs, and political analysis to understand how considerations that arise in the policy process beyond cost effectiveness influence the choice of policy. This chapter concludes by describing the main findings of the individual analyses, as well as the integrated conclusions.

1.1 Background

Passenger vehicles have grown in importance as a means of transport for the members of private households in the United States since the early twentieth century. As vehicle ownership and use have increased, so too have the required volumes of petroleum and the environmental impact of driving. Public concern about petroleum supply disruptions and climate change has prompted vigorous debate over the appropriate role of public policy, particularly for passenger vehicles, in mitigating these threats. As many developing countries seem prepared to follow a similar road toward motorization, designing and demonstrating effective policy approaches will have not only national, but global, import.

Consider for a moment the extent of the global passenger vehicle system. In 2010 light-duty vehicles (most of them owned by private households) were driven around seven trillion miles and account for around 20% of manmade carbon dioxide (CO_2) emissions in the United States, 12% in Europe, and about 5% of emissions worldwide (GMID, 2010; EPA, 2010c; IEA, 2010).[2] Trends of increasing vehicle ownership and use suggest that additional policy intervention will be required to reduce the contribution of passenger vehicles to greenhouse gas (GHG) emissions. Households are adding vehicles and driving ever greater total distances each

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[1] In Emerson (1841).

[2] CO_2 accounts for 94-95% of the greenhouse gas (GHG) emissions associated with a passenger vehicle, calculated on the basis of global warming potential. The remaining 5-6% of emissions is comprised of CH_4, N_2O, and HFC emissions (EPA, 2005).

year (Davis et al., 2009). While engine efficiency has improved markedly over the past few decades, these gains have been offset by increases in horsepower, size, and vehicle weight over the same period, resulting in more modest improvements in on-road fuel economy (An & DeCicco, 2007).

Designing a policy approach to reduce GHG emissions from household-owned vehicles involves several decisions. First, policymakers must define a regulatory goal or goals—for instance, reducing petroleum use, GHG emissions, or both. Second, policymakers must identify an appropriate regulatory target and level of coverage. The target may be several steps removed from the controlled substance or pollutant, and focused on a single part of an interconnected system. For instance, regulators may choose to target new vehicle fuel economy or fuel consumption (the volume of fuel required per unit distance traveled), which affects only a limited portion of total fuel used by passenger vehicles each year. Third, for a given policy, decision makers face choices about which sources of fuel use or GHG emissions to cover, the timing of reduction targets under a policy, and other policy design variables. The way that vehicles, fuels, and associated GHG emissions are treated by the regulation may have a large impact on the cost effectiveness of the policy, as well as the distribution of impacts across households and sectors. Support for policies is influenced by affected stakeholders, and so these distributional impacts will affect political feasibility to the extent that the policy harms or rewards powerful influences.

One approach to policy analysis is the development and application of models, or simplified representations of the world that can simulate the relationships between the assumptions and outcomes of interest. To simulate the costs and impacts of policies, models must include both broad sectoral coverage as well as an appropriate amount of system detail that resolves key variables and the relationships among them as they evolve over time. Few models used for policy analysis attempt to address both needs, whether for the case of passenger vehicles or for other sectors, and indeed the nature of the detail required depends on the question being asked. This thesis is partially about introducing new capability into one class of economic models—computable general equilibrium (CGE) models—to represent better the consumer response to energy and environmental policy focused on passenger vehicles. An economy-wide economic model is important in this analysis because it captures how prices change endogenously and how price changes are transmitted across sectors. These features are essential to capturing the effects of policies on demand for passenger vehicle ownership and use, which accounts for a large share of household expenditures, petroleum use, and GHG emissions. Moreover, the primary fuels presently used (or proposed for use) in passenger vehicles are used in other sectors beyond household vehicle transportation. Capturing how policies affect primary fuel use across sectors through changes in underlying prices helps to identify interactions or unintended consequences that may erode or alter the expected benefits of a policy.

However, models alone cannot, due to their deliberately simplified nature, capture the richness of factors that could influence a policy's political feasibility or effectiveness once on the books. Thus I have structured this dissertation to include both empirical modeling as well as political analysis components. Considering household heterogeneity is important when assessing the impacts of policies. As a complement to the modeling work, I begin with a detailed econometric study using micro-level household data to investigate the household response to the fuel price fluctuations that occurred over a thirteen-month period in 2008 and 2009.

I then develop a new modeling capability that involves a richer description of key economic and physical system variables in the passenger vehicle transportation sector of a macroeconomic model, the MIT Emissions Prediction and Policy Analysis model. The goal is to represent long term global trends in demand for passenger vehicle transport, new versus used vehicle stock, and both incremental as well as radical changes to vehicle technologies that could be adopted in response to policies. With the new modeling capability in hand, I am able to compare several policies and policy combinations in terms of their effects on travel demand and technology outcomes, impact on energy use and the environment, as well as cost and its distribution across sectors.

Finally, I focus on the relationship between policy designs that emerge as cost effective from the economic modeling analysis and the traction these policies have achieved in the political arena, past and present. Sector impacts identified in the modeling analysis suggest that stakeholder interests often do not overlap. A comparison between the United States and several other advanced industrialized nations helps to suggest additional factors that may have contributed to low rates of motor vehicle fuel taxation in the United States relative to other regions. The work concludes by suggesting some possible paths for incentivizing a transition to more cost-effective policy approaches over time.

1.2 Contributions of this Research

This dissertation is structured as follows. **Chapter 2** frames the topic of climate and energy policy for passenger vehicles, providing essential background for the analysis presented in the following chapters. I then study the short-run household response to gasoline prices, undertaking an econometric study to examine the effect of fuel price on vehicle use decisions within household-owned fleets, both in the aggregate as well as by income category, degree of urbanization, and level of vehicle ownership (**Chapter 3**). This analysis relies on a detailed data set that captures the daily driving patterns by U.S. households and spans a period of gasoline price fluctuations during 2008 and 2009 in order to investigate whether U.S. households switch to rely on vehicles with higher fuel economy when gasoline prices increase.

Second, I develop a richer description of household vehicle transportation in a macroeconomic model, using historical data on vehicle ownership and expenditure trends, technologically-based bottom-up estimates of the responsiveness of internal combustion engine (ICE) vehicle fuel economy to fuel price signals, and detailed technology cost estimates for advanced low carbon vehicles and fuels (**Chapter 4**).

Third, I use this modeling capability to conduct an economic analysis of climate and energy policies, implemented individually and in combination (**Chapters 5** and **6**). The effects of policies that target a fixed reduction in cumulative fuel use are compared, considering sensitivity to assumptions about the cost and availability of advanced vehicle and fuel options. I then consider the consequences of combining policies that bear separately on either vehicle efficiency or the fuel supply, and identify the costs and outcomes in terms of fuel demand, GHG emissions, and technology adoption. Finally, I consider the effects of combining an economy-wide cap-and-trade (CAT) policy aimed at reducing GHG emissions at least cost with several policies aimed at reducing petroleum-based fuel use from passenger vehicles.

Fourth, this analysis is followed in **Chapter 7** by a discussion of the relationship between the prescriptions for policy that emerge from the economic modeling analysis and considerations of political feasibility.

Finally, the contribution of this dissertation and its implications are summarized in **Chapter 8**.

1.3 Detailed Research Questions

The studies in Chapters 3 through 7 focus on distinct yet complementary research questions. Here I briefly introduce these questions, the motivation for inquiry, and the choice of methodology used to address each.

1.3.1 Part 1: Do Households Switch Vehicles to Minimize the Effects of a Fuel Price Shock?

The first part of this work involves an investigation of the short-run household response to a fuel price increase, focusing specifically on the role of vehicle switching (the ability of the household to reallocate its miles across household-owned vehicles, which may differ in terms of their fuel economy). I will examine how this response varies in the aggregate sample, as well as conditional on household income, degree of urbanization, and vehicle ownership. Using a large and detailed data set from the 2009 U.S. National Household Transportation Survey, I am able to estimate the extent of switching both in terms of total distance traveled and by trip. My hypothesis is that vehicle switching will differ depending on household characteristics. For instance, I expect that the most cash-constrained households in the sample will show the highest propensity to switch to their higher fuel economy vehicles when gasoline prices increase, given that potential savings are likely to constitute a larger share of their household budgets.

I first investigate whether households reduce fuel use more than they reduce VMT in response to a fuel price increase, which would be consistent with switching behavior. Elasticities of demand for fuel and VMT with respect to fuel price are calculated both for the aggregate sample and conditional on household characteristics. Specifically, I ask:

Question 1.1: Are the short-run gasoline price elasticities of demand for VMT and gasoline significantly different at the level of the aggregate sample, and do they vary by income level, degree of urbanization, or the number of vehicles a household owns?

Second, I estimate a generalized linear model with logit link and a conditional logit model to evaluate the effect of changes in the per-mile fuel savings available to the household on the choice to drive a high efficiency vehicle, both in terms of the fraction of total miles-traveled and on a per-trip basis. The household response depends on both the fuel economy of the vehicles owned by the household (assumed to be fixed in the short run for households that have not purchased a new vehicle or scrapped a used vehicle) and fuel price (the independent variable of interest). The two main questions of interest are:

Question 1.2: How does an increase in the per-mile savings from switching affect the fraction of miles-traveled in the high efficiency vehicle? Does this response vary significantly by income category and by degree of urbanization?

Question 1.3: Does an increase in per-mile savings from switching affect the choice of a high efficiency vehicle *by trip*? Does this effect vary by trip purpose?

This analysis provides insight into the role of within-fleet differences fuel economy in offering households short-run flexibility to reduce fuel use in response to a fuel price increase. Understanding the role of vehicle switching may grow more important if households adopt vehicles that use little or no gasoline, creating conditions under which full switching to an alternative fuel vehicle could offer large potential savings by displacing gasoline fuel use entirely.

1.3.2 Part 2: Representing Passenger Vehicle Transport in a Macroeconomic Model

The goal of the second part of this work is to introduce technological and fleet detail into a macroeconomic model to explicitly capture relationships among household income, fuel prices, demand for VMT, fuel use, and resulting GHG emissions as they evolve over time. The modeling work is guided by the need to explicitly represent the major levers by which policy can influence vehicle and fuel technology, fuel use, and GHG emissions outcomes in the context of the larger energy system. This model development is performed in the Emissions Prediction and Policy Analysis model, a CGE model with energy system detail developed by the MIT Joint Program on the Science and Policy of Global Change (Paltsev et al., 2005).

This part of the work involves three main model developments. First, I introduce into the structure of the model a variant of the Linear Expenditure System (LES) for consumer demand with quasi-homothetic preferences. This approach allows the specification of empirically-based income elasticities of demand with respect to particular classes of consumption. Here I use observed empirical trends and econometric estimates to calibrate the relationship between income and demand for VMT over the period 2010 to 2050. Income elasticities of demand for vehicle ownership have been shown to vary with per capita income, the expected vehicle ownership saturation level, and other regional characteristics such as urban density (Dargay et al., 2007). In this analysis I focus on per capita income as the main driver of rising vehicle ownership, calibrating elasticities to reflect underlying demographic and vehicle ownership and use projections as they vary by world region. With this addition, the model now captures the expectations of more rapid growth in vehicle transport demand in developing regions as a first vehicle purchase becomes affordable for an ever-greater fraction of the population, while reflecting slower growth as a function of income in developed regions.

Second, I develop a new, more disaggregated structure of the household transportation sector in the EPPA model that explicitly represents a new (less than five-year-old) vehicle fleet and a used (more than five-year-old) vehicle fleet in each of the sixteen world regions. I also develop a production structure for household vehicle transport services that represents technological substitution between fuel and investment in vehicle efficiency in response to changes in their relative prices. For each powertrain type, I estimate an elasticity of substitution that determines investment in vehicle efficiency in response to gasoline price changes, based on technology cost and effectiveness data (EPA, 2010b).

Third, I represent advanced vehicle and fuel technologies in the model. Constraints on the adoption of these technologies are also explicitly represented. These constraints include the turnover of the vehicle fleet, learning that reduces the cost of a pre-competitive technology over time, and constraints on technology adoption in the market, once that technology becomes cost competitive. Opportunities for increasing the on-road fuel economy of today’s dominant ICE vehicles are also represented using engineering-cost data.

With the new model in hand, I develop and explore the sensitivities of model outputs to the underlying inputs in a reference (No Policy) scenario, which is compared against, and informed by, external analyses. The main question of interest here is:

Question 2: What does the baseline scenario and sensitivity analysis suggest about the ability of the United States to reach aggressive petroleum use or GHG emissions reduction targets in the absence of policy intervention through 2050?

This work lays the foundation for the analysis in **Part 3**, which focuses on the effects of policies, alone and in combination.

1.3.3 Part 3: Economic Analysis of Climate and Energy Policies for Passenger Vehicles

The model is applied to compare existing or proposed policies aimed primarily at reducing petroleum use (as well as GHG emissions) by passenger vehicles. In 2009, the Obama Administration announced an increase in the vehicle fuel economy standard to 34.1 mpg by 2016 (a harmonized standard that is consistent with vehicle per-mile GHG emissions of 250 grams of carbon dioxide per mile), and has suggested that this standard will be tightened through 2050 (EPA, 2010a; EPA, 2010b). Meanwhile, a renewable fuel standard that mandates fixed volumes of biofuels be blended into the fuel supply has been implemented under the Energy Independence and Security Act of 2007. An important question for national policymakers is, how do alternative policy designs compare in terms of the cost effectiveness of achieving petroleum-based fuel use or GHG emissions reductions, and what are the associated vehicle technology, energy, and environmental outcomes? Do the outcomes of the policy change if, as some scholars have described, consumers only consider the first several years of fuel costs when deciding which vehicle to purchase? This section explores these themes by investigating four questions:

Question 3.1: How do the costs and technologies employed compare under a fuel economy (FES) standard and a renewable fuel standard (RFS)? How do these outcomes compare to a gasoline tax designed to achieve the same cumulative reduction in gasoline use?

Question 3.2: What is the impact of combining an FES and an RFS in terms of the cost, fuel use, and GHG emissions outcomes?

Question 3.3: What is the impact of combining either an FES or RFS with an economy-wide carbon constraint?

1.3.4 Part 4: Political Analysis of Climate and Energy Policies for Passenger Vehicles

This thesis then moves on to a discussion of the relationship between economic prescriptions and considerations of political feasibility. In particular, the political analysis focuses on the following four questions:

Question 4.1: What is the relationship between the policy prescriptions that emerge from the economic modeling analysis and the political considerations that affect coalition support?

Question 4.2: How do any tensions between the economics and politics play out at the levels of policy justification, policy type, and policy design choices for policies considered in the economic analysis?

Question 4.3: What can be learned from cross-national comparisons and the results of the modeling analysis about the underlying reasons why policies might gain more or less traction in the United States?

Question 4.4: What policy approach should the U.S. pursue today in order to increase the likelihood of moving to more cost-effective policies in the future?

1.4 Conclusions

This dissertation concludes by integrating the findings of the individual sections to highlight implications for research and policy. The main findings from each section are briefly described here, followed by a description of the overall conclusions.

First, the econometric analysis of the household vehicle use response to gasoline prices shows that the vehicle switching response, while modest, is employed by households to reduce gasoline costs on both a total distance and per trip basis. This response is found to be more pronounced for low income than high income households.

Second, this work develops a method of representing passenger vehicles in an economy-wide CGE model, advancing the state-of-the-art of modeling tools available to support energy and environmental policy decisions. This method offers a parsimonious way of representing key physical details that allows analysis of technology-specific policies such as a fuel economy standard (FES) and renewable fuel standard (RFS), individually or in combination with an economy-wide cap-and-trade system. The model structure is essential to capturing interactions among policies and unintended effects on non-covered sectors.

Third, the modeling analysis indicates, consistent with other studies, that a tax on petroleum-based fuel is most the cost-effective policy approach for displacing its use in passenger vehicle transportation (Goldberg, 1998; Austin & Dinan, 2005). Achieving the same reduction using a FES or RFS policy was found to be at least six to fourteen times as costly. Combining FES and RFS policies produces a reduction in petroleum-based fuel use that is around 20% lower than the sum of the reductions achieved when the policies are implemented individually, while costs remain close to additive. Finally, when an FES or RFS policy is combined with a CAT policy, two possible situations result. In cases where the FES or RFS policy binds and the amount of gasoline displaced from passenger vehicles increases relative to the CAT policy alone, the combination also raises the total policy cost, while having no effect on GHG emissions. In cases where the FES or RFS policy does not bind, there is no effect on the cost, fuel use, or GHG emissions under the CAT policy. Taken together, this multi-part analysis shows the importance of evaluating simultaneously the cost and effectiveness of multiple policies that act on separate parts of a system to achieve a single goal, or on the same system to achieve distinct goals.

Fourth, a political analysis shows how, in the case of climate and energy policy for passenger vehicles, sharp trade-offs exist between economic efficiency and political feasibility. These tensions are shown to exist at the level of policy justification, policy type, and design choices within policies. The pervasiveness of these tensions suggests that economically-preferred policies to address passenger vehicle energy use and GHG emissions will face the greatest hurdles to implementation. This argument is supported by an analysis of the predicted sectoral impacts of policies in the United States as well as a cross-national comparison of policy choices and their interaction with the evolution of passenger vehicle transport systems over time.

This work concludes by integrating the findings from each of the individual parts to make recommendations for policy. Recognizing the heterogeneity of household responses, the prescriptions of the economic analysis, and the tensions between these prescriptions and political feasibility, this analysis suggests that policies should be evaluated based not only on cost-effectiveness, but also on their ability to serve as stepping stones toward desirable end states by lowering political barriers to legislating more cost-effective policies over time.

Chapter 2: Background on U.S. Passenger Vehicle Transport and Policy

Every time I reduce the price of the car by one dollar I get one thousand new buyers.

Henry Ford[3]

This chapter describes the motivations for reducing petroleum use and greenhouse gas (GHG) emissions from passenger vehicles in the United States and around the world. It discusses the rationales often given for public policy intervention, and describes the range of policy instruments that have been proposed or implemented. Finally, it describes the range of analysis tools used to evaluate the impact of policies, and cites some of the advantages and limitations of different approaches.

This chapter draws on previous studies to provide the context and motivation for the work in this thesis on climate and energy policy for passenger vehicles in the United States. Given the diversity of topics covered in this work, I focus here on providing essential background common to all chapters. At the beginning of each subsequent chapter I discuss previous studies relevant to specific work in this thesis. This chapter serves primarily to set the stage.

Section 1 begins with an overview of the issue and the physical system of interest, including a description of U.S. passenger vehicle transport in a global context and its energy and climate impacts. **Section 2** briefly describes the policy designs that have been considered for reducing petroleum use and GHG emissions of passenger vehicles. **Section 3** describes the range of modeling methodologies that have been used to forecast future vehicle petroleum use and GHG emissions under alternative policy scenarios. It discusses the differences in how the models are used to generate policy insights, and potential blind spots associated with different modeling approaches. **Section 4** concludes by identifying the gaps in previous studies that this work seeks to fill.

2.1 U.S. Passenger Vehicle Transport in a Global Context

The transportation sector is responsible for a large fraction of both petroleum use and GHG emissions in the United States. Transportation accounts for 28% of U.S. end-use GHG emissions, while cars and light trucks, which together comprise the light-duty vehicle fleet, account for 16% of total GHG emissions in the United States, or 62% of total transport GHG

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[3] In Halberstam (2003).

emissions, nearly all of which is in the form of carbon dioxide (EPA, 2010c). Most of these light-duty passenger vehicles are owned and operated by private households.[4] Globally, light-duty vehicles account for around 5% of total GHG emissions, and this share is expected to grow significantly over the next several decades (IEA, 2010).

Privately-owned vehicles have become the dominant form of personal mobility and an important enabler of economic activity in the United States and around the world. A U.S. household owns around two vehicles on average and spends around 10% of its annual income on vehicle transport (FHWA, 2009c; U.S. Census Bureau, 2009).[5] Annual growth in the number of private vehicles has averaged about 2.3% per year since 1970, while miles-traveled per vehicle has trended slowly upward at 0.4% per year (Davis et al., 2009). This trend has prompted increasing concern about the externalities associated with passenger vehicles. Light-duty vehicles account for 47% of petroleum use in the United States, and petroleum-based fuels supply over 90% of the energy required by vehicles (Davis et al., 2009; Heywood et al., 2009). Recent U.S. federal energy legislation has targeted reductions in petroleum use, given concerns over the vulnerability of the U.S. to global oil price shocks and its associated national security implications (Energy Policy Act of 2005; EISA, 2007). In addition to energy and climate concerns, which are the focus of this thesis, public policy has targeted many other externalities associated with vehicle transport. For instance, legislation at both the federal and state levels has addressed health and environmental concerns by limiting allowable emissions of air pollutants from vehicle tailpipes.[6] These pollutants include NO_X and volatile organic carbon, which contribute to ozone formation and its associated human health impacts. Promoting vehicle and traffic safety as well as limiting road congestion have also long appeared on the list of national, state, and municipal policy priorities.

These problems have long persisted—and been largely tolerated—because private automobiles have enabled greater personal mobility and economic activity in many parts of the country. The 37% growth in vehicle-miles traveled between 1990 and 2008 has been tightly interlinked with economic and population growth, the persistence of low gasoline prices, the

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[4] In addition to passenger vehicles, the light-duty vehicle fleet is comprised of cars and light-duty trucks owned by commercial businesses and government. U.S. federal regulations consider a light-duty truck to be any motor vehicle having a gross vehicle weight rating (curb weight plus payload) of no more than 8,500 pounds (3,855.5 kg).

[5] This percentage is much lower for households that do not own a vehicle.

[6] Most prominently the Clean Air Act of 1970 under the oversight of the U.S. Environmental Protection Agency has historically focused on regulating local (or "criteria") air pollutants at the national level. Local air pollutants are also targeted in California as part of the state's Zero Emission Vehicle regulation.

growth of a vast road network, and the low density of urban and suburban development in many parts of the country (EPA, 2010c).

Although currently the vast majority of GHG emissions from passenger vehicles occur in industrialized nations, passenger vehicle use is rising rapidly in many rapidly developing countries. This growth will contribute significantly to future transport-related GHG emissions, despite uncertainty over the future fleet size and usage habits, as well as the role that public transport could play in offsetting this growth. As per capita income rises, history has shown that people shift to more rapid forms of transportation (Schafer, 2006). If this trend holds, it will result in a steady increase in VMT in these emerging countries for the foreseeable future.

2.2 Components of Vehicle Petroleum-based Fuel Use and GHG Emissions

The life-cycle petroleum use and GHG emissions of an individual passenger vehicle depend on both technological and behavioral factors. Impacts at the fleet level depend on both the rate at which technology and behavioral changes can be introduced into the fleet over time, as well as the composition of the fuel supply. The cost and timescales associated with undertaking different types of changes may vary widely. In this section, I work from the level of the individual vehicle to the level of the passenger vehicle fleet, discussing first the components of petroleum-based fuel use and GHG emissions, as well as associated reduction opportunities, at the vehicle level. I then discuss issues related to realizing reductions in fuel use and GHG emissions at the level of the passenger vehicle fleet, which depends on the rate of turnover of the vehicle fleet, the rate of new sales growth, the contribution of vehicles of different ages to total miles traveled, vehicle utilization patterns, and other factors.

2.2.1 Vehicle Level

At the level of the individual vehicle, fuel use can be decomposed into the product of the life-cycle fuel requirement per mile,[7] the average number of miles driven in the vehicle each year, and the number of years a vehicle is owned. GHG emissions depend on the same set of factors multiplied by the GHG emissions intensity per unit of fuel used. It is important to note

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[7] The total life-cycle fuel required per mile includes any energy requirement associated with the extraction and refining of fuel (well-to-tank), as well as the actual fuel consumed in the engine to move the vehicle forward (tank-to-wheels). The tank-to-wheels fuel use is typically expressed either as fuel economy in miles per gallon or as fuel consumption in liters per 100 km.

that the quantities on the right-hand side of the equation are not independent of each other. A potential concern is that reducing one term in the equation may lead to unintentional increases in one or more of the other terms. One well-studied example is the rebound effect, in which a decrease in vehicle fuel consumption per unit distance is accompanied by an offsetting increase in vehicle-miles traveled per year in response to a decrease in the cost of per mile of travel (Small & Van Dender, 2007; Greene et al., 1999).

$$Total\ vehicle\ fuel\ use = \frac{Fuel}{Mile} \times \frac{Miles}{Year} \times Years\ in\ use \quad \textbf{(2.1)}$$

$$Total\ vehicle\ GHG\ emissions = \frac{Carbon}{Fuel} \times \frac{Fuel}{Mile} \times \frac{Miles}{Year} \times Years\ in\ use \quad \textbf{(2.2)}$$

Looking at **Equations 2.1** and **2.2**, it is easy to see why a coordinated approach to the regulation of vehicle petroleum use and GHG emissions is needed.[8] Regulations that focus exclusively on vehicle fuel efficiency do not constrain the VMT response, which could offset the effectiveness of the regulation. This effect is likewise very important at the fleet level, as substitution of mileage across vehicle types occurs. Meanwhile, regulations that target the addition of more expensive, low carbon fuels to the fuel supply, if not subsidized, would likely result in an increase in fuel prices at the pump, inducing consumers to invest in fuel efficiency. The length of vehicle ownership in years is also related to average annual miles traveled.[9] Thus providing incentives to scrap older, less efficient vehicles, which are typically used less, may be less effective at reducing GHG emissions than policies focused new vehicles, which are used more.

2.2.2 Fleet Level

The previous section focused on contributions to fuel use and GHG emissions at the level of the individual vehicle. The relationships between the components become even more complex once the analysis is expanded to include two or more vehicles, especially if their usage patterns

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[8] Carbon dioxide (CO_2) accounts for 94-95% of the GHG emissions associated with a passenger vehicle, calculated on the basis of global warming potential. The remaining 5-6% of emissions is comprised of CH_4, N2O, and HFC emissions (EPA, 2005). Carbon dioxide emissions scale with fuel used, while non-CO_2 GHG emissions scale with VMT.

[9] In the United States a vehicle is driven around 15,000 miles in its first year of ownership, while by the sixth year of ownership average annual mileage drops to around 9,000 miles per year (Davis, Diegel, & Boundy, 2009).

are not independent. Taking a fleet-level view of the issue is important because it helps to understand how the contributions of each component could change due to household decision-making involving multiple vehicles, or due to the timescales involved in changing characteristics of vehicles or of the fuel supply.

As mentioned above, most private households in the United States own two or more vehicles, and decisions about which vehicles to buy and drive are made by the members of the household. The decisions of what vehicles to purchase and how far to drive them are mutually dependent (Mannering & Train, 1985; Mannering, 1986). These decisions depend in turn on the opportunities and limitations imposed by the vehicles the household (already) owns and the household's driving needs.

At the level of the entire passenger vehicle fleet, the contributions of individual vehicles of various ages and fuel economies to total vehicle-miles traveled over a period of interest determine the aggregate petroleum use and GHG emissions impact. Again here dependencies among variables are important, and some of the variables may be easier and less costly to change than others. For instance, it may take many years for new, more efficient vehicle technologies to enter into the fleet and contribute to reductions in gasoline use. By contrast, changing the composition of the fuel supply would displace petroleum use and GHG emissions in a given year, assuming that the alternative fuel could be used in a large fraction of existing vehicles. In order for alternative fuels not compatible with existing vehicles to displace petroleum use on a large scale, vehicle technology must be changed simultaneously through the introduction of alternative fuel vehicles, which is limited by fleet turnover.

As a result of these dependencies, policy instruments that target different parts of the vehicle-fuel-user system will differ in the costs they impose. A policy intervention—for example, a gasoline tax—would incentivize a multi-faceted household response that includes reducing miles-traveled, investing in more efficient vehicles, relying less on vehicles with low fuel economy, or driving vehicles less aggressively. By contrast, regulations that focus on reducing fuel use by providing incentives for earlier scrappage of less efficient vehicles might lead households to purchase new vehicles, which, even if more efficient, would likely also be driven greater total distances, reducing the cost effectiveness of the scrappage policy.

2.3 Options for Reducing Petroleum Use and GHG Emissions

The impact of technological and behavioral opportunities to reduce petroleum use and GHG emissions will depend on both the ease of implementing changes at the vehicle level and propagating these changes through the vehicle fleet. Here I describe these technological and behavioral opportunities, along with factors that affect the associated cost and ease of achieving scale. The first two options are related to vehicles, the next two options are related to the fuel supply, and the final two options are related to vehicle usage and driver behavior.

2.3.1 Improving the Efficiency of New ICE Vehicles

Many engineering and economic studies suggest that there is still a large opportunity to improve the on-road fuel economy of existing internal combustion engine (ICE) vehicles. Improvements could be accomplished both by adding new, efficiency-improving technology to vehicles, as well as by scaling back energy-intensive vehicle attributes such as horsepower, vehicle weight, and features that trade off with on-road fuel economy (DeCicco, 2010; Knittel, 2009; MacKenzie, 2009). The former approach includes both incremental changes to the vehicle such as low rolling resistance tires, weight reduction, improving aerodynamics, or transmission tuning, as well as more significant changes including hybridization, turbo-charging, or dieselization. While impossible to pursue all changes simultaneously, combinations of technologies are estimated to have the potential to increase fuel economy of the ICE vehicle significantly (for instance, to 50 mpg for conventional gasoline vehicles and 75 mpg for hybrid vehicles) (Greene & Plotkin, 2011). Since these technologies can only be introduced through the sales of new vehicles, the impact of incremental changes in ICE vehicle efficiency at the fleet level will be limited by fleet turnover.

2.3.2 Increasing the Adoption of Alternative Fuel Vehicles

As an alternative to vehicles that can run on existing petroleum-based fuels, alternative fuel vehicles involve introducing both a new vehicle and its dedicated fuel (or energy carrier, in the case of electricity or hydrogen) into the vehicle fleet. Examples of such vehicle-fuel pairs include electric vehicles or EVs (electricity), hydrogen fuel cell vehicles or FCEVs (hydrogen), compressed natural gas vehicles or CNGVs (natural gas), and flex-fuel vehicles or FFVs (biofuels). Alternative fuel vehicles also include hybrids that run on at least one alternative fuel, such as the plug-in hybrid electric vehicle or PHEV (which can run on both gasoline and electricity). Adoption of these vehicles requires overcoming a number of hurdles, including cost, limitations on range, and limited or nonexistent refueling infrastructure. Indeed, changing the vehicle fleet and the fuel supply at the same time—especially when the viability of one goal depends on progress towards the other—is an additional challenge involved in the scale up of alternative fuel vehicles (Struben & Sterman, 2008). Discussion of these issues as they relate to alternative fuel vehicles is included in **Chapter 4** and **Appendix A**.

2.3.3 Reducing Upstream Petroleum-based Fuel Use and GHG Emissions

Life-cycle assessment draws particular attention to the contribution of upstream fuel and related emissions to the petroleum-based fuel use and GHG emissions footprint of passenger vehicles. Indeed, as petroleum supply evolves to tap reserves that are more energy-intensive to extract and refine, the energy and GHG emissions penalty associated with conventional fuels will increase (Chan et al., 2010). This well-to-tank contribution to energy use and GHG emissions is not only an issue for petroleum-based fuels. If vehicles in the future rely on energy carriers such as electricity or hydrogen, the upstream processes used to produce the fuels will be the primary contributor to energy and environmental impact. Cultivation of land to produce biomass feedstocks likewise can make large contributions to the total energy use and GHG emissions impact of biofuels, especially if dense carbon sinks such as rainforests are displaced in the process (Searchinger et al., 2009). Thus the upstream component of fuel production can significantly affect life-cycle estimates of the per-mile fuel requirement or the per-mile GHG emissions footprint associated with a particular fuel.

2.3.4 Displace Petroleum-based Fuels in the Fuel Supply

The displacement of petroleum-based fuels (preferably with low carbon substitutes) is another way to reduce the petroleum use and GHG emissions from passenger vehicles. Petroleum use reduction depends on the life-cycle impact of the newly introduced fuel relative to the fuel it displaces. If petroleum products are used in the production of the alternative fuel (for instance, in the case of petroleum inputs to fertilizer production when growing corn), it will offset the overall impact on petroleum use. Ensuring that petroleum-based fuel is reduced may be easier than achieving reductions in GHG emissions, given the contribution of upstream processes to GHG emissions of alternative fuels. If an alternative fuel vehicle is required, this vehicle type will be limited by its share of new vehicle sales, further limiting the potential impact of the alternative fuel. However, if the alternative fuel can be used by a large share of the existing vehicles without the need for expensive retrofits, it could have a much larger impact.

2.3.5 Reduce Vehicle Distance Traveled

One way to achieve reductions in both petroleum use and GHG emissions is to reduce demand for vehicle travel itself (without displacing it to other energy-intensive transport modes). An increase in the price of the vehicle or in the price of fuel would encourage a reduction in vehicle travel demand. A higher vehicle price will tend to discourage new vehicle purchases, while a higher fuel price will initially tend to curb miles-traveled at the margin. A reduction in miles driven can be accomplished through consolidating trips, carpooling, or eliminating certain types of trips entirely. This response can be employed in any vehicle, irrespective of age or technology, and therefore has a large potential to impact petroleum-based fuel use and GHG emissions. However, increasing the fuel price, for instance through an increase in the U.S. Federal Excise Tax on gasoline, has a highly visible impact on consumers and has encountered significant opposition in the policy debate.

2.3.6 Encourage Changes in Driver Behavior

There are many ways in which drivers might realize fuel savings without reducing VMT or without investing in new technology. By encouraging less aggressive driving (rapid acceleration and maintaining high highway speeds are two examples of driver aggressiveness), drivers could achieve significant fuel savings and associated reductions in GHG emissions (Heywood et al., 2009). For example, efforts to incorporate eco-driving into driver education programs offer one possible approach. Knowledgeable consumers may also selectively employ these techniques when fuel is particularly expensive in order to reduce overall impact on the household budget. Another example of behavioral change is switching to rely as much as possible on more fuel efficient vehicles, and reserving the less efficient vehicles for trips that require additional horsepower or cargo capacity, thereby displacing fuel use and GHG emissions without reducing total miles of travel.

2.4 Policy Designs: A Review

If past and current trends are any indication, passenger vehicles will continue to account for a significant part of petroleum-based fuel use and GHG emissions in the United States. Although demand for fuel use in passenger vehicles has shown signs of tapering off in advanced industrialized countries due to fuel economy improvements and shifts to non-transport consumption, reaching the ambitious targets for petroleum-based fuel use and GHG emissions reduction will require additional policy intervention. Policy intervention, in turn, would have to act through one or more of the leverage points described above. **Table 2.1** summarizes a wide range of policies that have been considered for the purpose of reducing fuel use, GHG emissions, or both, in terms of the abatement strategies they incentivize.

Table 2.1 List of policies and primary target(s).

Policy	Increase new ICE vehicle efficiency	Introduce alternative fuel vehicles	Reduce life-cycle fuel emissions	Displace petroleum from fuel supply	Reduce VMT	Encourage changes in driving style
1) Fuel Supply Policies						
Renewable Fuel Standard				X		
Low Carbon Fuel Standard				X		
Clean Electricity Standard			X			
2) Vehicle Efficiency Policies						
Fuel Economy (per-mile GHG emissions) Standards	X	X				
Feebates	X	X				
Tax incentives for vehicle efficiency	X	X				
3) Fuel Price Policies						
Fuel Tax	X	X		X	X	X
Cap and Trade/Carbon Tax	X	X		X	X	X
Clean fuel subsidy				X		

2.4.1 Renewable Fuel Standards

A renewable fuel standard (RFS) mandates that a certain volume or percentage of the fuel supply be comprised of a particular renewable fuel. In the U.S., the Energy Independence and Security Act of 2007 mandates a volumetric target for blending biofuels (around half of which was initially expected to be derived from non-food crops and to be carbon neutral) into the fuel supply, reaching 36 billion gallons by 2022 (EISA, 2007). For passenger vehicles, the near term fuel of choice has tended to be ethanol, which can be blended into the gasoline supply up to an allowed percentage (currently 10% for non-flex fuel ICE vehicles and up to 15% for approved model years).[10] The feasibility of this standard has been called into question, since it is not clear that enough flex-fuel vehicles will be available to absorb the high volumes required, especially if total fuel demand falls as a result of policies that increase vehicle efficiency (Blanco, 2010). Both the RFS and similar standards employed in other sectors have been justified in part as a way to promote learning in the early stages of technology deployment, which is expected to bring down cost in the long run (Morris, 2009; Fischer & Newell, 2008). However, this approach requires choosing to support one technology over its alternatives, with the risk that other technologies might have been less costly or more successful candidates for support.

Low carbon fuel standards (LCFS) are similar to renewable fuel standards in that they focus on the composition of the fuel supply, but instead of targeting a particular fuel type, they require the introduction of fuels with low carbon content. Although these standards do not directly promote certain fuel types, they could have the effect of favoring certain fuels depending on the underlying emissions accounting procedures. California has passed an LCFS as part of its state-level climate legislation, which includes upstream processes in the calculation of the GHG emissions footprint by fuel type (CARB, 2009). This accounting approach means that indirect GHG emissions from land clearing to cultivate biofuels and from generating the electricity used in vehicles will be included in GHG emissions intensity estimates.

2.4.2 Fuel Price Instrument

The common feature of policies in the fuel price instruments category is that the incentive to reduce GHG emissions is linked to the price of fuel. In the case of a gasoline or carbon tax, a known charge is levied based on the volume of gasoline fuel or its carbon content, and passed along to consumers at the pump. A quota on either transport or economy-wide emissions with tradable permits (cap-and-trade) system would also produce an increase in the price of fuel, with a price increase proportional to the carbon price required to maintain compliance with the overall constraint. A clean fuel subsidy would reduce the price of the clean fuel relative to petroleum-based fuels, providing an incentive for consumers to switch if the price difference is favorable.

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[10] In 2011 the EPA determined that ethanol blends of up to 15% (E15) can be used in model years 2001 or later (EPA, 2011).

An important difference between a CAT policy and a carbon tax is that the CAT policy fixes the quantity of reduction while the carbon tax fixes the price. For a given carbon price or level of tax, households with low fuel economy vehicles will experience a bigger increase in the cost per mile of driving compared with households owning high fuel economy vehicles, but all will face a financial incentive to reduce petroleum-based fuel.

Economic theory suggests that households will respond to a fuel price increase by pursuing the least costly opportunities to reduce fuel use. The choice of fuel abatement strategy is in turn determined by the availability and cost of fuel-saving technologies as well as consumer willingness to forego energy-intensive vehicle attributes in favor of higher fuel economy. One strong argument in favor of a price signal is that regulators do not need to know these costs of abatement, and firms will have an incentive to identify the least-cost compliance strategy. Under the traditional set of economic assumptions, a price signal that achieves the desired level of abatement is widely recognized as the most economically efficient approach.

Since a price signal has either petroleum-based fuel use or GHG emissions reduction as its primary objective, it does not *a priori* favor particular technological solutions. Under these circumstances, political consensus may be more difficult to achieve than for policies that deliver clear benefits to stakeholder groups. Attempts to introduce cap and trade legislation in the United States have included a broad range of provisions to make them more palatable to industry and consumers, including large allocations of permits to parties likely to be most directly affected.[11] Proposals involving taxes—based either on fuel volume or on carbon content—have been less successful in gaining broad public support (Levine & Roe, 2009).

2.4.3 Fuel Economy Standards

Fuel economy standards have long been part of U.S. energy policy, and in 2010 were at the center of the debate over how to regulate the energy use and GHG emissions characteristics of new passenger vehicles. First established in 1975, the U.S. Corporate Average Fuel Economy (CAFE) Standards have since required manufacturers to achieve a fleet-average fuel economy target in their new vehicle fleets (EPCA, 1975). Fuel economy standards have been widely

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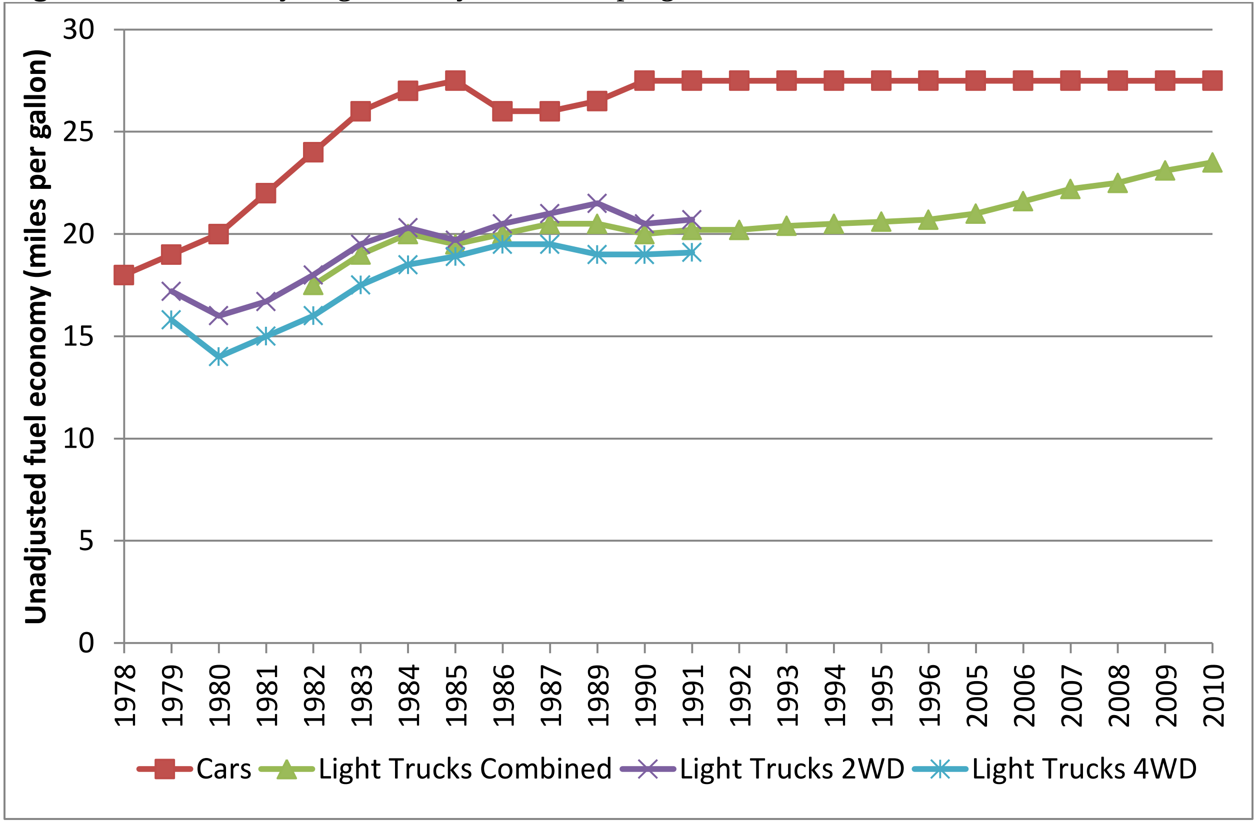
[11] For more information see the two most recent climate legislation proposals, the American Clean Energy and Security Act of 2009 (House of Representatives) and the American Power Act (Senate).

adopted in many countries and regions, including China, Japan, and the European Union (An & Sauer, 2004).

In the early 1970s, rising oil prices drew attention to the inefficiency of the rapidly growing U.S. light-duty vehicle fleet. The CAFE Program was created under the Energy Policy and Conservation Act to regulate the fuel economy of new vehicles, identifying separate targets for cars and light-duty trucks (EPCA, 1975). Specifically, manufacturers had to achieve a certain sales-weighted average for new vehicles sold in each year. The National Highway Traffic Safety Administration was charged with program oversight, while the U.S. Environmental Protection Agency assumed responsibility for fuel economy testing.

Fig. 2.1 Fuel economy targets set by the CAFE program, 1978 to 2010.



Source: EPA, 2008.

A graph of the CAFE Standard unadjusted (test-cycle) fuel economy targets for cars and light-trucks is shown in **Figure 2.1**. In its early years, the CAFE Standard had the effect of increasing fuel economy dramatically. Compliance strategies included both scaling back attributes of the vehicle that trade off with fuel economy (such as horsepower, size, or weight) as well as adding fuel-saving technology (An & DeCicco, 2007). However, by the mid-1990s fuel economy standards leveled off, while over the same period many manufacturers (in the U.S. in particular) shifted towards producing sport-utility vehicles (SUVs), shifting the sales mix in favor of light-duty trucks (the SUV is considered a light-duty truck for CAFE compliance purposes). This resulted in an effective decrease in on-road fuel economy over the same period (Shiau et al., 2009). CAFE Standards were tightened once again in the mid-2000s, for trucks starting in 2005 and for cars as well after 2010. The Energy Independence and Security Act of 2007 mandated another major jump in fuel economy, creating a harmonized standard for cars and light-duty trucks that targeted a sales-weighted test-cycle new vehicle fuel economy average of 35 miles per gallon by 2020 (EISA, 2007).

Developments over the past several years paved the way for the acceleration and broadening of the CAFE Standard to include GHG emissions. First, the start of the Obama Administration signaled a shift towards greater emphasis on climate change mitigation in U.S. policy. Second, the U.S. Supreme Court decided in *Massachusetts v. U.S. Environmental Protection Agency (EPA)* that the EPA had the authority to rule on the status of GHG emissions from vehicles as air pollutants under the Clean Air Act. The EPA issued its Endangerment Finding in the fall of 2009, stating that GHGs constituted a threat to human health and the environment (EPA, 2009). This determination cleared the way for the EPA to regulate GHG emissions from vehicles. The result was a combined fuel economy and per-mile GHG emissions standard issued jointly by the EPA and National Highway Transportation Safety Administration (NHTSA) that accelerated implementation to 2016 of a 34.1 mpg fuel economy standard and a 250 gram per mile GHG emissions standard. Like the EISA target, the new harmonized standard creates a single fuel economy target for both cars and light-duty trucks (EPA, 2010b).

Although the new CAFE standard creates a target that is harmonized for cars and light-duty trucks, it recognizes diversity in manufacturer portfolios and has taken measures to minimize potential resulting inequalities across firms. In response to concerns that a single standard might encourage manufacturers to make engineering changes that compromise the safety and diversity of vehicle options in the process of increasing fuel economy, the regulation is designed to be “footprint-based,” meaning that its stringency scales with the size of the vehicle’s “footprint,” defined as the average track width multiplied times the wheelbase (the distance between the centers of the axles) (EPA, 2010b).

The net benefit calculation for the 2012 to 2016 compliance period includes a fuel savings of 1.8 billion barrels of oil and a reduction of 960 million metric tons of carbon dioxide (EPA, 2010b). Beyond these reductions, the EPA also includes additional benefits of the regulation including reductions in particular matter (PM2.5), energy security, increased driving and reduced refueling time. Also included are costs associated with fuel economy increases, such as increases in congestion, crashes, and noise that accompany increased driving.

The new CAFE Standard considers only tailpipe emissions, which means upstream GHG emissions that result from the extraction, production, or generation of fuel could actually grow worse under the standard if fuels are not regulated simultaneously. For instance, emissions produced in the generation of electricity used in plug-in hybrid electric vehicles (PHEVs) or electric vehicles (EVs) are not counted for the first 200,000 vehicles produced, and these vehicles are also subject to advanced technology credits that assign increased weight to alternative fuel vehicles in the sales-weighted average (EPA, 2010b). Flex-fuel vehicles, which are capable of running on high percentage biofuel blends, have also been counted using a higher fuel economy rating for CAFE purposes, regardless of whether or not they are operated using these fuels (Rubin & Leiby, 2000). The new CAFE standard also allows credit trading across manufacturers, enabling firms that fail to meet the target to purchase credits from firms that exceed the standard (EPA, 2010b). This provision may especially benefit small entrepreneurial firms focused on producing vehicles that qualify as zero emissions.

Part of the justification often cited for fuel economy standards and similar policies such as feebates and tax incentives for alternative fuel vehicles is the fact that consumers do not fully value the fuel economy of their vehicles at the time of purchase, in the sense that they are unwilling to accept an increase in upfront vehicle cost in return for an equivalent or even a greater reduction in lifetime discounted fuel savings. This observation—known broadly as the energy paradox—probably reflects a combination of factors, such as the time cost of working out savings, uncertainty over future driving, gasoline prices, and vehicle ownership lifetime, resale value, and high opportunity cost of money, due for instance to high interest rates on credit card debt (Hassett & Metcalf, 1993; Greene et al., 2008). Turrentine and Kurani (2007) found that almost no household systematically analyzed their fuel costs in either their automobile or gasoline purchases, while several papers have found the magnitude of the gap between the vehicle cost premium and fuel economy savings to be significant (Allcott & Wozny, 2010).

Others have failed to find evidence that consumers systematically undervalue fuel economy, leading to an active debate (Sawhill, 2008).

Feebates are an incentive system that would have the effect of adding a fee to the cost of less efficient vehicles and rebating part of the cost of more efficient vehicles (Heywood et al., 2009). In both cases costs are assessed based on deviations measured from a fixed fuel economy level or “pivot point.” The main difference is that the cost of policy is more visible to consumers at the point of vehicle purchase, with the potential effect that consumers would respond more directly to financial penalties or rewards associated with their fuel economy choices. The costs of a fuel economy standard, by contrast, are less visible as the manufacturers bear the costs of compliance and price their vehicles accordingly. Feebates are not a major focus of this work.

Subsidies for the purchase of energy efficient or alternative fuel vehicles are another way of encouraging purchases of vehicles that require less or no petroleum-based fuel. One example of such a program is the tax credit announced for PHEVs and EVs by the Obama administration, which offers an income tax rebate of up to $7,500 if a household purchases a full EV, which is expected to be included in the 2011 Federal Budget (Restuccia, 2011).

2.4.4 Other proposals

Eco-driving courses, fuel economy labeling, a per-mile tax, encouraging a shift to public transport, and other proposals not mentioned here may have potential to reduce emissions, although for most of these policies reducing GHG emissions is not the primary goal. Although not covered in detail here, more information on these programs can be found in the literature (Heywood et al., 2009).

2.5 Models used for policy assessment

Figuring out which policy, or combination of policies, is best suited to the task of accomplishing petroleum-based fuel use and GHG emissions reductions goals is not an easy task. In order to simulate the complex relationships among the different parts of the vehicle-fuel-user system that would govern the response to policy intervention, researchers have developed models that vary in their level of detail, assumptions, and representation of key feedbacks. **Table 2.2** includes a description of several models that have been developed for the purpose of forecasting vehicle energy use and GHG emissions, and for assessing the impact of policies.

The models listed in the table can be essentially grouped into two categories: 1) models that contain significant vehicle technology and fleet detail, but lack broad sectoral coverage as well as price and other macroeconomic feedbacks (Heywood et al., 2009; Yang et al., 2008; Greene & Plotkin, 2011), and 2) models that contain less technological detail, but are broader in terms of sectoral coverage and include macroeconomic feedbacks (Morrow et al., 2010; Schafer & Jacoby, 2006; Walther et al., 2010).

Table 2.2 A comparison of models used to evaluate the impact of policies on passenger vehicle energy use and GHG emissions.

Author	**Method**	**Advanced vehicle and fuel technology**	**Endogenous fuel economy response to fuel price**	**Fleet turnover: vehicle sales and scrap**	**Economy-wide coverage of energy use**	**Macro-economic feedbacks to income and prices**
Heywood et al., 2009 / Bandivadekar et al., 2008	Fleet modeling (SAL Fleet model) / scenarios	X		X		
Yang et al., 2008	Fleet modeling (LEVERS model) / scenarios	X		X		
Greene & Plotkin, 2011	Fleet modeling / scenarios	X		X		
Morrow et al., 2010	NEMS model (sector-specific models ties to a macro-model)	X		~	X	~
Schafer & Jacoby, 2006	Coupled CGE, MARKAL, mode share models	~	~		X	X
Walther et al., 2010	System dynamics	X	X			

The symbol “~” indicates that the issue is partially addressed.

Each of these two broad categories of models is applied to policy analysis in a slightly different way. The first category—technologically detailed, sector specific models—has generally been used to develop technology scenarios that are consistent with achieving particular policy targets. The second category—multi-sector, feedback-rich models—has been used to evaluate the costs or impacts of policies based on the way that they alter the economic incentives of agents inside the model. Both of these categories of models can generate insights for policy. Results from the first type have typically focused on how aggressive technological and behavioral changes would need to be to meet stringent policy targets, while the second category is designed to help policymakers compare policies in terms of their cost or impact on technology, energy use, and the environment. Both models are useful when their applications are carefully tailored to the questions analysts want to investigate.

2.5.1 How does the type of model relate to policy prescriptions?

When it comes to comparing policies, models differ in the extent to which they rely on exogenous assumptions about energy prices, the availability, cost, and uptake of advanced technologies, as well as the way they represent other relevant variables (if at all). As mentioned above, some models represent only physical aspects of the system—number of vehicles, fuel consumption, and composition of the fuel mix—and rely largely on expert engineering judgments to define input parameters, such as a the rate of new vehicle sales growth. Typically these models do not optimize the solution with respect to cost, and do not produce sector-specific or economy-wide measures of economic impact. Therefore, policy prescriptions are limited to judgments of the technical feasibility of meeting the policy target, without explicit attention to policy costs. These studies tend to emphasize the relative aggressiveness of technology deployment required to meet the constraint (Bandivadekar et al., 2008; Yang et al., 2008; Greene & Plotkin, 2011).

Models that include economic logic will differ in terms of the extent to which they rely on exogenous versus endogenous relationships to drive the system response under policy. Bottom-up energy-economic models retain a detailed, disaggregated representation of the economy as well as technological options and costs. These models typically do not represent macroeconomic feedbacks that result in changes in underlying factor prices or trade patterns, which are characteristics of top-down energy-economic models. Coupled CGE-MARKAL approaches, such as Schafer and Jacoby (2006), have attempted to capture the effect of these macroeconomic feedbacks on transportation mode shares and technology choices by linking a top-down model of the global energy and economic system with detailed bottom-up models of vehicle and mode choice. Purely top-down models tend to forego technological detail in favor of a single, parsimonious, integrated modeling framework.

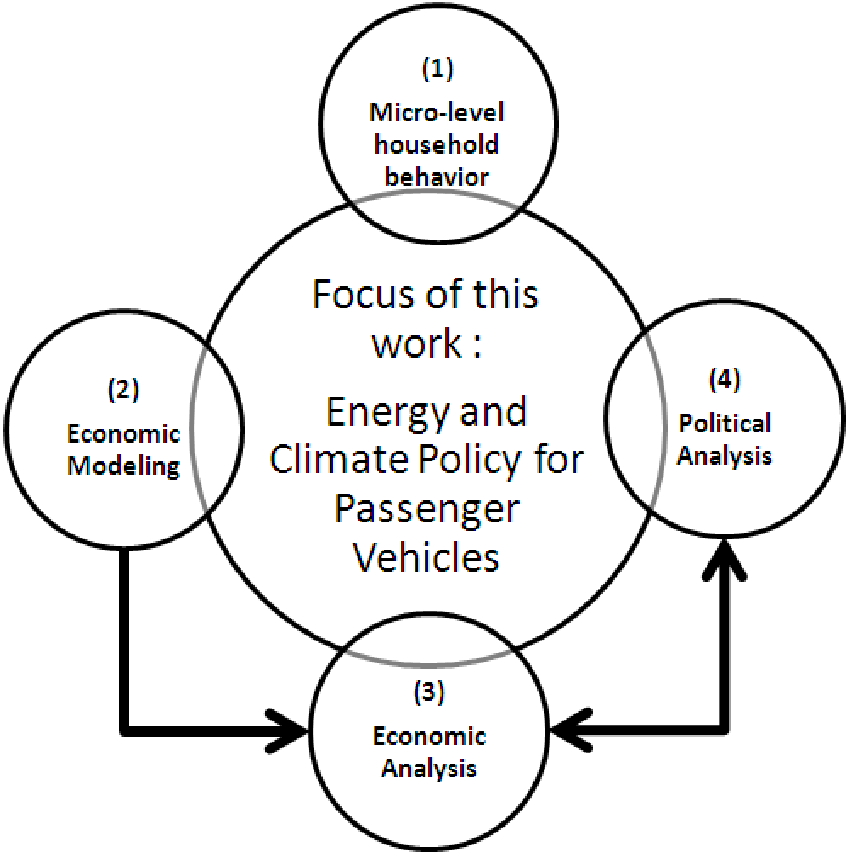
Top-down models (and hybrid modeling approaches) are perhaps most likely to capture the many ways in which policies introduce distortions that raise the cost, for example, by limiting options for abatement in space or in time, or displacing energy use or GHG emissions to other sectors. By contrast, bottom-up economic models, as well as engineering fleet models, are likely to maintain greater realism in the physical aspects of the system as they evolve over time, constraining solutions according to detailed estimates of technological potential and deployment constraints. Depending on the number of technologies included and the costs assumed, a particularly policy may appear more or less aggressive or difficult to achieve.

2.6 What gaps does this work seek to fill?

Given the numerous, interconnected dimensions of the question of how to design energy and climate policy for passenger vehicles, progress towards better answers must proceed on many fronts simultaneously. There is therefore significant opportunity for inquiry across a wide range of disciplines to bring tools to bear on different parts of the problem. For example, there is a need to better understand how households respond to both price and non-market signals in their vehicle purchase and use decisions. This type of inquiry requires methods very different from an investigation of how attitudes toward policies have varied across household categories over time. Formal modeling can help to test intuition about the mechanisms of policy action. The list of potential projects that could yield useful insights for the public policy discourse is virtually endless.

In developing this work, I have followed an integrative approach, carving out studies that lend insight into disparate corners of the debate, but can be usefully combined to provide complementary insights for policy. A schematic overview of the components of this dissertation is shown in **Figure 2.2**. By choosing to study the role of household heterogeneity in the short-run response to gasoline prices, I am able to capture diversity at the level of household decision-making around vehicle use that the modeling analysis in Part 2 and Part 3 does not. I then develop a modeling approach that captures in a parsimonious way the technological and behavioral richness of the household response to policy in an economy-wide model with price feedbacks, combining the capabilities of the two previous classes of models described above.

Fig. 2.2 A map of the present project as it relates to different aspects of the question of how to design an integrated energy and climate policy for passenger vehicles.



This model is then applied to compare policies in terms of their aggregate economic cost and impact on petroleum-based fuel use and total economy-wide (life-cycle) GHG emissions. Finally, recognizing that policies are only as effective as the strength of the political will to implement them, I examine the relationship between economic efficiency and political feasibility at the level of individual policies—an exercise made possible only by combining multiple disciplinary approaches. The result is a set of insights that can inform the choices of decision makers charged with developing energy and environmental policy for passenger vehicles in the United States.

Chapter 3: Do U.S. Households Favor High Fuel Economy Vehicles When Gasoline Prices Increase? A Discrete Choice Analysis

Our SUV gets around 20 miles to the gallon, but these days we leave it in the garage and only drive the Prius.

My mother's neighbor, Moraga, California, Summer 2008

Households owning multiple vehicles could reduce the impact of rising fuel prices by switching to increase reliance on their more fuel-efficient vehicle(s). This chapter estimates the extent of vehicle switching by households in the United States that occurred during the gasoline price fluctuations of 2008 to 2009 using cross-sectional household vehicle ownership and vehicle trip data from the 2009 U.S. National Household Transportation Survey. First, a comparison of short-run elasticities of vehicle-miles traveled (VMT) and fuel demand with respect to gasoline price show that in almost all cases, gasoline demand is reduced proportionately more than VMT, suggesting that households are achieving higher efficiencies of travel. Second, vehicle switching by two-vehicle households as a function of the potential per-mile savings available was found to be modest, with every one cent increase in per-mile savings corresponding to an average increase in the fraction of miles-traveled in the most fuel efficient vehicle of 0.014. This response was found to vary significantly by household income level and by degree of urbanization. Third, the likelihood that a two-vehicle household assigned its higher efficiency vehicle to a particular trip also increased. This effect was most prevalent for trips involving daily activities (i.e. commuting, shopping or medical visits), while only vacation trips, which typically require more passenger or cargo capacity and involve longer travel distances, did not show a significant effect.

3.1 Context and Background

While many studies have investigated how fuel prices affect household demand for fuel economy at the point of vehicle purchase, fewer have focused on the very short-run response of households to gasoline price fluctuations. This analysis explores whether or not, and under what conditions, "vehicle switching" is observed for households that own multiple vehicles, since in response to a fuel price increase these households could conserve fuel and offset increased expenditures without reducing vehicle-miles traveled (VMT) by switching to a higher fuel economy vehicle. For instance, a commuter may prefer the comfort and spaciousness of a sport utility vehicle (SUV) as long as gasoline prices remain low, but switch to the car and reserve the SUV for occasional use when fuel prices are high.

Past studies have suggested that fuel demand is reduced more than travel demand in response to a fuel price increase. Short-run estimates of the gasoline price elasticity of demand prior to 1990 range from -0.21 to -0.34, while elasticities of demand for vehicle-miles traveled (VMT) are consistently smaller (in magnitude), ranging from -0.12 to -0.15 (see **Table 3.1**)

(Hughes et al., 2006; Goodwin et al., 1992; Espey, 1996; Dahl & Sterner, 1991; Graham & Glaister, 2004; Brons et al., 2006). Estimates available based on more recent data suggest that the own-price elasticity of fuel demand has decreased, with a range estimated between -0.034 to -0.1601 (Hughes et al., 2006; Small & Van Dender, 2007).[12] These aggregate elasticity estimates mask diversity in household-level responses that may vary with income level, degree of urbanization, and the number and type of vehicles owned. For example, households owning more vehicles tend to travel longer distances and use more fuel. As a result, the response patterns of these households will disproportionate influence on aggregate elasticity calculations.

Table 3.1 Summary of several studies on the elasticity of demand for a) gasoline and b) VMT with respect to gasoline price.

a)

Study	Elasticity	Comments
Graham & Glaister, 2004	-0.25	Based on 377 estimates
Goodwin, 1992	-0.27	
Hughes et al., 2006	-0.034 to -0.077	2000-2006
Hughes et al., 2006	-0.21 to -0.34	1975-1980
Espey, 1996	-0.23	Median based on 300 prior estimates
Dahl & Sterner, 1991	-0.26	Based on 97 studies
Small & Van Dender, 2007	-0.1601	1997-2001 (U.S. only)

b)

Study	Elasticity	Comments
Graham & Glaister, 2004	-0.15	Uses vehicle-miles traveled
Brons et al., 2006	-0.12	Uses miles-traveled per vehicle

In the meta-study by Graham and Glaister (2004), the discrepancy between fuel demand and travel demand elasticities with respect to fuel price suggests an endogenous increase in the fuel efficiency of driving in response to fuel price increases. This increase may be due to many factors, for instance, the retirement of older, less efficient vehicles, the purchase of new, more

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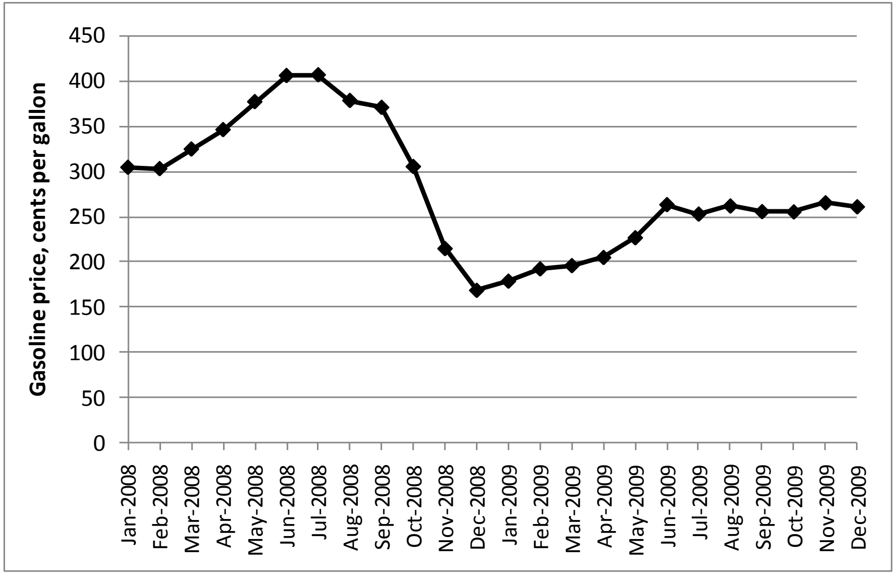
[12] Hughes et al. (2006) suggest the shift may be due to changes in land use, social or vehicle characteristics.

efficient vehicles, the adjustment of driving style or speed to conserve fuel, or switching to favor higher fuel economy vehicles owned by the household. Since this last type of switching potentially requires the lowest capital cost and a minimal amount of behavioral change (for instance, compared to mastering eco-driving techniques), it is of interest to know how much it contributes to the household response. This type of response may grow more important if vehicles that use much less or no gasoline are adopted. A single gasoline-free vehicle may offer a household the ability to reduce fuel use dramatically depending on which household vehicle-miles it replaces. Examining the role of fuel economy in existing household vehicle usage decisions provides insight into the factors that will affect the utilization of these advanced vehicle types.

This research employs a new publically available data set on household vehicle usage in the United States, the 2009 National Household Transportation Survey, during a period of fuel price fluctuations. The gasoline price rose from $3.24 per gallon in March 2008 to $4.06 in July 2008 before falling to $1.69 in December 2008 and then gradually inching upwards in the early months of 2009 (see **Figure 3.1**) (FHWA, 2009a). The data set includes information on household demographics, vehicle ownership, and vehicle utilization on a randomly assigned travel day. The relatively short time span of the survey data (fourteen months) and depressed vehicle sales leading up to and during the economic downturn provide a unique opportunity to observe the short-run, fixed fleet response to fuel prices.

Fig. 3.1 U.S. monthly gasoline prices in 2008 and 2009.



Source: EIA, 2010.

This analysis is organized as follows. **Section 2** provides a brief literature review and develops a model of the household response as a function of per-mile cost savings from switching, which is determined by the fuel economy difference between vehicles owned by the household and the magnitude of the change in fuel price. **Section 3** describes the data set and how it was used to investigate the relationship of interest. **Section 4** lays out the empirical strategy, which includes a combination of elasticity estimates for gasoline and vehicle-miles traveled with respect to gasoline price, estimates of the effect of potential savings on vehicle mileage shares, and a discrete choice analysis of the effect of per-mile savings on vehicle switching propensity by trip, and describes the results. **Section 5** offers some preliminary conclusions and extensions for future work.

3.2 Literature Review

Interest in understanding the role of energy efficiency in consumer decisions has motivated a prolific and diverse literature in economics and, to lesser extent, engineering (Hausman, 1979; Train, 1985). Recent economics literature has focused on consumer perceptions and trade-offs between upfront costs and lifetime savings at the point of new vehicle purchase (Allcott & Wozny, 2010; Klier & Linn, 2008; Sallee & Slemrod, 2010). Others have focused on describing the engineering trade-offs associated with increasing fuel economy and other energy-requiring vehicle attributes, such as performance, size, and weight (Knittel, 2009; An & DeCicco, 2007). Since consumer vehicle purchase and use decisions are closely related (and often considered to be simultaneously determined), understanding the role of fuel economy in the vehicle usage response is important and complementary to these previous studies. The effectiveness and distributional impact of policies to address local air quality, congestion, and climate change will depend on both short- and long-run vehicle usage responses (Austin & Dinan, 2005; Bento et al., 2009; Feng et al., 2005; Small & Van Dender, 2007).

3.2.1 The Role of Household Vehicle Reallocation

This analysis begins with a stylized model of how the household response to rising gasoline prices could differ depending on the number of vehicles owned, fuel economy differences within the household vehicle fleet, and the household's ability or willingness to reallocate mileage. Inputs to household vehicle transport include motor gasoline, the vehicle itself, and other non-fuel operating requirements (insurance and maintenance, for example). Household fleets are largely fixed in the short term, and fuel accounts for a significant percentage of total annualized vehicle ownership costs, more than 50% for most vehicle types in 2009 (AAA, 2009).

A change in fuel price increases the operating cost for some vehicles more than others, depending on the fuel economy of the vehicles in question. Fuel use (F) is equivalent to total miles-traveled (M_T) divided by the on-road fuel economy (ē) in miles per gallon realized by the household as shown in **Equation (3.1)**. For a two-vehicle household, ē is computed in **Equation (3.2)** by weighting the efficiency of each vehicle (e_1, e_2) by the fraction of total miles it provides:

$$F = M_T/\bar{e} \qquad \textbf{(3.1)}$$

$$\bar{e} = (M_1/M_T)e_1 + (M_2/M_T)e_2 \qquad \textbf{(3.2)}$$

The important point here is that ē is endogenous, in part because the household is able to choose how it allocates its vehicles to meet its travel needs. The household is also able to choose its total travel distance. Small and Van Dender (2007) relate the own-price elasticity of fuel demand to the fuel price elasticities of fuel economy, VMT, and vehicle-miles traveled as follows:

$$\varepsilon_{\mathrm{f,pf}} = \varepsilon_{\mathrm{M_T,p_f}}\left(1 - \varepsilon_{\bar{\mathrm{e}},\mathrm{p_f}}\right) - \varepsilon_{\bar{\mathrm{e}},\mathrm{p_f}} \qquad \textbf{(3.3)}$$

where the first term on the right-hand side of **Equation (3.3)** represents the interaction of vehicle-miles traveled with respect to fuel price ($\varepsilon_{\mathrm{M_T,p_f}}$) with the elasticity of fuel efficiency with respect to fuel price ($\varepsilon_{\bar{\mathrm{e}},\mathrm{p_f}}$). The second term ($\varepsilon_{\bar{\mathrm{e}},\mathrm{p_f}}$) captures the fuel savings that result directly from the efficiency improvement. The interpretation of this equation is straightforward—households can reduce fuel use by increasing the efficiency of travel or reducing miles, but higher average vehicle efficiency will, all else equal, encourage more travel. In the short run the elasticity of fuel efficiency with respect to fuel price includes the effect of household vehicle reallocation.[13] In this analysis the assumption of fixed household vehicle ownership over the period considered prevents vehicle purchase and scrappage decisions from affecting the average per-mile fuel economy realized by the household. It is also important to acknowledge that the potential switching opportunity resulting from the fuel economy difference between a newly purchase vehicle and the households' existing vehicles could plausibly have factored into a household's vehicle purchase decision. This analysis therefore focuses primarily on the existence and extent of switching, rather than on prediction.

3.2.2 Constraints on Household Vehicle Reallocation

The degree of switching is likely to be constrained by household, vehicle, and trip characteristics. If the household has more members, the household's vehicles are more likely to be in use at any given time. Also, in addition to household size, the average number of passengers that need to be transported will vary, depending on the household's daily activities and trip characteristics. The number and type of vehicles owned by the household will further affect flexibility. For example, haulage or terrain requirements may necessitate the use of a more powerful or rugged vehicle, characteristics that are often negatively correlated with fuel efficiency. Urbanization is also likely to play a role, since it influences the ease with which public transit, carpooling, biking, or walking can be substituted for vehicle trips in response to higher fuel prices. Switching is also hypothesized here to vary by income category, since low income households owning vehicles tend to spend a higher fraction of their income on vehicle-related costs compared to higher income households.

3.3 Data Set and Descriptive Statistics

3.3.1 The U.S. National Household Transportation Survey, 2009

The U.S. National Household Transportation Survey (NHTS) has been conducted every five to eight years by the Federal Highway Administration (FHWA). It includes nationally-representative repeated cross-sectional data on households, vehicle ownership, and the daily travel patterns of household members. The 2009 survey builds on the 2001 NHTS and the Nationwide Personal Transportation Survey conducted in 1969, 1977, 1983, 1990, and 1995

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[13] A household could also increase on-road fuel economy in the short run through other methods, for example through better maintenance or less aggressive driving style, which are not quantified here.

(FHWA, 2009a). The survey includes a record of the travel behavior of randomly-sampled households during an assigned twenty-four hour period. For each trip taken, the interviewer collected information about the purpose of the trip, means of transportation, how long the trip took, the time of day that it took place, and the day of the week on which household travel was observed. If the trip was taken in a private vehicle, data was collected on vehicle occupancy, driver characteristics, and vehicle attributes (including make, model, and age). The total number of households included in the full data set is just over 150,000. Average monthly fuel prices were mapped to the month in which the household travel occurred, and adjusted to account for variation in state-level gasoline taxes. Sample weights were provided by the NHTS administrators to correct for non-response and other factors described in FHWA (2009a), and used in this analysis to weight observations in order to obtain population-level estimates.[14]

Fuel economy information for each of the vehicles owned was not directly collected as part of the NHTS. In order to match the make and model data supplied for each household-owned vehicle to its fuel economy, I employed a database compiled by Ward's that reports detailed specifications on new vehicle makes and models for the model year 2008, including city and highway fuel economy (Ward's, 2008). For older vehicles not included in the database, I match the make and model of each vehicle to its closest model year 2008 counterpart and apply a fuel economy degradation factor of 1% per year of vehicle age. For per trip estimates where average travel speed was known, I used the vehicle's city or highway fuel economy to determine the per-mile cost savings, assuming highway fuel economy was achieved on any trip with an average travel speed over 40 miles per hour. When a trip-independent measure of per-mile cost savings was required, I used the weighted harmonic average of city and highway fuel economy used by the U.S. Environmental Protection Agency fuel economy label calculations, which assumes total miles-traveled for one vehicle occurs 45% in the city and 55% on the highway (EPA, 2004).

3.3.2 Data Set and Descriptive Statistics

For the first part of this analysis, elasticities are estimated for the aggregate sample and multiple subsamples of U.S. households, conditional on the decision to drive on the observed

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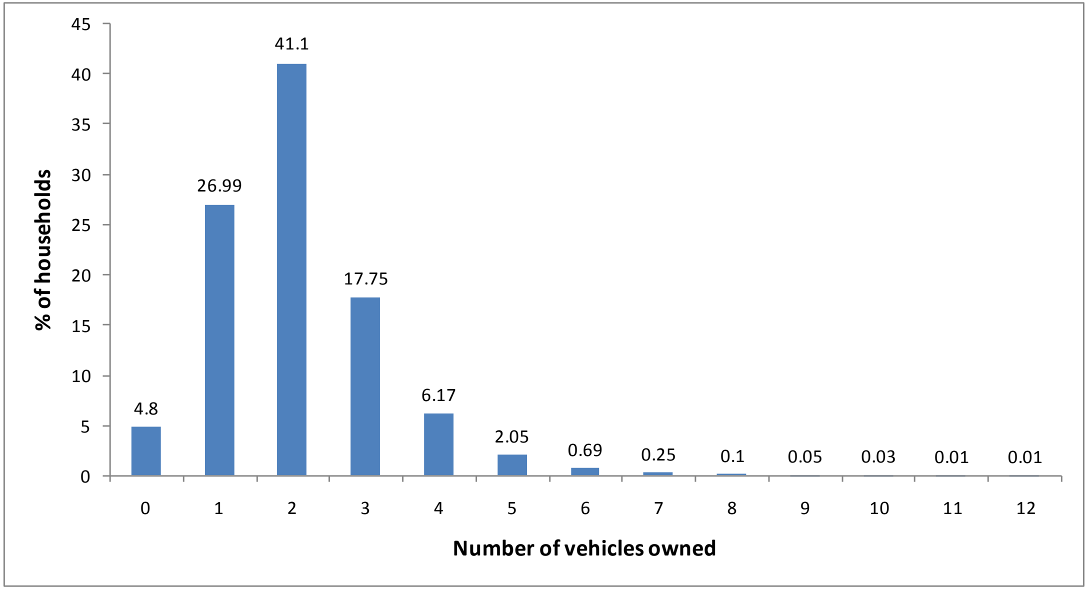
[14] In late spring 2010 the NHTS announced that they were revising the sampling weights in order to improve the representativeness of the data particularly for transit trips. As of this draft, the new weights had not been published, although significant changes to the results of this analysis as a result of using updated weights are not expected.

travel day. The proportion of households choosing to drive at all does not change noticeably with gasoline price and thus the analysis is carried out conditional on the decision to utilize at least one vehicle. The number of households included in this sample was 73,321.

For the second and third parts of this analysis, I focus on sampled U.S. households that own two vehicles only. Two-vehicle households account for 41% of all households, 42% of vehicles, and 46% of vehicle-miles traveled. The distribution of households by number of vehicles owned is shown in **Figure 3.2**.

Fig. 3.2 Distribution of household vehicle ownership in the sample.



Household observations were then matched with fuel price using monthly fuel price data by state. The precise survey date was not reported for each household, but only the day of the week, month, and year. Given this reporting convention, the best proxy for fluctuations in gasoline price is the national monthly average price of motor gasoline reported by state for 2008 and 2009 (FHWA, 2009b; FHWA, 2010). A few state gasoline price observations were missing from this data set and were filled in using regional monthly gasoline prices reported by the EIA (2010). Diesel fuel was not considered because it does not account for a significant share of fuel used by light-duty passenger vehicles in the United States. Using monthly average prices by state masks day-to-day fluctuations in gasoline price perceived by the household. However, state level taxes, which range from near zero to 50 cents, provided an additional source of variability.

3.4 Model Description and Results

The goal of this research is to understand the extent to which within-fleet substitution formed part of the household response to the 2008-2009 gasoline price fluctuations, and to investigate whether household characteristics affect its magnitude. Three approaches were used to test for the existence of an effect. First, elasticities of demand for gasoline and VMT were estimated with respect to gasoline price, conditional on the income level, degree of urbanization, and the number of vehicles owned by the household. Second, the relationship between the potential per-mile savings associated with switching and the fraction of total household miles driven in the household's relatively high fuel economy vehicle on the household's assigned travel day were estimated. Third, a logit model was used to investigate the effect of per-mile savings on the choice of the high-efficiency vehicle by trip.

3.4.1 Elasticities

To investigate whether or not households reduced fuel use more than total mileage as gasoline price increased, gasoline price elasticities of demand for VMT and gasoline were calculated for the aggregate sample and conditional on household characteristics. The models estimated are shown in **Equations (3.4)** and **(3.5)**.

$$\ln G_i = \beta_0 + \beta_1 \ln P_i + \beta_2 \ln Y_i + \gamma(Z_\mathrm{i}) + \mathrm{s_i} + \varepsilon_\mathrm{i} \qquad \textbf{(3.4)}$$

$$\ln VMT_i = \beta_0 + \beta_1 \ln P_i + \beta_2 \ln Y_i + \gamma(Z_\mathrm{i}) + \mathrm{s_i} + \varepsilon_\mathrm{i} \qquad \textbf{(3.5)}$$

Equation (4) is similar to the specification used in Hughes et al. (2006). The model estimates the relationship between gasoline price (P_i) (determined by month of observation and household state) and household gasoline use (G_i) as well as vehicle-miles traveled (VMT_i), expressed as elasticities using log-log robust ordinary least squares (OLS) regression. The effect of income, household size, and whether or not household travel took place on a weekday were included as a vector of household-specific characteristics $\gamma(Z_\mathrm{i})$. Seasonal changes, including the effect of summer travel and possibly also economic downturn in the fall of 2008, were captured using dummy variables $\mathrm{s_i}$ spanning three-month periods, which were assigned according to the month in which the household travel day occurred.

3.4.1.1 Aggregate Elasticity Estimates

The elasticities of demand for VMT and gasoline use with respect to gasoline price are reported for the aggregate sample as shown in **Table 3.2**. The fuel price elasticity of demand estimates for VMT (-0.112) and for gasoline fuel (-0.144) fall within the ranges reported by earlier studies, and the magnitudes are consistent with a differential response (Table 1). The fuel price elasticity of demand for VMT was found to be smaller in magnitude than the own-price elasticity of gasoline. Positive short-run income elasticities for both gasoline and VMT demand are also consistent with previous estimates. Household size also has a significant effect on fuel use, while the negative coefficients on *weekday* indicate that VMT and fuel use are reduced for weekday relative to weekend travel.

Table 3.2 Aggregate gasoline price elasticity of demand for VMT and gasoline. Log indicates natural log.
(* p<0.05 ** p<0.01 *** p<0.001)

	Log VMT	**Log Gasoline Use**
Log gasoline price	-0.112***	-0.144***
	(-3.74)	(-4.88)
Log household income	0.316***	0.301***
	(39.08)	(37.69)
Spring	0.113***	0.142***
	(4.35)	(5.59)
Summer	0.135***	0.157***
	(5.23)	(6.16)
Fall	0.0491**	0.0681***
	(2.89)	(4.08)
Household size	0.251***	0.259***
	(63.87)	(67.05)
Weekday	-0.0942***	-0.0895***
	(-9.73)	(-9.41)
Constant	0.107	-2.645***
	(1.22)	(-30.56)
N	73321	73321

3.4.1.2 Elasticities Conditional on Income Level

Aggregate elasticity estimates may mask important differences in the responses of population subgroups. To find out whether subgroups might have significantly different elasticities that are not resolved in the aggregate estimates, I condition on income level and degree of urbanization. In **Table 3.3**, elasticities are presented conditional on household income level. The lowest income category (< $25,000 per year) shows the most inelastic behavior, with the elasticity of demand for VMT not significantly different from zero. Since these households are likely the most cash-constrained, reducing fuel consumption without reducing VMT may be a particularly attractive option, especially if the proportion of vehicle-miles devoted to more essential (non-discretionary) household activities (such as grocery shopping or commuting) is greater than for higher income households. As income increases, household responses generally become more elastic, consistent with the notion that reducing the number and length of vehicle trips may be easier if those marginal miles are devoted to vacation or other discretionary trips, which can be reduced without affecting income, or for which less expensive substitute modes of transport may be available.

Table 3.3 Elasticities by income level. (* p<0.05 ** p<0.01 *** p<0.001)

	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**
	< $25,000/yr		**$25,000-$60,000/yr**		**$60,000-$100,000/yr**		**>$100,000/yr**	
	VMT	**Gasoline**	**VMT**	**Gasoline**	**VMT**	**Gasoline**	**VMT**	**Gasoline**
Log gasoline price	0.00436	-0.0354	-0.141**	-0.170***	-0.0993	-0.119*	-0.133*	-0.178**
	(0.05)	(-0.38)	(-2.76)	(-3.38)	(-1.76)	(-2.15)	(-2.33)	(-3.18)
Spring	0.108	0.131	0.0912*	0.126**	0.109*	0.133**	0.139**	0.172***
	(1.33)	(1.63)	(2.05)	(2.86)	(2.22)	(2.75)	(2.86)	(3.62)
Summer	0.0000312	0.0300	0.140**	0.159***	0.157**	0.173***	0.156**	0.185***
	(0.00)	(0.37)	(3.14)	(3.62)	(3.24)	(3.62)	(3.19)	(3.84)
Fall	-0.0340	-0.00789	0.0559	0.0733*	0.0358	0.0533	0.0895**	0.109***
	(-0.63)	(-0.15)	(1.91)	(2.54)	(1.13)	(1.73)	(2.79)	(3.47)
Household size	0.271***	0.276***	0.271***	0.279***	0.243***	0.252***	0.222***	0.234***
	(21.58)	(22.15)	(37.37)	(39.17)	(34.76)	(36.32)	(32.54)	(35.22)
Weekday	-0.0726*	-0.0682*	-0.0738***	-0.0686***	-0.0720***	-0.0682***	-0.150***	-0.145***
	(-2.47)	(-2.34)	(-4.45)	(-4.20)	(-3.91)	(-3.76)	(-8.15)	(-8.05)
Constant	3.044***	0.157*	3.447***	0.534***	3.654***	0.722***	3.892***	0.966***
	(45.41)	(2.38)	(91.49)	(14.37)	(87.27)	(17.47)	(92.51)	(23.47)
N	11709	11709	26697	26697	18395	18395	16520	16520

3.4.1.3 Elasticities Conditional on Degree of Urbanization

Next I condition on the degree of urbanization. A comparison of the elasticities suggests that urban households are somewhat more elastic while rural households are less elastic in their responses to gasoline prices (measured elasticities for the latter are not significantly different from zero) (**Table 3.4**). Relatively higher elasticities in urban areas may reflect the availability of public transportation, carpooling, or other substitutes for household-owned vehicle travel.

3.4.1.4 Elasticities Conditional on Vehicle Ownership

The role of household vehicle ownership was also considered. The natural log of household income, household size, the weekday dummy, and the instrument for seasonality were included in the regression.

Table 3.4 Elasticities by degree of urbanization. (* p<0.05 ** p<0.01 *** p<0.001)

	(1)	(2)	(3)	(4)	(5)	(6)
	Urban		**Semi-urban**		**Rural**	
	VMT	Gasoline	VMT	Gasoline	VMT	Gasoline
Log gasoline price	-0.0916**	-0.130***	-0.0931	-0.106	-0.0642	-0.0781
	(-2.70)	(-3.89)	(-0.71)	(-0.83)	(-0.97)	(-1.21)
Log household income	0.357***	0.344***	0.337***	0.322***	0.259***	0.235***
	(38.00)	(37.05)	(10.12)	(9.91)	(15.47)	(14.18)
Spring	0.0775**	0.110***	0.0641	0.0676	0.0922	0.116*
	(2.63)	(3.81)	(0.57)	(0.62)	(1.65)	(2.13)
Summer	0.110***	0.136***	0.101	0.105	0.0880	0.0986
	(3.75)	(4.71)	(0.89)	(0.95)	(1.55)	(1.77)
Fall	0.0423*	0.0650***	0.0543	0.0601	0.0259	0.0351
	(2.22)	(3.47)	(0.71)	(0.80)	(0.68)	(0.93)
Household size	0.252***	0.263***	0.256***	0.253***	0.243***	0.245***
	(56.69)	(60.04)	(14.58)	(14.73)	(28.87)	(29.31)
Weekday	-0.0952***	-0.0879***	-0.105*	-0.107**	-0.0825***	-0.0860***
	(-8.66)	(-8.12)	(-2.52)	(-2.64)	(-3.88)	(-4.14)
Constant	-0.451***	-3.230***	-0.110	-2.831***	1.088***	-1.562***
	(-4.44)	(-32.16)	(-0.30)	(-7.88)	(5.97)	(-8.66)
N	53628	53628	4833	4833	14859	14859

Interestingly, households owning one vehicle showed a relatively elastic response, with elasticities estimated at -0.154 for VMT and -0.181 for gasoline. Households owning two vehicles had a significantly smaller (in magnitude) response, while households owning three vehicles had the largest response of any category, as shown in **Table 3.5**. These results are consistent with the notion that many two-vehicle households have two adult drivers, while three-vehicle households may have more vehicles than drivers, may include a teenage driver, or may reserve the third vehicle for occasional use that can easily be reduced. In addition, once a new vehicle is purchased, households may keep older vehicles on hand in case of emergencies or to allow vehicle use by multiple household members at once.

Table 3.5 Gasoline price elasticity of demand for VMT and gasoline for a) one-vehicle, b) two-vehicle, and c) three-vehicle households. (* p<0.05 ** p<0.01 *** p<0.001)

	(1)	(2)	(3)	(4)	(5)	(6)
	One-vehicle households		**Two-vehicle households**		**Three-vehicle households**	
	VMT	**Gasoline**	**VMT**	**Gasoline**	**VMT**	**Gasoline**
Log gasoline price	-0.154*	-0.181**	-0.0865*	-0.115**	-0.192**	-0.230***
	(-2.35)	(-2.77)	(-2.05)	(-2.75)	(-2.89)	(-3.56)
Log household income	0.157***	0.135***	0.212***	0.192***	0.211***	0.191***
	(10.56)	(9.20)	(16.42)	(15.08)	(10.53)	(9.56)
Spring	0.157**	0.189***	0.100**	0.125***	0.129*	0.165**
	(2.78)	(3.37)	(2.72)	(3.44)	(2.28)	(3.00)
Summer	0.162**	0.184**	0.115**	0.126***	0.185**	0.224***
	(2.84)	(3.25)	(3.14)	(3.47)	(3.28)	(4.06)
Fall	0.0894*	0.111**	0.0537*	0.0679**	0.0789*	0.0999**
	(2.39)	(3.00)	(2.22)	(2.84)	(2.12)	(2.75)
Household size	0.255***	0.270***	0.196***	0.207***	0.181***	0.186***
	(21.26)	(23.01)	(31.41)	(33.44)	(22.27)	(22.97)
Weekday	-0.0325	-0.0295	-0.0932***	-0.0876***	-0.120***	-0.114***
	(-1.54)	(-1.41)	(-6.68)	(-6.38)	(-5.95)	(-5.76)
Constant	1.433***	-1.281***	1.385***	-1.310***	1.705***	-0.975***
	(8.87)	(-8.03)	(9.77)	(-9.37)	(7.63)	(-4.40)
N	19949	19949	32778	32778	13701	13701

3.4.2 The Relationship between Fraction of Miles-Traveled in the High Efficiency Vehicle and Per-Mile Cost Savings

To investigate the extent of vehicle switching, I consider only two-vehicle households owning vehicles with differences in fuel economy. Vehicle switching is measured as a change in the fraction of miles driven in the higher efficiency vehicle, a distance-normalized measure of a household's relative reliance on their high efficiency vehicle on its randomly-assigned travel day. Reliance on the high efficiency vehicle could change by season or day of the week, for example, if summer or weekend driving required a roomier or more powerful vehicle. The model includes covariates to capture variation in driving by season and weekday versus weekend.

3.4.2.1 Model Specification

I specify a model that is designed to quantify the relationship between per-mile savings and the fraction of miles ($milfrac$, a value between zero and one) traveled in the higher fuel economy vehicle (versus the alternative choice, designated the lower fuel economy vehicle), conditional on the decision to drive. The reduction in price per mile achievable by driving the higher instead of the lower fuel economy vehicle was included on the right-hand side of the equation as the primary independent variable of interest.[15] Price per mile is computed by dividing the gasoline price (dollars per gallon) by the vehicle's fuel economy (miles per gallon).

The effect of per-mile savings on the fraction of miles driven in the more efficient vehicle will not be constant over the range of values between zero and one. Ordinary least squares (OLS) regression will therefore not provide the best estimates of the effect of interest, and indeed predicted values using the OLS specification lie outside of the 0-1 interval (Papke & Wooldridge, 1993). In both the proposed model and in the observations a large number of zeros and ones are likely to occur because on their randomly assigned travel day, some households will use only one of their two vehicles, even if the second vehicle is used regularly. Following Papke and Wooldridge (1993), I apply a generalized linear model (GLM) with logit link to estimate the coefficient on per-mile savings using quasi-likelihood methods, and report the predicted margins as well as marginal effects. Equations were constructed to explicitly account for nonlinear behavior of the relationship between $milfrac_i$ and per-mile savings, and compared to the OLS

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[15] Price per mile is a function of the vehicle combination and the gasoline price (including state tax) that each household faces.

estimates. **Equations (3.6)** and **(3.7)** show the model specification, first in its generalized form and then with variables explicitly labeled. **Equation (3.8)** shows the logit link specification.

$$E(y_i|x_i) = G(X_i\beta), 0 \leq G(z) \leq 1 \; \forall \, z \in R \qquad \textbf{(3.6)}$$

$$milfrac_i(0 < y < 1) = G(\beta_0 + \beta_1(savings_i) + \beta X_i + \epsilon_i) \qquad \textbf{(3.7)}$$

$$G(u) = \ln(\frac{u}{1-u}) \qquad \textbf{(3.8)}$$

For the aggregate sample, the sensitivity of the coefficient on per-mile savings ($savings_i$) to the inclusion of several covariates that may influence its magnitude was tested, starting with income. Households with higher incomes may be less sensitive to small changes in the cost of using particular vehicles, especially if the lower fuel economy vehicle offers improved comfort or performance. To account for the fact that, all else equal, households may use larger vehicles for a higher percentage of miles in the summer (for instance, for family road trips), I included seasonal dummy variables in the equation. Average household vehicle occupancy over all trips at the level of each household was included to capture vehicle passenger capacity requirements. Household size was also added to control for additional factors that might affect the choice of each vehicle, such as its likelihood of being in use and thus unavailable for any particular trip. In order to facilitate interpretation of the β_1 estimates, the predicted margins and marginal effects were calculated.

3.4.1.2 Aggregate Estimates of Vehicle Switching

Switching was first estimated at the level of the aggregate two-vehicle sample and shown in **Table 3.6a**. The GLM estimates are shown in columns (1) through (6) and the OLS estimates are included for comparison in column (7). The marginal effects estimated with both the GLM and OLS specifications are included in **Table 3.6b**. For the GLM approach, the marginal effect of an increase in per-mile savings decreases with the magnitude of the savings. On average a 1 cent increase in the per-mile cost savings raises the fraction of miles traveled in the higher fuel economy vehicle by a magnitude between 0.005 and 0.016. The average increase in per-mile cost savings was 3.5 cents, which would result in a modest but significant shift in the fraction of miles traveled in the high fuel economy vehicle by around 0.048. As expected the GLM estimates of marginal effect bracket the OLS estimate. The average fraction of miles driven in the high fuel economy vehicle for the two-vehicle sample was measured at 0.523. For the remainder of the analysis the GLM specification is used and only the predictive margins and marginal effects are reported.

Table 3.6 Effect of per-mile savings on switching behavior in the aggregate sample with a) GLM coefficients and z-statistics shown in columns (1) through (6) and OLS coefficients and statistics shown in (7) and b) predictive margins and marginal effects for the GLM model.

a)

	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**
Per-mile savings	0.0540***	0.0517***	0.0541***	0.0562***	0.0556***	0.0556***	0.0136***
	(11.68)	(10.83)	(10.52)	(10.94)	(10.77)	(10.78)	(11.00)
Log of household income		-0.176***	-0.177***	-0.142***	-0.151***	-0.151***	-0.0371***
		(-6.57)	(-6.58)	(-5.20)	(-5.53)	(-5.53)	(-5.58)
Spring			-0.0234	-0.0282	-0.0280	-0.0283	-0.00694
			(-0.61)	(-0.74)	(-0.74)	(-0.75)	(-0.74)
Summer			-0.0537	-0.0659	-0.0523	-0.0514	-0.0126
			(-1.34)	(-1.64)	(-1.31)	(-1.28)	(-1.27)
Fall			0.000494	-0.00581	-0.00306	-0.00270	-0.000568
			(0.01)	(-0.16)	(-0.09)	(-0.08)	(-0.06)
Household size				-0.104***	-0.0488***	-0.0482***	-0.0119***
				(-8.84)	(-3.69)	(-3.64)	(-3.66)
Average passengers per vehicle					-0.140***	-0.141***	-0.0347***
					(-7.00)	(-7.06)	(-7.17)
Weekday						-0.0251	-0.00611
						(-0.84)	(-0.83)
Constant	-0.0954***	1.857***	1.870***	1.784***	1.992***	2.012***	0.994***
	(-4.69)	(6.22)	(6.24)	(5.95)	(6.60)	(6.66)	(13.55)
N	17965	16766	16766	16766	16766	16766	16766

b)

savings	**Predicted *milfrac***		**Marginal effect (*milfrac*|*savings*)**	
(cents per mile)	**Estimate**	**S.E.**	**Estimate**	**S.E.**
0	0.474555	0.005482	0.013734	0.001262
2.5	0.508954	0.003452	0.013764	0.001278
5	0.543266	0.003718	0.013665	0.001259
7	0.577173	0.0059	0.01344	0.001205
10	0.61037	0.008479	0.013099	0.00112
15	0.673561	0.013241	0.012117	0.00088
20	0.731053	0.016796	0.010843	0.000589

Table 3.7 Predictive margins and marginal effects of per-mile savings on fraction of miles traveled in higher efficiency vehicle by income category. S.E. – standard errors

	Predicted *milfrac*		**Marginal effect**	
Income <$25,000				
Per-mile savings (cents)	**E(*milfrac*|X$\boldsymbol{\beta}$)** $A = \pi r^2$**)**	**S.E.**	**(*milfrac*|*savings*)**	**S.E.**
0	0.4767	0.0221	0.0245	0.0049
2.5	0.5379	0.0135	0.0244	0.0050
5	0.5980	0.0135	0.0236	0.0047
7	0.6553	0.0207	0.0222	0.0040
10	0.7084	0.0282	0.0203	0.0031
15	0.7989	0.0376	0.0158	0.0012
20	0.8667	0.0386	0.0114	0.0006
Income $25,000 - $60,000				
Per-mile savings (cents)	**E(*milfrac*|X$\boldsymbol{\beta}$)**	**S.E.**	**(*milfrac*|*savings*)**	**S.E.**
0	0.4706	0.0098	0.0221	0.0023
2.5	0.5259	0.0061	0.0221	0.0023
5	0.5805	0.0066	0.0216	0.0022
7	0.6332	0.0102	0.0206	0.0020
10	0.6829	0.0140	0.0192	0.0016
15	0.7703	0.0194	0.0157	0.0008
20	0.8394	0.0210	0.0120	0.0002
Income $60,000 - $100,000				
Per-mile savings (cents)	**E(*milfrac*|X$\boldsymbol{\beta}$)**	**S.E.**	**(*milfrac*|*savings*)**	**S.E.**
0	0.4809	0.0100	0.0102	0.0023
2.5	0.5063	0.0062	0.0102	0.0023
5	0.5318	0.0067	0.0101	0.0023
7	0.5570	0.0109	0.0101	0.0023
10	0.5820	0.0159	0.0099	0.0022
15	0.6306	0.0257	0.0095	0.0019
20	0.6767	0.0343	0.0089	0.0016
Income >$100,000				
Per-mile savings (cents)	**E(*milfrac*|X$\boldsymbol{\beta}$)**	**S.E.**	**(*milfrac*|*savings*)**	**S.E.**
0	0.4678	0.0095	0.0062	0.0022
2.5	0.4834	0.0061	0.0062	0.0022
5	0.4989	0.0068	0.0062	0.0022
7	0.5144	0.0109	0.0062	0.0022
10	0.5300	0.0159	0.0062	0.0022
15	0.5608	0.0264	0.0061	0.0021
20	0.5911	0.0366	0.0060	0.0020

3.4.1.3 Estimates of Vehicle Switching by Income Level

The propensity to switch vehicles strongly decreases with increasing income (**Table 3.7**). In addition to per-mile savings, the independent variables included in the model were weekday and seasonal dummies as well as household size. The marginal effect for the lowest income households ranges from 0.0245 to 0.0114 as the per-mile savings increases, while the effect for highest income households is much lower, decreasing from 0.0062 to 0.0060. The difference in response across these two different income categories was found to be statistically significant at the 0.1% level. This result is consistent with higher income households placing less value on the switching opportunity, given that vehicle transportation costs account for a smaller percentage of the household's budget. The second and third highest income categories fall in between these extremes in terms of vehicle switching propensity.

Table 3.8 Predictive margins and marginal effects of per-mile savings on fraction of miles traveled in higher efficiency vehicle by degree of urbanization. S.E. – standard errors

	Predicted *milfrac*		**Marginal effect**	
Urban				
Per-mile savings (cents)	$E(milfrac \mid X\beta)$	**S.E.**	$(milfrac \mid savings)$	**S.E.**
0	0.4772	0.0062	0.0108	0.0014
2.5	0.5041	0.0039	0.0108	0.0015
5	0.5311	0.0043	0.0107	0.0014
7	0.5578	0.0069	0.0106	0.0014
10	0.5843	0.0099	0.0105	0.0014
15	0.6356	0.0160	0.0100	0.0012
20	0.6840	0.0211	0.0093	0.0009
Semi-urban				
Per-mile savings (cents)	$E(milfrac \mid X\beta)$	**S.E.**	$(milfrac \mid savings)$	**S.E.**
0	0.4373	0.0236	0.0263	0.0054
2.5	0.5037	0.0146	0.0267	0.0057
5	0.5699	0.0157	0.0262	0.0055
7	0.6337	0.0247	0.0248	0.0047
10	0.6932	0.0337	0.0227	0.0036
15	0.7941	0.0440	0.0175	0.0012
20	0.8681	0.0437	0.0123	0.0009
Rural				
Per-mile savings (cents)	$E(milfrac \mid X\beta)$	**S.E.**	$(milfrac \mid savings)$	**S.E.**
0	0.4736	0.0131	0.0221	0.0029
2.5	0.5290	0.0081	0.0221	0.0030
5	0.5836	0.0083	0.0216	0.0029
7	0.6363	0.0128	0.0205	0.0025
10	0.6860	0.0178	0.0191	0.0021
15	0.7730	0.0246	0.0156	0.0010
20	0.8415	0.0266	0.0119	0.0002

3.4.1.4 Estimates of Vehicle Switching by Level of Urbanization

Vehicle switching also seems to be greater in semi-urban or rural areas relative to urban areas (**Table 3.8**). The natural log of household income was included in the model as an explanatory variable in addition to weekday and seasonal dummies along with household size. The marginal effect of a change from zero in per-mile savings is likely to increase the fraction of miles traveled in the more efficient vehicle by 0.0108 for urban households but by more than twice as much for semi-urban (0.0263) and rural (0.0221) households. The reduced propensity of urban households to switch vehicles suggests that these households may be on average less able to reallocate use of their vehicles, perhaps because vehicle allocation is already tightly optimized around necessary functions, households can take advantage of public transport, or because adult household members in urban areas require all vehicles owned for commuting to work.

Table 3.9 Effect of per-mile savings on the choice of a high efficiency vehicle by trip for the aggregate sample.

	(1)	(2)	(3)	(4)
Per-mile savings	0.0280***	0.0285***	0.0284***	0.0286***
	(9.88)	(10.06)	(10.02)	(10.08)
Household size		-0.0769***	-0.0711***	-0.0703***
		(-11.24)	(-10.10)	(-9.97)
Average passengers			-0.0735***	-0.0962***
			(-3.52)	(-4.20)
Trip distance (miles)				0.000222*
				(2.41)
_cons	0.0209	0.228***	0.346***	0.375***
	(1.79)	(10.46)	(8.65)	(8.99)
N	64563	64563	64563	64563

3.4.3 Relationship between Per-Mile Cost Savings and the Choice of a High Efficiency Vehicle by Trip

The analysis of vehicle switching at the household level suggests a modest level of switching takes place, but does the probability of choosing the high efficiency vehicle for any particular trip actually increase? A trip is defined is any contiguous period of travel for which the same vehicle is used and for which a single decision of which vehicle to use is made. For example, a household cannot use one vehicle to drive to the grocery store and the second vehicle to drive home. Chained trips (contiguous trips often combining multiple purposes without returning home) are thus considered as a single trip. In this analysis the dependent variable is either 0 or 1, depending on whether the household assigned the high fuel economy vehicle to a particular trip. Covariates included in the model include per-mile savings, household size, average passengers per vehicle, and trip distance. The results are shown in **Table 3.9**. The estimates of the effect of per-mile savings are robust to alternative model specifications and highly significant. On a per trip basis, the probability of choosing the high efficiency vehicle increases with per-mile cost savings. The probability of choosing the high efficiency vehicle for a particular trip increases by 2.8-2.9% for each one cent increase in per-mile savings.

Table 3.10 The effect of per-mile cost savings by trip purpose.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	To / From Work	**Work-related business**	**Shopping**	**Other family / personal business**	**School / church**	**Medical / dental**	**Vacation**	**Visit friends / relatives**	**Other social / recreation**
Per-mile savings	0.0330***	0.0220	0.0366***	0.0306***	0.0332***	0.0471***	-0.0206	0.0424***	0.0344***
	(6.21)	(1.73)	(8.50)	(6.46)	(4.29)	(4.59)	(-1.07)	(4.98)	(7.50)
Household size	0.0155	0.0808**	-0.103***	-0.0942***	-0.175***	-0.114***	-0.170**	-0.160***	-0.110***
	(1.20)	(2.62)	(-9.15)	(-8.46)	(-10.17)	(-4.12)	(-3.27)	(-7.49)	(-9.24)
Average passengers	-0.00573	0.0299	-0.0829**	-0.0933**	-0.0334	-0.0740	-0.0710	-0.0614	-0.109**
	(-0.10)	(0.32)	(-2.61)	(-2.61)	(-0.56)	(-0.82)	(-0.87)	(-1.19)	(-3.28)
Trip distance (miles)	0.00151***	0.000697	0.0000884	0.000367	-0.0000493	0.00158**	-0.000158	0.000376	0.000191
	(4.36)	(1.49)	(0.67)	(1.94)	(-0.14)	(2.97)	(-0.81)	(1.85)	(1.37)
Constant	-0.0934	-0.391*	0.415***	0.447***	0.667***	0.406**	0.652***	0.539***	0.526***
	(-0.90)	(-2.07)	(7.21)	(6.87)	(6.15)	(2.59)	(3.34)	(5.50)	(8.63)
N	19077	3218	27929	23774	9099	5055	1302	7535	24060

To investigate the possibility that switching may vary by trip purpose, I consider nine subcategories of trips grouped by the fact that part or all of a trip was dedicated to a particular task or function. The trip purposes considered include travel to/from work, work-related business, shopping, other family/personal business, school or church, medical or dental, vacation, visiting friends or relatives, and other social or recreational trips. In addition to per-mile savings, household size, average number of passengers, and trip distance were also included as covariates in the regression. The results are shown in **Table 3.10**. The coefficient on household size as a predictor of high efficiency vehicle choice is negative and significant for all trips except commuting to work and work-related business. Trip distance modestly increased the odds of choosing the efficient vehicle (at a statistically significant level) only for commute trips. Switching is most pronounced for trips involving daily functions such as commuting, shopping, medical or dental visits, and visiting friends and relatives, but not significant for vacation trips.

3.5 Conclusions and Extensions

3.5.1 Conclusions

This analysis provides strong evidence that households increase their relative reliance on high fuel economy vehicles when gasoline prices rise, but the extent of switching is modest. Switching occurs both in terms of the share of high efficiency vehicle use in household travel and on a per-trip basis.

Vehicle switching is likely to form part of the household response to an increase in fuel prices, whether or not that increase is mandated by policy or driven by markets. The results presented here suggest that for the average two-vehicle household in our sample (with average on-road fuel economy for the high efficiency vehicle equal to 22.7 miles per gallon and low efficiency vehicle equal to 17.5 miles per gallon), a $2 increase in gasoline price assuming a base price of $2 per gallon would result in an increase of in per-mile cost of 5.21 cents. The per-mile savings associated with switching would induce the household to increase the fraction of miles traveled in the more efficient vehicle by 0.0242. If total VMT remains unchanged, a household that drives an average of 25,000 vehicle miles per year will have saved 7.9 gallons of fuel, or around $32, over the course of the year. By contrast, complete switching would reduce fuel use by 155 gallons, or $622. This effect is comparable to the effect of a modest mileage reduction—a 1% decrease in household mileage would result in a reduction of between 11 to 14 gallons, or $44 and $57 in fuel expenditures, each year.

The modest size of the savings achieved by the household through switching may partially explain why the response seems to be most prevalent among low income households. The lower level of switching observed in urban areas could be influenced by the existence of more substitutes for vehicle transport (including public transit and carpooling) that cause the VMT response to dominate, or simply the fact that urban households more tightly optimize the use of both vehicles and are less able to reallocate them (e.g. they have two commuters in the family).

On a per trip basis, the fact that switching occurs more readily for shorter non-discretionary trips such as commuting, shopping, or medical/dental visits suggests that both trip frequency and contribution to overall mileage are important factors. Distance may constrain switching to the extent that low on-road fuel economy is correlated with attributes that increase in value with trip distance. Consistent with this hypothesis, switching does not seem to occur on vacation (generally longer-distance) trips. For these longer trips, comfort and performance may grow more important—to the extent that these attributes trade off with propulsion system efficiency to influence on-road fuel economy, it would increase the household's propensity to choose its lower efficiency vehicle for longer trips. Moreover, since vacation trips account for only 1% of total trips and a relatively small fraction of total household mileage, the household may not have a strong financial rationale to prioritize the high fuel economy vehicle on these trips. Moreover, households may require vehicles with greater carrying capacity or specialized functionality on recreational trips that make them attractive, even if such vehicles have relatively low fuel economy.

By quantifying the role of vehicle switching, I have shown that its contribution to the overall household response to changes in the gasoline price is relatively modest. While complete switching would obviously produce greater savings, it may be difficult or even impossible to achieve depending on the characteristics of individual households. Understanding the factors that enable or constrain a household's ability to reduce fuel use will be important in identifying the impacts of policies aimed at influencing fuel use and emissions from U.S. passenger vehicles.

3.5.2 Extensions

The analysis of the effect of per-mile savings on switching could be usefully extended to households owning more than two vehicles, given that three-vehicle households appear to have more elastic VMT and gasoline demand responses to gasoline price increases. For households with more than two vehicles, a logit specification that accommodates multiple alternatives would be needed. Further conditioning on the type and characteristics of vehicles owned could lend insight into the role of vehicle attributes in switching decisions.

This paper has relied on model specifications that could mask any discontinuities in consumer vehicle usage behavior that result from large or unprecedented increases in gasoline prices. For instance, anecdotal reports that consumers left their hummers in the garage in favor of hybrids only when gasoline prices spiked above $4 would not be captured fully in the present analysis. An alternative modeling strategy that allows for this type of threshold behavior would provide a better estimate of any such nonlinear effects.

Chapter 4: A New Approach to Modeling Passenger Vehicles in Computable General Equilibrium (CGE) Models

"Everything should be made as simple as possible, but not simpler."

Albert Einstein[16]

A well-known challenge in computable general equilibrium (CGE) models is to maintain correspondence between the forecasted economic and physical quantities over time. Maintaining such a correspondence is necessary to ensure that economic forecasts reflect, and are constrained by, relationships within the underlying physical system. This chapter develops a method for projecting global demand for passenger vehicle transport, retaining supplemental physical accounting for vehicle stock, fuel use, and greenhouse gas (GHG) emissions. This method is implemented in the MIT Emissions Prediction and Policy Analysis Version 5 (EPPA5) model and includes several advances over previous approaches. First, the relationship between per capita income and demand for passenger vehicle transport services (in vehicle-miles traveled, or VMT) is based on econometric data and modeled using quasi-homothetic preferences. Second, the passenger vehicle transport sector is structured to capture opportunities to reduce fleet-level gasoline use through the application of vehicle efficiency or alternative fuel vehicle technologies, introduction of alternative fuels, or reduction in demand for VMT. Third, alternative fuel vehicles (AFVs) are introduced into the EPPA model. Fixed costs as well as learning effects that could affect the rate of AFV introduction are captured explicitly. This model development lays the foundation for assessing policies that differentiate based on vehicle age and efficiency, alter the relative prices of fuels, or focus on promoting specific advanced vehicle or fuel technologies.

4.1 Introduction

Computable general equilibrium (CGE) models are widely used to understand the impact of policy constraints on energy use, the environment, and economic welfare at a national or global level (Weyant, 1999; Clarke et al., 2007; Ross et al., 2009). However, for certain research questions, results from these models can produce misleading forecasts if they do not capture accurately the relationships in the underlying physical system. These relationships include links between income and demand for services provided by energy-intensive durable goods, as well as the richness of opportunities for technological or behavioral change in response to policy.

Maintaining dual accounting of physical and economic variables is particularly important when modeling consumer durable goods such as passenger vehicles. Vehicles are an example of a complex multi-attribute consumer product with a long lifetime. Consumer preferences across attributes—such as horsepower and fuel economy in the case of vehicles—involve engineering trade-offs at the vehicle level. For instance, over the past several decades, fuel efficiency gains

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[16] In Calaprice (2000).

have been offset by a shift toward larger, more powerful vehicles in some regions, offsetting improvements in on-road fuel economy (An & DeCicco, 2007). As policymakers consider how to most cost-effectively regulate the air, climate, and security externalities associated with vehicle use, macroeconomic forecasting models that capture the range of technological and behavioral responses to regulation will become increasingly important.

The goal of this work is to develop a new method of projecting physical demand for services from passenger vehicles in a recursive-dynamic CGE model. This new method is applied to the MIT Emissions Prediction and Policy Analysis Version 5 (EPPA5) model, a CGE model of the global economy (Babiker et al., 2001; Paltsev et al., 2005; Paltsev et al., 2010). The method captures the richness of the technological response at an appropriate level of detail, without sacrificing sectoral and regional coverage or the ability to capture the macroeconomic feedbacks that make this modeling system advantageous over other approaches.

The text is organized as follows. **Section 4.2** identifies the shortcomings of current practices for representing energy-intensive consumption at the household level in CGE models, including the representation of durable goods, and the rationale for a new approach. **Section 4.3** presents the new approach, divided into three parts. **Section 4.3.1** explains how the relationship between income and demand for vehicle services was parameterized using econometric information and implemented using the well-established Stone-Geary (quasi-homothetic) preference system. **Section 4.3.2** describes how vehicle engineering and fleet detail were used to parameterize the structure of the passenger vehicle transport sector and opportunities for fleet-level fuel efficiency improvement. **Section 4.3.3** describes the representation of alternative fuel vehicles. **Section 4.4** offers conclusions and directions for future work.

4.2 Bottom-Up Technology in Top-Down Models: Issues and Previous Work

4.2.1 Background on the CGE Modeling Approach

The CGE model structure is based on the circular flow of the economy in which households supply labor and capital to firms that produce goods and services, which are in turn purchased by households. The CGE model has its origins principally in neoclassical modeling developments and invokes microeconomic principles (Arrow & Debreu, 1954; Shoven & Whalley, 1984). Based on their endowments and preferences, one or more representative agents maximize utility subject to a budget constraint, while producers maximize profits, with production functions specified as constant returns-to-scale. A vector of prices and quantities for which demand equals supply (market clearance), household income equals expenditures (income balance), and the profits of firms are driven to zero (zero profit) comprises an equilibrium solution. The basis for CGE model calibration is typically National Income and Product Account data, which is used to develop a Social Accounting Matrix (SAM) that captures economic flows across all sectors in a single model benchmark year. The SAM has its origins in traditional input-output (I/O) analysis (Leontief, 1937). Many CGE models are written in the GAMS software system and may be formulated in the MPSGE programming language (Rutherford, 1999).

In the structure of a CGE model, elasticities of substitution represent the willingness or ability of households and firms to substitute among inputs to production or consumption in response to changes in input costs. The elasticity values are typically based on econometric evidence or other methods as appropriate (Arndt et al., 2002; Balistreri et al., 2003; Zhang & Verikios, 2006). Most CGE models also include some form of capital stock accounting, either using a putty-clay representation (Phelps, 1963; Lau et al., 2002) or a sector-specific capital vintaging structure (Paltsev et al., 2005).

4.2.2 A Common Challenge in CGE Modeling

A perennial challenge in the CGE modeling community has been how to forecast both expenditures and physical quantities consistently, especially in a dynamic model setting in which elasticities act over longer periods or agents' preferences change over time. The difficultly of maintaining consistency has been noted in previous research (see for example Sue Wing, 2006). Expenditure shares and elasticities are parameterized based on physical quantities, prices, and abatement costs in the benchmark year and are expressed in value terms. Expressing a quantity in value terms means that the benchmark year quantity is defined as the price multiplied by the quantity in that year and prices are normalized to unity. In future model years, however, pinning down the relationship among spending, physical goods purchased, and the impact on demand for efficiency-improving technologies can be difficult, since it requires assumptions about how these relationships will evolve over time.[17] The assumptions, if incorrect or unconstrained by the

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[17] An example of the introduction of thermodynamic efficiency in CGE models can be found in McFarland et al., (2004).

technical possibilities in the underlying system, can mislead analysts into territory unsupported by the laws of physics.

The problems that arise from imprecise physical accounting can be particularly pronounced in the case of complex, quality-differentiated consumer durable goods because forecasted expenditures must capture changes in demand for the service itself. The relationship between expenditures and service demand may change due to a variety of factors, including diversification of expenditures toward or away from the service of interest or changes in the attributes of the good that provides the services. Omitting such factors can produce misguided forecasts because the attributes of durable goods are defined in the benchmark year, and unless otherwise specified change only due to price-driven substitution among inputs. The total energy requirement may also be misestimated because trade-offs between fuel economy and other product attributes are often not well specified. Functional attributes can be energy saving—i.e. technology that decreases fuel consumption per mile—or energy intensive—i.e. technology that increases fuel consumption per mile, or possibly have no net effect on fuel consumption at all. Forecasting energy requirements is difficult when the model does not resolve how income and input costs (including fuel cost) affect physical demand for vehicle services and product attributes, and its relationship to household spending. This discomforting fact tarnishes the reputation of CGE models in the eyes of those that—rightly for many purposes—demand forecasts supported by a unique characterization of the physical system.

Nevertheless the task when selecting a model is to ask, which approach is best suited to the question at hand? For the case of energy-intensive durable goods purchased by the household such as vehicles, water heaters, and washing machines—which rely on diverse energy sources, depend closely on household income, and account for a significant fraction of household expenditures—CGE models offer important advantages in terms of sectoral coverage and their ability to capture macroeconomic feedbacks. However, the quality of insights depends in turn on whether or not models resolve adequately how policy interacts with the underlying engineering system, which requires modeling additional detail at the level of the vehicle, fuel, and user. Resolution at this level is essential to capture the impact of technology- and sector-specific energy and environmental policies, which may depend on evolving household spending patterns, act differently across capital vintages, or prompt choice from a range of technologies that reduce petroleum-based fuel use or GHG emissions.

4.2.3 Modeling Approaches: A Literature Review

Before describing the approach developed in this work, I briefly review the range of modeling approaches used to assess the impact of policy on consumption of energy-intensive durable goods. In developing models for energy and environmental policy analysis, researchers have tried various strategies to address the problem of how to simultaneously forecast physical and economic variables. One approach is to focus on the detailed physical system while holding exogenous macroeconomic variables (including in some instances prices) fixed, and forecast energy use (and technology adoption) using a cost minimization algorithm that takes policy, if imposed, as a constraint. By definition many macroeconomic models—including partial and general equilibrium models—encompass more than one market and capture the price changes that result from inter-market interactions. These models often sacrifice technological detail in the interest of generalizable insights and computational tractability, representing production and consumption activities in a deliberately simplified and aggregated fashion. Without additional structure it is impossible to determine, for instance, how demand for vehicle-miles traveled is changing with income and gasoline prices—only how much value services provided by the durable product are delivering to the economy.

One approach designed to preserve bottom-up technological detail without sacrificing macroeconomic feedbacks involves the coupling of highly aggregated macroeconomic models with detailed models of the physical system. An example for transport is the analysis by Schafer and Jacoby (2006), which coupled a top-down (CGE) model with a bottom-up (MARKAL) model and a mode share forecasting model to evaluate the impact of climate policy on transportation mode shares and technology adoption. Other examples of this approach have been implemented for the electric power sector (Sue Wing, 2006) and for aggregated production and consumption activities (Messner & Schrattenholzer, 2000).

Still other models construct a system of fleet and fuel use accounting to forecast the impact of technology scenarios (which are an input to the model). These scenarios may be carefully designed to achieve compliance with a particular policy target. Models in this category include the Sloan Automotive Lab U.S. Fleet Model as well as the International Energy Agency's global fleet model, which demonstrate the relative aggressiveness of different targets relative to baseline projections in terms of the degree of technological and/or behavioral change required to meet them (Bandivadekar et al., 2008; Fulton & Eads, 2004).

However, all of these approaches—and the CGE approaches in particular—are not generally capable of tracking both the economic and physical variables simultaneously and consistently within a single model framework. A review of the models in **Table 4.1** reveals that few existing CGE models treat energy-intensive durable goods explicitly in household consumption—here we focus on the example of passenger vehicle transport. Of the models included in Table 4.1, only the MIT EPPA model and the ADAGE model (which follows the EPPA formulation) disaggregate transport services and explicitly represent the fuel input to passenger vehicle transportation in the household consumption bundle (Paltsev et al., 2005).

To be fair, most CGE models were not designed to produce technology-rich forecasts for specific sectors. Many global CGE models are instead focused on analysis of the impacts of macroeconomic policy on production, consumption, and trade flows among regions. For other policies, particularly sector-specific policies that target attributes such as embodied energy efficiency, producing consistent forecasts of the economic and physical variables is more challenging. This work develops a new method that largely addresses this challenge.

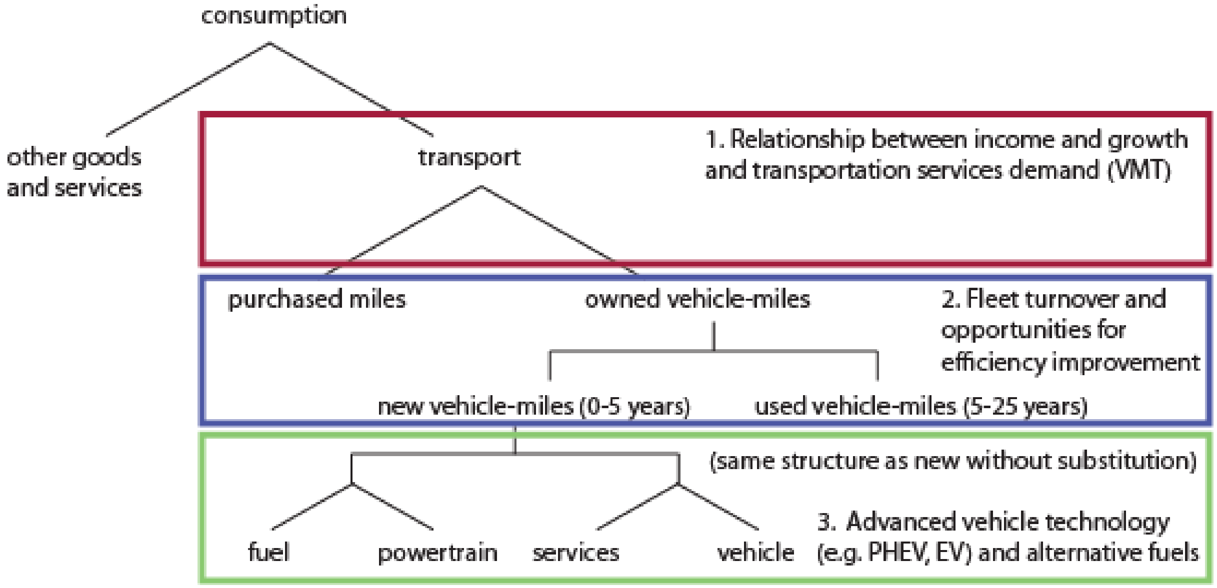
4.2.4 Modeling Approach

With the above challenge in mind, I develop a model of passenger vehicle transport that introduces constraints on forecasts of economic and physical variables by implementing a technology-rich model structure and parameter calibration. The new model developments can be grouped into three categories, and are shown graphically in **Figure 4.1**.

First, the model captures how expenditures on passenger vehicle transport will change with per capita income, as consumers increase their vehicle holdings and travel more miles according to their travel needs. The income elasticity of demand for VMT has been shown to vary with per capita income, geography, availability of substitute modes, and other factors. To account for this variation I estimate country- or regional-level income elasticities of demand for VMT. I implement these elasticities in the CGE framework using quasi-homothetic (Stone-Geary) preferences.

Second, I add new structure to the vehicle sector that separately describes miles traveled in new and used vehicles as well as the response of new vehicle fuel efficiency to fuel price changes or policy mandates. These features are important because they allow the analysis of policies focused only on new vehicles, capture the impacts that technology adoption will have on the overall efficiency characteristics of the fleet, and reflect regional differences in average vehicle age, new vehicle investment, and vehicle retirement patterns. The new structure also captures the relationship between vehicle attributes and per-mile fuel consumption, as well as how per-mile fuel consumption of the fleet responds to changing fuel prices through demand response and investment in efficiency-improving technology.

Fig. 4.1 Schematic overview of the passenger vehicle transport sector incorporated into the representative consumer's utility function of the MIT EPPA model.[18] New developments are highlighted on the right-hand side of the utility function structure.



Third, I represent opportunities for reducing GHG emissions and fuel consumption through the adoption of alternative fuel vehicles. Alternative fuel vehicles are then implemented to compete directly with the internal combustion engine (ICE)-only vehicle. These advanced "backstop" technologies are parameterized using current and future cost estimates based on engineering data and projections.

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[18] Other CGE models also employ a similar household consumption structure.

Table 4.1 Comparison of several computable general equilibrium (CGE) models applied to energy and environmental policy analysis.

Model	Home	Coverage	Calibration data and year	Perfect foresight ?	Treatment of link to physical quantities in transport sector	Documentation
Applied Dynamic Analysis of the Global Economy (ADAGE) Model	RTI International	Global, individual country, U.S. regional	GTAP, IMPLAN, IEA/EIA 2010	Yes	No explicit physical accounting in transport sector	Ross et al., 2009
Inter-temporal General Equilibrium Model (IGEM)	Harvard University	U.S.	Jorgenson (1980) approach integrates capital accounts with the National Income Accounts	Yes	No explicit physical accounting in transport sector	Goettle et al., 2007
GTAP in GAMS	University of Colorado	Global	2001	No	No explicit physical accounting in transport sector	Rutherford, 2005
Global Trade and Environment Model (GTEM)	Australian Bureau of Agricultural and Resource Economics	Global	GTAP6, IEA 2001	No	No explicit physical accounting in transport sector	Pant, 2007
Policy Analysis based on Computable Equilibrium (PACE)	University of Mannheim	Global	GTAP-EG 1997	No	No explicit physical accounting in transport sector	Böhringer et al., 2004
G-Cubed Model	Brookings and University of Texas at Austin	Global (8 regions)	BEA, BLS (for U.S.), Int’l I/O tables	Yes	No explicit physical accounting in transport sector	McKibben & Wilcoxen, 1998
MESSAGE-MACRO	International Institute for Applied Systems Analysis	Global		No	No explicit physical accounting in transport sector	Messner & Schrattenholzer, 2000
MIT Emissions Prediction and Policy Analysis (EPPA) model	MIT Joint Program on the Science and Policy of Global Change	Global	GTAP7 2004	No	Transport services disaggregated in household consumption but limited physical accounting	Paltsev et al., 2005
US REP Model	MIT Joint Program on the Science and Policy of Global Change	U.S. regional	GTAP7, IMPLAN 2004	No	Transport services disaggregated in household consumption but limited physical accounting	Rausch et al., 2010

The model used to illustrate this three-part approach for the case of passenger vehicle transport is the MIT Emissions Prediction and Policy Analysis model (listed in Table 4.1). The EPPA model is a recursive-dynamic general equilibrium model of the world economy developed by the MIT Joint Program on the Science and Policy of Global Change. The EPPA model represents production and consumption activities as Constant Elasticity of Substitution (CES) functions (or the Cobb-Douglas and Leontief special cases of the CES).[19] A detailed description of the model can be found in **Appendix A**. Earlier development of this model disaggregated household vehicle transport and added detail to represent alternative fuel vehicles (Paltsev et al., 2004; Sandoval et al., 2009; Karplus et al., 2010).

4.3 Modeling Approach

The approach to modeling passenger vehicle transport is described here in a manner that is intentionally not specific to the MIT EPPA model. The goal is to provide an approach that can be easily adapted to a variety of CGE modeling environments. In instances where specific features of the EPPA model are involved, they will be explicitly described. The next three sub-sections provide a detailed description of the three-part modeling approach, working from top to bottom through the changes to the utility function described in Figure 4.1.

4.3.1 Development 1: Income Elasticity of Demand for Vehicle-miles Traveled (VMT) in a CGE Framework

The objective of the first model development is to introduce an income elasticity of demand for vehicle transport services that differs by model region. In a CGE model the relationship between total household expenditures and spending on passenger vehicle transport is defined by an expenditure share, or the fraction of total expenditures devoted to services provided by passenger vehicles. Typically CGE models assume homothetic preferences, with the result that expenditure shares do not change as a function of income—in other words, the income elasticity of demand is equal to unity. For some goods—particularly goods that fulfill a basic need such as food, transport, or shelter—it is important to consider how this expenditure share will change as a function of income. Capturing this trend is important because in reality the

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[19] Formulation as a Mixed Complementarity Problem in the Mathematical Programming Subsystem for General Equilibrium (MPS/GE) facilitates parsimonious model representation as well as provided an efficient solution method (Rutherford, 1999).

expenditure share devoted to vehicle transport in a region is nonexistent or small when only a few households own vehicles, but grows as vehicle ownership comes within reach of an ever larger fraction of households.

4.3.1.1 Income Elasticity of Demand for VMT: Empirical Evidence

To add empirical foundations to the new model structure, this work builds on previous studies that have attempted to measure how the household vehicle transport expenditure share and vehicle ownership vary over time and with per capita GDP (Schafer & Victor, 2000; Meyer et al., 2007; Dargay et al., 2007). Trends in vehicle ownership and the total household transport expenditure share[20] in developed countries since the early twentieth century suggest that the expenditure share devoted to transport increases from 5% to 15% as vehicle ownership increases from zero to 200 cars per 1000 capita and then stays roughly constant thereafter (Schafer, 1998). Other studies have projected vehicle ownership using Gompertz models (in which the relationship between per capita income and vehicle ownership is modeled with a sigmoid equation) as well as economic approaches based on empirical demand system estimation.[21]

Since this work focuses on the United States in a global context, significant effort was made to obtain the best available estimates of income elasticity of demand for vehicle-miles traveled using detailed U.S. data. The long-run rates of growth in spending on passenger vehicle transportation and of growth in VMT in the United States are shown in **Figure 4.2.** Over the period considered (1970-2007), spending on passenger vehicle transportation increased at an average compounded growth rate of 3.9% per year, while VMT increased by 2.7% per year.[22] The number of vehicles has grown at 2.3% per year, while growth in vehicle-miles traveled has averaged around 0.4% per year. This graph provides evidence that CGE models, which rely on exogenous gross domestic product (GDP) paths and fixed expenditure shares, are likely to

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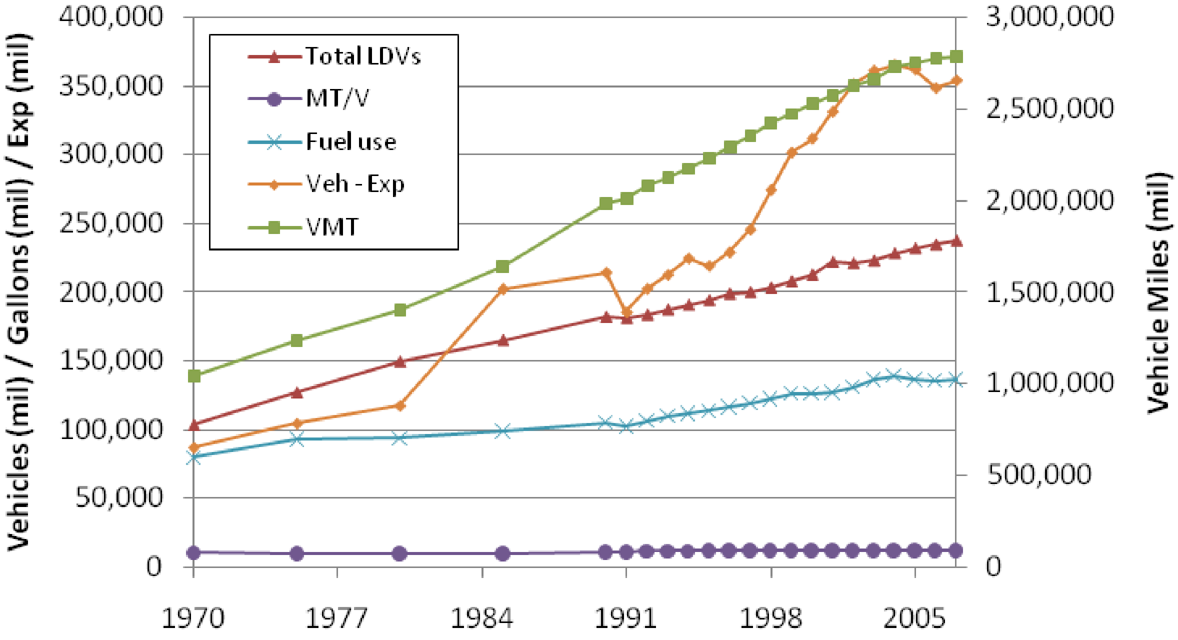
[20] The total household transport expenditure share includes expenditures on vehicle ownership as well as purchased transport modes, such as rail, road, aviation, and marine.

[21] Dargay et al. (2007) estimates a model that relates per capita GDP to long-term income elasticities, and includes a term that accounts for a country-specific vehicle ownership saturation level. Meyer et al. (2007) compare projections using a Gompertz approach and a Stone-Geary based approach. In this study we are interested in the elasticity of demand for vehicle services (VMT), not only vehicle stock. If the number of miles-traveled per vehicle changes with per-capita income and vehicle stock, income elasticities of vehicle ownership may not be a good proxy for income elasticities of VMT demand.

[22] Part of this discrepancy can be explained by an increase in the average real vehicle price over the same period of around 2% per year (Abeles, 2004), which reflects the changes in the aesthetic and functional attributes of the vehicles themselves. A brief review of this trend is provided in **Appendix A**.

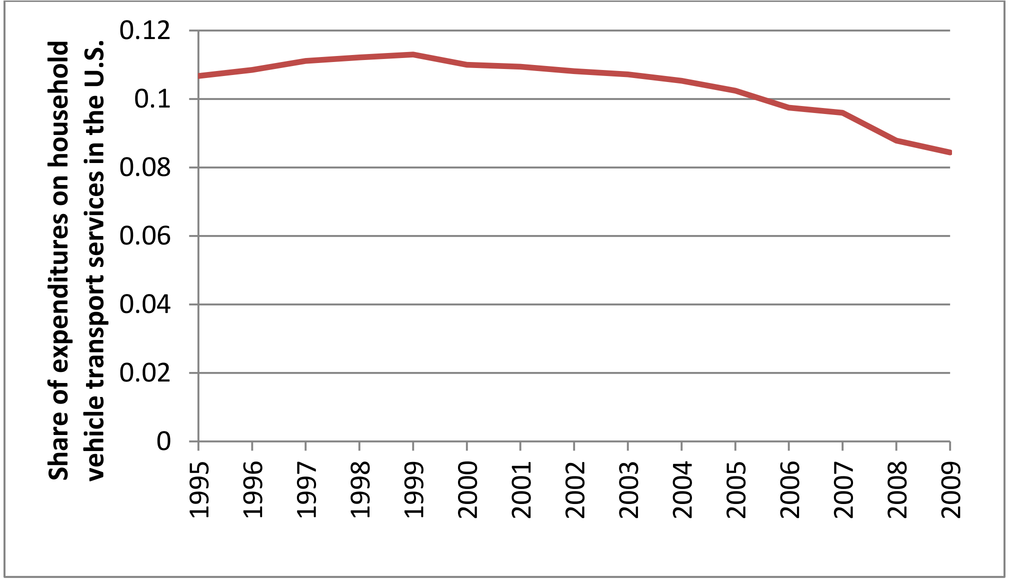
underestimate or overestimate VMT growth if they do not consider explicitly how expenditure shares may changes with income.

Fig. 4.2 Long-run trends in the growth of expenditures on vehicle transport, VMT, vehicle ownership, gasoline usage, and miles-traveled per vehicle in the United States.



Source: U.S. Census Bureau, 2009; Davis et al., 2009.

Fig. 4.3 The share of real household expenditures on passenger vehicle transport over the past 15 years.



Source: BEA, 2010.

This observation is consistent with other empirical estimates of the income elasticity of demand, which have been estimated to range from 0.3 (short run) to 0.73 (long run) (Hanly et al., 2002).[23] This is reflected in the declining share of real expenditures on vehicle transport services, shown in **Figure 4.3** (BEA, 2010).

4.3.1.2 Forecasting Passenger Vehicle Transport Services in a CGE Framework

Calibrating the income elasticity of demand for transport services in a CGE model presents several challenges. CGE models assume a form of preferences that governs the consumption activities of households. The most common form, homothetic preferences, provides a clean and simple structure that requires minimal parameter assumptions.[24] As mentioned, in this preference system, the shares of consumption activities in total spending are assumed to remain constant as income increases (expansion path through the origin with slope of unity).

Generically speaking, the problem is that many categories of expenditures—for example, food, clothing, and vehicles—do not increase uniformly with income, either in terms of the share of total consumption expenditures or in natural units.[25] As a result, expenditures on passenger vehicle transport may not be tightly correlated with VMT beyond the base year, although historical evidence indicates that they tend to move in the same direction. The modeling challenge is to develop a structure that captures both changes in the underlying input prices (and thus cost of providing transport services) as well as changes in the income elasticity of demand for the service itself (in this case, VMT), which together determine the relationship between passenger vehicle transport expenditures and vehicle-miles traveled.

The cornerstone of this part of modeling strategy is a relationship defined in the benchmark year between spending on VMT (denoted here as $VMT\text{-}\$$) and the quantity of VMT in its natural units (denoted here as $VMT\text{-}Q$). The output of passenger vehicle transport in value terms over time can thus be interpreted using this benchmark year relationship, which is shown in **Equation 4.1**. In this equation, $c(p_i, \sigma_i)$ refers to the cost-per-mile of driving, which is used to

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[23] This estimated income elasticity of demand for VMT represents the role of income as distinct from price (and other region-specific) effects.

[24] The constant elasticity of substitution (CES) utility function (including the special case of the Cobb-Douglas utility function) gives rise to homothetic preferences, which means that the ratio of goods demanded depends only on their relative prices, and not on the scale of production (constant returns to scale).

[25] In CGE models the energy-intensive activities that rely on an underlying capital stock are modeled in terms of the levelized cost of providing the service, assuming a time cost of money to obtain the rental value of capital across the full ownership horizon. This approach is described in detail for other sectors in the EPPA model in Paltsev et al., 2005.

determine $VMT\text{-}\$$ in the benchmark year. In each subsequent model period the expenditure share of $VMT\text{-}\$$ is determined using the income elasticity of demand, while underlying changes in input costs p_i and the substitution elasticities σ_i in region i influence the price and level of output. Substitution elasticities reflect how an increase in the price of one input results in compensating shifts to rely on other inputs, and the calibration of relevant elasticities is described later in **Section 4.3.2**.

$$VMT\text{-}\$ = VMT\text{-}Q * c(p_i, \sigma_i) \qquad \textbf{(4.1)}$$

Forecasted $VMT\text{-}Q$ can be calculated by dividing the value of sector output at each five-year interval by the cost-per-mile and the relative price of output (which has been normalized to unity in the base year). The number of vehicles on the road is calculated using the non-powertrain capital input, which provides an index for vehicle stock growth.

The main advantage of this method is that it allows the expenditure share to be determined uniquely in each five-year time step as a function of the income elasticity of demand for VMT (vehicle transport services). By defining the expenditure share in terms of $VMT\text{-}Q$ and underlying cost per mile, the income elasticity of demand for VMT can be applied directly to capture changing demand for vehicle services (VMT), vehicles, and energy use. This improves on previous approaches, which often do not account for income-dependent variation in the vehicle transport budget share over time.[26] The practical result of this approach, which I will describe in the following paragraphs, is to produce more realistic and empirically-based forecasts of spending on passenger vehicle transport services over time.

4.3.1.2 Implementing Income Elasticity of Demand as a Function of Per capita Income

In order to implement this approach in a CGE framework, a different, quasi-homothetic preference relationship is used to define the household utility function and demand for passenger vehicle transport services—implemented at the level of the top (red) box in Figure 4.1—to allow

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[26] A careful reader might raise the question of how the new structure accounts for improvements in vehicle attributes that deliver more value to the consumer and could thus lead to an increase in the vehicle price over time. The model structure is designed to capture net changes in energy-savings versus energy-intensive attributes that have implications for vehicle travel.

the calibration of an income elasticity of demand for VMT that differs from unity and changes as a function of per capita income. The following section describes the procedure in detail.

Stone-Geary preferences are a well-known formulation of the utility function that capture the intuition that a subsistence level of consumption in one or both goods must be satisfied before demand for each good will increase according to its respective marginal utility. In emerging markets where vehicle transport demand is growing rapidly, the income elasticity of demand for vehicle transport in the base year is likely to be greater than 1. Developed countries are assumed to be in the advanced (flattening) part of the curve that relates per capita income to level of vehicle ownership and demand for miles-traveled per vehicle (Meyer et al., 2007; Dargay et al., 2007).

Stone-Geary preferences are implemented in the CGE framework in the following manner. The basic logic involves computation of the "subsistence consumption level" for the good of interest (which can be recovered from base year expenditure share and consumption data), subtracting the quantity from benchmark consumption, and specifying this consumption level as a negative endowment for the consumer (Markusen, 1995). Here I present the derivation of the minimum consumption level and its relationship to the income elasticity of demand for vehicle transport services.

The Stone-Geary utility function for goods A and is B given by **Equation 4.2**:

$$U(A,B) = \alpha \ln(A - \bar{\mathrm{A}}) + (1-\alpha)\ln(B) \qquad \textbf{(4.2)}$$

The variable $\bar{\mathrm{A}}$ represents the minimum consumption level (or the level of expenditure when utility is equal to zero). Goods A and B have prices p_A and p_B, and α represents the share of spending on good A. Similar to the constant elasticity of substitution (CES) utility function, all Engel curves (the expansion path of utility as a function of income) are linear, but unlike the case of CES or Cobb-Douglas preferences, they do not have to go through the origin. Expenditures exceeding the subsistence level of consumption for each good are allocated according to CES preferences. We derive the demand functions as follows by maximizing the utility function in Equation 4.2 subject to the constraint that income must be fully allocated to expenditures on goods A and B.

The demand functions for goods A and B are shown in **Equation 4.3a** and **4.3b**, respectively:

$$A = \bar{A} + \alpha \frac{I - p_A \bar{A}}{p_A} \tag{4.3a}$$

$$B = (1 - \alpha) \frac{I}{p_B} \tag{4.3b}$$

The income share of good A (left-hand side) derived by rearranging **Equation 4.3a** is given by **Equation 4.4**:

$$\frac{p_A A}{I} = \bar{A} + (1 - \alpha) \frac{\bar{A} p_A}{I} \tag{4.4}$$

By rearranging this equation for A, differentiating A with respect to I, and multiplying the derivative times the expression for $\frac{I}{A}$, gives an expression for income elasticity of demand (**Equation 4.5**):

$$\eta_A = \frac{I}{A} \frac{dA}{dI} = \frac{I\alpha}{\alpha I + (1 - \alpha) \bar{A} p_A} \tag{4.5}$$

Rearranging the above equation for $\bar{A}$, the subsistence level can be calculated as shown in **Equation 4.6**:

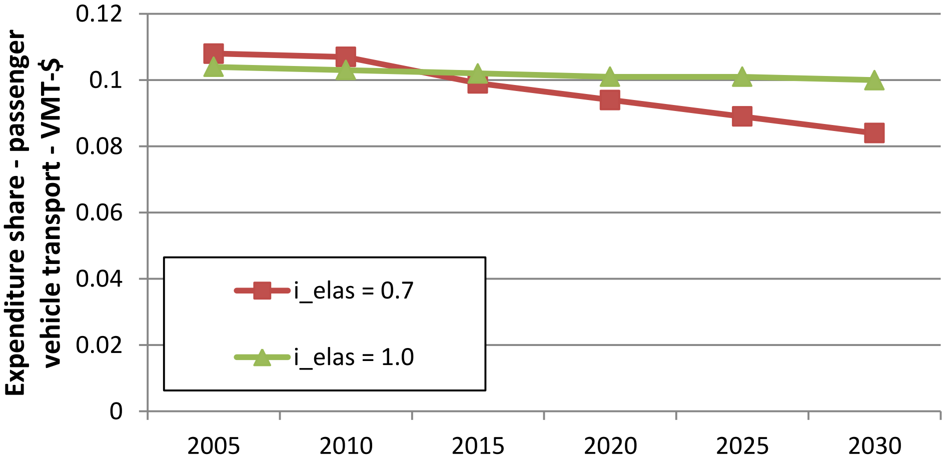
$$\bar{A} = \frac{\alpha I (1 - \eta_A)}{(1 - \alpha) \eta_A} \tag{4.6}$$

The variable α represents the share of passenger vehicle transport in household consumption, I is total household consumption expenditures, and η_A is the income elasticity of demand (which could, if desired, be indexed by t). The subsistence demand $\bar{A}$ is specified as a negative endowment for the household, and subtracted from the passenger vehicle transport nest in the utility function.

The income elasticity of demand for passenger vehicle transport can be updated over time by calculating a new subsistence level (A_t), which is then used in the solution of the model (although initial model runs assume that the income elasticity of demand is constant and less than or equal to 1). Although some discrepancy will always exist between the specified η_A (used to calculate the subsistence expenditure) and the observed η_A (calculation based on model outputs), the discrepancy is the result of price effects and substitution effects within the model. The input elasticities are defined based on empirical estimates that attempt to separate the effect of income on demand for vehicle services from price and other effects, while output elasticities reflect the combined influence of income and price effects over time. The effect of changing the input income elasticity of demand for VMT-\$ in the United States from 1 to 0.70 is shown in **Figure 4.4**. The expenditure share of passenger vehicle transport declines slightly even when the income elasticity is equal to 1 because of substitution allowed between services supplied by purchased transport and passenger vehicle transport. Modest increases in fuel prices over the same period increase the relative price of vehicle transport services, inducing a weak shift to other modes.

Fig. 4.4 The effect of changing the specified income elasticity of demand in the United States in the MIT EPPA model from 1 to 0.70 in the reference (No Policy) case on a) expenditures share for passenger vehicle transport and b) growth rates for VMT, vehicles, refined oil demand, and per capita income through 2030.

a)



b)

Input income elasticity values	Compound annual growth rate, 2005 to 2030				Output income elasticity of demand for VMT
	Refined oil	Vehicle ownership	VMT	Per capita income	
η_A = 0.7	0.9%	1.1%	1.2%	1.5%	0.58
η_A= 1	1.7%	1.9%	2.0%	1.4%	1.17

A description of the data sources used to calibrate income elasticities of demand in the 16 EPPA model regions, the full derivation of relevant equations, and an analysis of sensitivities to income elasticity of demand assumptions are described in **Appendix A**.

4.3.2 Development 2: Modeling Opportunities for Vehicle Efficiency Improvement

Investment in vehicle fuel efficiency provides one option for reducing fuel use and associated expenditures in response to an increase in fuel prices. This investment can take the form of improvements to existing ICE-only vehicles, or the adoption of alternative fuel vehicles (AFVs, discussed in **Section 4.3.3**). Often vehicle efficiency improvements are modeled using exogenous engineering projections to specify a rate of efficiency improvement over time, without considering the role of fuel prices or any trade-offs in vehicle attributes required to achieve efficiency improvements. For instance, vehicle downsizing decreases vehicle size and weight, attributes that the consumer may value and may be unwilling to forego in favor of fuel savings. Moreover, policies that set different vehicle fuel economy targets or that result in fuel price increases are likely to affect investment in existing vehicle fuel economy and in alternative fuel vehicles (AFVs). Model developments implemented here aim to capture endogenously the underlying relationships among policy, fuel prices, and consumer investment in fuel economy.

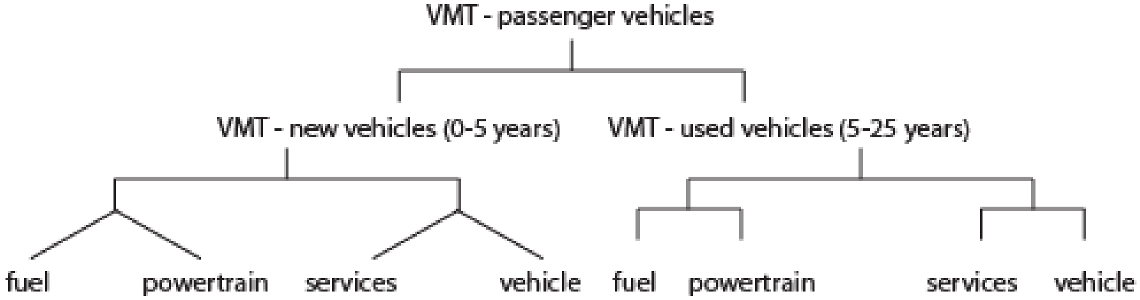
The extent to which fuel efficiency improvements translate into direct reductions in fuel use depends primarily on two factors—the rate of fleet turnover (the net of sale of new vehicles and scrappage of old vehicles, which is limited to a fraction of the total fleet each year), and the willingness of manufacturers to produce—and consumers to invest—in more fuel efficient vehicles as fuel prices rise. A new structure of the passenger vehicle transport sector was introduced to simulate both of these constraints on raising the average efficiency of the vehicle fleet. Here I consider only incremental improvements to existing vehicles. Development 3 (**Section 4.3.3**) involves introducing alternatives to today's gasoline-powered ICE.

4.3.2.1 Opportunities for vehicle efficiency improvements: New sector structure

To model the technological opportunities for improving vehicle efficiency in a manner consistent with engineering and related cost (bottom-up) data, a new structure was introduced into the passenger vehicle transport sector. The guiding intuition for the new structure was the need to model the fuel and base vehicle as complementary goods, while allowing for investment in fuel efficiency in response to changes in fuel price.

A schematic representation of the split between VMT from new and used vehicles is shown below in **Figure 4.5**. This new structure fits into the utility function in the second level (blue) box shown in Figure 4.1. The new sector structure for new (zero to five) year old vehicles is shown in Figure 4.5a. The structure of the used vehicle sector is the same, but with a fixed (Leontief) structure to reflect the fact that efficiency characteristics have been determined in earlier periods. The main departure from past approaches is to separate the powertrain efficiency cost component from a base vehicle capital cost component. Initially, I assume that the base vehicle capital cost component (which captures a range of energy-neutral vehicle attributes) of driving one mile remains constant in mature vehicle markets (i.e. the United States) and represents the capital expenditure on an average vehicle absent the powertrain, while the powertrain capital cost component trades off with fuel expenditures as determined by an elasticity of substitution between fuel and powertrain capital ($\sigma_{F,K_{PT}}$).[27] The balance of powertrain capital cost and fuel cost reflects the relative mix of energy-saving and energy-intensive technology implemented in the average U.S. vehicle in the initial model calibration year, 2004. The substitution elasticity between fuel and vehicle capital determines how investment in vehicle efficiency responds to fuel price changes. Parameterization of this key elasticity will be discussed later in this section and in **Appendix A**.

Fig. 4.5 Structure of the passenger vehicle transport sector, illustrating the separation of VMT provided by new and used passenger vehicles and the underlying sector structure.



4.3.2.2 Modeling Fleet Turnover Using a Two-vintage Approach

The approach to fleet turnover taken here is essentially to model the miles-traveled by vehicles divided into two vintages: a “new” vehicle vintage (zero- to five-year-old vehicles) and a “used” vehicle vintage (over five years old). The used vehicle fleet is in turn characterized by four sub-vintages, which have unique average efficiencies and reflect the differential

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[27] Non-price changes in consumer preferences for energy-intensive (horsepower, vehicle weight) and energy-saving (downsizing, higher fuel efficiency) vehicle attributes could be reflected in exogenously-imposed shifts in the relative shares of spending on fuel or on fuel efficiency, respectively.

contributions to VMT. Older vehicles tend to be less efficient (especially if regulations force new vehicle efficiency to improve), and are also driven less. The two-vintage structure has several advantages: 1) it allows detailed vehicle efficiency, driving, and fleet turnover data to be used in regions where available, 2) it provides a simple representation of stock turnover that can be parameterized with minimal data in regions where data is not available, and 3) it is consistent with the EPPA structure, which uses five-year time steps.

The rate of vehicle stock turnover limits how fast new technology can be adopted into the in-use vehicle fleet. Even the most inexpensive, off-the-shelf technologies will be limited by the rate of fleet turnover since they are mostly applied in new vehicles sold (as opposed to being used to retrofit existing vehicles). The differentiation of vehicle services according to age (vintage) introduces a first constraint on the rate of adoption of new technologies. A new technology can only be applied to zero- to five-year-old vehicles that provide the new vehicle transport services.

The preservation of efficiency characteristics in vehicles as they age is an important function of the vintaging structure. In each period the efficiency characteristics assumed for the new vehicles are passed to the first vintage of the used fleet, characteristics of the first vintage of the used fleet is passed to the second, and so forth. The fifth (oldest) vintage (vehicles 20 years old or more) from the previous period is scrapped. In a CGE model efficiency characteristics are captured in the underlying cost shares, which are handed off from one vintage to the next (see Paltsev et al., 2005 for more detail on capital vintaging in the MIT EPPA model). In the model only the values of capital services provided by the new and used vehicle fleet are represented explicitly. The shares for the used fleet represent the average of the shares for the surviving vintages, weighted by the share of miles they contribute to total used VMT according to **Equation 4.7**:

$$\theta_{i,used\ in\ t} = \left(\frac{M_{V=1,t}}{M_{used}}\right)\theta_{i,V=1,new\ in\ t-1} + \sum_{V=2}^{4}\left(\frac{M_{V,t}}{M_{used}}\right)\theta_{i,V,used\ in\ t-1} \qquad \textbf{(4.7)}$$

In this equation θ are the expenditures shares for each input i to a used vehicle vintage V in period t. The coefficients in front of each term on the right-hand side of the equation represent the mileage shares of each vintage in the used fleet, where $M_{V,t}$ corresponds to the vehicle-miles driven by each of the four used vintages V in period t, and M_{used} corresponds to total miles driven by the used vehicle fleet.

Representing the contributions of new and used vehicles to passenger vehicle transport has several advantages over previous approaches. First, it constrains the rate at which new technology can be adopted in the vehicle fleet, adding realism to projections. Second, it allows for the simulation of vintage-differentiated policies (e.g. policies that bear on technology choices in the new vehicle fleet only, such as the Corporate Average Fuel Economy (CAFE) standard in the United States). Third, it can provide insight into the impact of policies on fleet turnover, for example, if consumers respond by substituting between usage of new and used vehicles, which may differ in terms of their efficiency.

4.3.2.3 Fuel Efficiency Response to Fuel Price in New Passenger Vehicles

Advanced vehicle technology will predominantly affect fuel use and GHG emissions through its installation in new vehicles. Econometric studies have documented that consumer demand for fuel efficiency in new vehicles responds to fuel prices (Klier & Linn, 2008). A model therefore needs to capture how policy signals induce consumers and manufacturers to respond by increasing vehicle fuel efficiency at different levels of policy stringency.

The modeler faces a decision about how to parameterize the elasticity of substitution between fuel and vehicle powertrain capital. Passenger vehicle transport is essentially a production function for VMT that enters directly into the representative agent’s utility function. A perfectly rational economic agent will respond to rising fuel costs by investing in efficiency improvements according to the cost-effectiveness of technologies, starting with the solution that offers reductions at the lowest marginal cost of abatement. This willingness to substitute capital to reduce fuel consumption is captured by the elasticity of substitution, $\sigma_{F,K_{PT}}$ in Figure 4.5.

To estimate $\sigma_{F,K_{PT}}$ the approach adopted here stems from a method previously used in CGE models to parameterize substitution elasticities using bottom-up data. I construct a marginal abatement cost curve for vehicle fuel use reduction, following previous work (Hyman et al., 2002). By identifying the piece cost (or direct manufacturing cost, before retail margins are included) of various abatement technologies and the associated reduction in fuel consumption (on the vehicle level), it is possible to gain a sense of the order in which these technologies would be adopted in different vehicle segments. Together with appropriate assumptions about maximum adoption rates in various size and weight classes that comprise the passenger vehicle fleet, it is possible to order the potential contribution of individual technologies to total reduction in gasoline use at the fleet level according to cost per gallon of gasoline displaced. The composition of the vehicle fleet used to estimate technological potential and the associated costs of each technology must be specified at a particular point in time. A technology-cost curve thus reflects a static picture of fuel or GHG emissions reductions that could be achieved at given an increase in fuel cost, in this case for the benchmark year 2004. Following Hyman et al. (2002), it is possible to derive a relationship between the price elasticity of demand for fuel required per mile and the elasticity of substitution between fuel and vehicle powertrain capital:

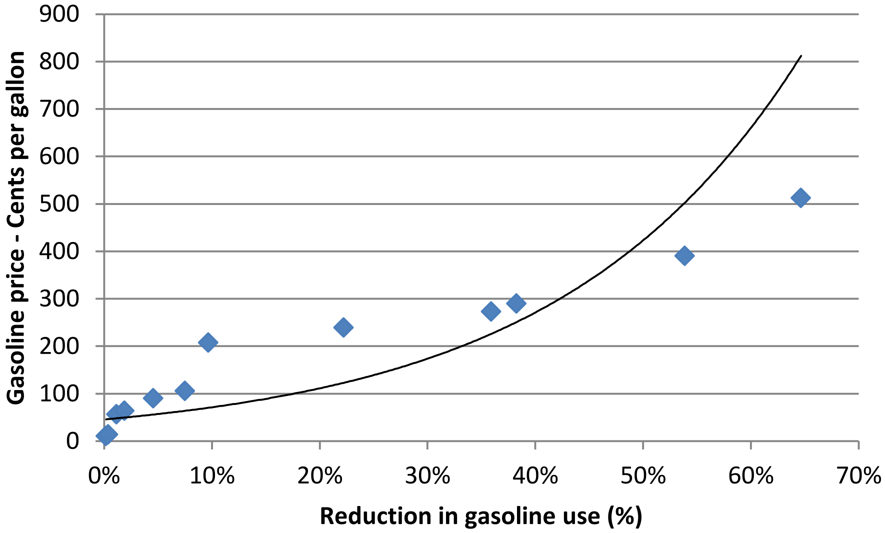
$$\sigma_{F,K_{PT}} = -\frac{\epsilon_{\mathrm{F,PF}}}{1-\alpha_{\mathrm{F}}} \tag{4.8}$$

As before α is the expenditure share for the primary good of interest—in this case, the per-mile fuel requirement. The elasticity of demand for fuel can be found by fitting an exponential function to the empirically-derived ordering of reductions according to cost. The composite curve for all passenger vehicles is shown in **Figure 4.6**. The fitted parameters are related to the elasticity of supply of GHG emissions abatement. Given that total output of the fuel-powertrain capital nest is fixed by the Leontief (zero) substitution assumption in the upper nest in the structure (intuitively, a base vehicle will start from some fixed combination of fuel and fuel abatement), the elasticity of supply of abatement technology is identically equal to the elasticity of demand for fuel (for a full derivation see **Appendix A**). Using **Equation 4.8** and the value of the expenditure share on fuel in the fuel-powertrain capital bundle, it is straightforward to obtain $\sigma_{F,K_{PT}}$, the elasticity of substitution.

Care was taken when constructing the engineering-cost relationship associated with increases in vehicle fuel efficiency to ensure that mutually exclusive technology trajectories were not included. For example, the engineering-cost curve for today's ICE-only vehicles is intended to capture incremental changes to the internal combustion engine that include hybridization, ICE turbo-charging and downsizing (TCD), as well as dieselization. However, since TCD and dieselization represent a mutually exclusive technology trajectories (while, by contrast, hybridization and TCD could be complementary), only the most cost-effective path was included (in this case, hybridization and TCD). A similar procedure is applied to estimate the engineering-cost curve for light-trucks as well as for alternative powertrains. Differences in the cost-effectiveness of the technology across vehicle market segments were considered in the estimation of total fuel reduction potential.

Fig. 4.6 Marginal abatement cost curves for passenger vehicles in 2011, with a) marginal cost of reducing fuel use through application of technology graphed against cumulative fuel use reduction, b) the table of cost-effectiveness values from EPA (2010b) used to parameterize the curve, and c) estimated values of the substitution elasticity and related variables for each curve.

a)



b)

Technology	Cumulative % gasoline reduced	Cents per gallon displaced
Low friction lubricants (Light Trucks)	0.2%	10
Low friction lubricants (Cars)	0.4%	14
Engine friction reduction (Cars)	1.2%	56
Engine friction reduction (Light Trucks)	1.9%	63
Stop-Start Hybrid (Light Trucks)	4.6%	90
Stop-Start Hybrid (Cars)	7.5%	106
Turbo-Downsize (Light Trucks)	9.7%	208
2-Mode Hybrid (Light Trucks)	22.2%	239
2-Mode Hybrid (Cars)	35.9%	273
Turbo-Downsize (Cars)	38.3%	290
PS Electric Hybrid (Cars)	53.9%	390
PS Electric Hybrid (Light Trucks)	64.7%	512

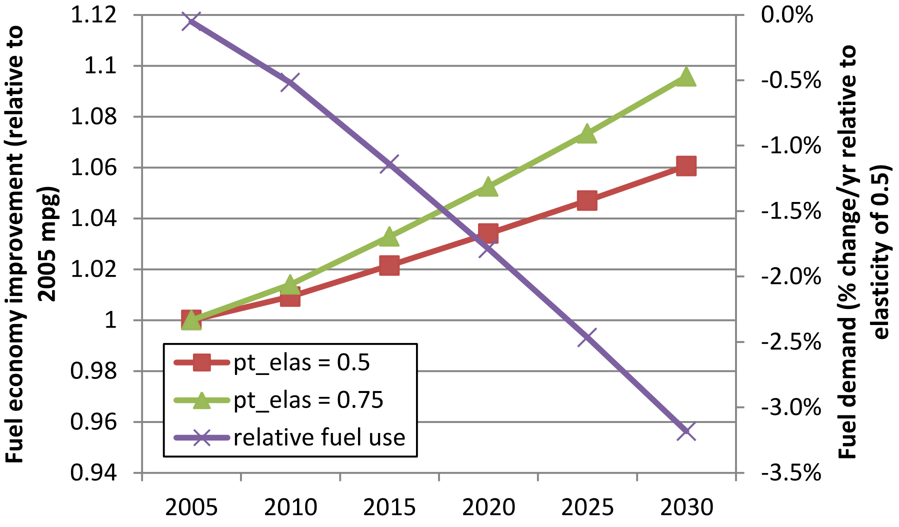
c)

Variable	Estimate
σ	0.73
ϵ_D	-0.225
β	4.449
θ	0.70

Source: EPA, 2010b.

An initial range of estimates for $\sigma_{F,K_{PT}}$ obtained from the calibration exercise was 0.5 to 0.76 (see **Appendix A**). By implementing these two alternative parameter values in the EPPA model, total fleet fuel economy and the discrepancy in fuel use over time were simulated in the absence of policy as shown in **Figure 4.7**.

Fig. 4.7 Simulated improvement in the vehicle fleet fuel economy (both new and used vehicles) and total fuel use using alternative elasticities of substitution (pt_elas) between fuel and powertrain capital in the MIT EPPA model in a reference (no policy) scenario.



The parameterization of shares and the elasticity of substitution assume that the production and adoption of more efficient vehicles will respond to fuel cost given a particular consumer discount rate. In the MIT EPPA model, the discount rate used is 4 percent; other models may assume slightly higher or lower rates. As such it reflects the decision of a rational manufacturer responding to a rational consumer—i.e. each is indifferent between $1 of expenditures today and $1 of future discounted expenditures. Our analysis initially proceeds based on the lower discounting assumption (4%). However the new model structure allows this assumption to be relaxed in order to simulate higher discount rates, which have been observed in the econometrics literature (Hausman, 1979; Allcott & Wozny, 2010) (see **Chapter 6**).

4.3.3 Development 3: Representation of Alternative Fuel Vehicles

Alternative fuel vehicles (vehicles that run on fuels other than conventional petroleum-based fuels, such as gasoline and diesel) have been advocated as a breakthrough that will enable reductions in fuel use beyond those attainable with incremental improvements to ICE-only vehicle technology. These vehicles are often the target of public policy initiatives aimed at achieving reductions in both petroleum consumption and GHG emissions. These vehicles include electric and plug-in hybrid electric vehicles (EVs and PHEVs), compressed natural gas vehicles (CNGVs), and hydrogen fuel cell electric vehicles (FCEVs). These vehicles currently cost more to purchase than an ICE-only vehicle of comparable size and performance, but could offer fuel savings relative to ICE-only vehicles, depending on gasoline prices, which lead to a wide range of current estimates and forecasts of total ownership costs. Below I describe how AFVs are represented in the EPPA model.

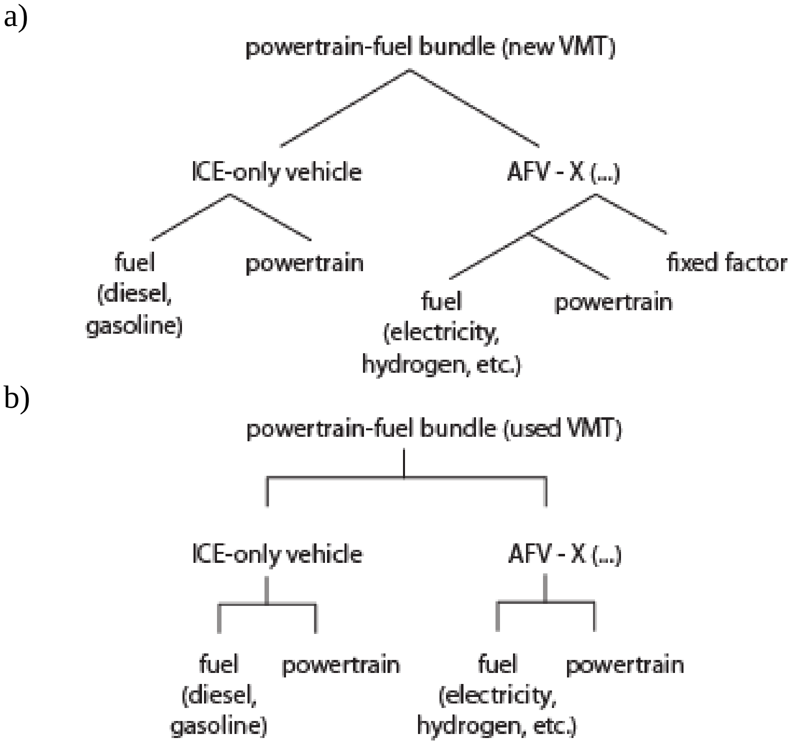
Recent developments in vehicle technology and related policy suggest that some fraction of future VMT may come from alternative fuel vehicles over the next 40 years, particularly if changing conditions (including relative prices of fuels and the availability of infrastructure) make these technologies attractive to consumers. The degree of adoption may in turn be influenced by policy design. The cost and abatement potential offered by alternative fuel vehicles is represented in the model as follows.

4.3.3.1 Parameterization and Key Elasticities

In previous CGE models that include a disaggregated transport sector, AFVs have been represented as a separate sector that competed with internal combustion engine (ICE-only) vehicles in the provision of passenger vehicle transport services (see for example Karplus et al., 2010). Each AFV variant (PHEV, EV) was described by a vehicle capital, services, and fuel shares, plus a markup assigned to the vehicle share to capture the incremental cost of the alternative propulsion system. Our new approach (see Figure 4.1, green box at the bottom of the consumption nest) is to contain all of the powertrain options within a single household vehicle transport services nest (the left side of each diagram in **Figure 4.8**), and to have alternative powertrains compete as perfect substitutes at the level of the fuel-vehicle capital nest. The base vehicle and services inputs (on the right-hand side of the nest in Figure 4.7) are assumed to remain constant across powertrain types. This procedure reduces the number of unique inputs required to estimate cost shares for each powertrain type. It is based on the assumption that the primary distinguishing feature of alternative fuel vehicles is the powertrain, and that the incremental cost reflects the contribution of the powertrain and its impact on the fuel requirement as it compares to other powertrain-fuel combinations.

So far, plug-in hybrid electric vehicles (PHEVs) and electric vehicles (EVs) are represented as backstop technologies to the ICE-only vehicle. A backstop technology is a potential alternative to an in-use technology that is not cost competitive in the benchmark year but may be adopted in future model periods as a result of changing relative input costs or policy conditions. A description of the previous method for implementing plug-in hybrid electric vehicles as a backstop technology can be found in Karplus et al. (2010). Although this analysis is focused on electric-drive vehicles, other vehicle types, such as the compressed natural gas vehicle (CNGV) or fuel cell electric vehicle (FCEV) could be easily added to this structure for specific studies.

Fig. 4.8 The inclusion of alternative powertrain types (denoted by AFV–X, where X could be a PHEV, EV, CNGV, and/or FCEV) in the a) new and b) used passenger vehicle transport sectors in the MIT EPPA model.



The criterion for including an advanced vehicle type as a separate powertrain (as opposed to capturing any fuel reduction potential through the elasticity of substitution between fuel and abatement capital) is whether the technology requires a fuel not mixable with conventional formulations of gasoline or diesel. Modifications to the internal combustion engine, including the addition of a turbo-charger, engine downsizing, or transmission improvements do not represent fundamentally new vehicle technology platforms and are thus represented as opportunities for reducing the fuel use of the internal combustion engine as described in Section 4.3.2 above. However, plug-in hybrid electric vehicles and electric-only vehicles require grid-supplied electricity and are thus represented separately. Cost shares based on the levelized cost of ownership for alternative fuel vehicles are discussed in **Appendix A**.

As in the case of the ICE vehicle, for each of the alternative fuel vehicle types, fuel consumption can be reduced with increased capital expense. To parameterize the values of these elasticities, we follow a method similar to our approach for the ICE and estimate an engineering-cost relationship that starts by assuming the existing fuel efficiency and emissions characteristics for each backstop technology and models the fuel reduction in percentage terms. Supply curves for abatement by powertrain type are described in **Appendix A**.

4.3.3.2 Constraints on Adoption

Several hurdles must be overcome before an advanced vehicle technology can gain a significant share of the new vehicle market and contribute to emissions reductions. The new modeling approach captures separately the effect of three constraints on the development and deployment of AFVs. First, fleet turnover (described in Section 4.3.2) allows advanced technologies to only enter through the new vehicle fleet, while the used vehicle fleet transforms only gradually over time. Second, we capture how the incremental cost of the advanced technology relative to the existing technology changes over time by parametrically varying an exogenous assumption about the rate of cost reduction. Third, we represent fixed costs associated with scaling up production of advanced technologies and obtaining acceptance in a heterogeneous consumer market. Since fleet turnover has been described previously, this section focuses on the modeling of the second and third constraints.

Reduction in the incremental vehicle capital cost on a precompetitive technology could occur as a result of ongoing technological progress (possibly through a substantial research and development effort aimed at a particularly promising technology). Here I include the possibility to model an assumption about cost reduction potential if desired by the analyst. One method for representing cost reduction involves using a negative exponential function that causes the incremental cost of the advanced technology to asymptote to a predefined level relative that is closer to the cost of the incumbent. The rate of cost reduction can be adjusted to reflect a wide range of assumptions about the potential for cost reductions. The goal is to capture the intuition that a technology expected to have large market potential will attract research funds even before it becomes cost competitive, and these investments will have the effect of bringing the technology closer to cost parity. I start by setting the learning rate to zero and compare it to the case where we parameterize it using the following function shown below as **Equation (4.9)**:

$$M_{\mathrm{t+1}} = 1 + \gamma + (M_{t=2004} - \gamma)e^{(rt)},\ 0 \leq \gamma < \ M_{t=2004} \qquad \textbf{(4.9)}$$

Here M is the markup (the percentage difference in cost between the new and the incumbent technology), t is the number of years since the 2004, and r is the annual rate of change in the markup.[28] The value of r is negative because the size of the markup is expected to fall over time and approach the cost of the incumbent technology. The γ term is included to allow the exponential decay to be applied to a fixed fraction of the markup, for example, the battery cost in the case of an EV, while maintaining the intuition that some cost difference between the AFV and ICE powertrain would remain.

Finally, once a vehicle technology reaches cost parity with the incumbent, we still expect its market adoption to be constrained by a variety of factors on both the supply and demand sides of the market. Incorporating new vehicle technology into production-ready models can take multiple years, and cannot be implemented across all new vehicle segments simultaneously without requiring additional resources. Production capacity must be allocated and scaled up in response to rising demand. Consumers may hesitate to adopt a particular vehicle technology if specialized refueling infrastructure is required but not readily available. Moreover, only a subset of consumers will be willing to buy and have driving needs well suited to take advantage of particular alternative fuel vehicle types. To capture these additional barriers to adoption, we parameterize a small share of the new powertrain production structure to include an additional fixed cost associated with AFV adoption, denoted fixed factor in Figure 4.7 (Karplus et al., 2010). Although these costs are often not directly observed, the value of this fixed cost requirement is parameterized based on evidence of the adoption rates for vehicle powertrain technology, including dieselization in Europe and the global adoption of off-grid hybrid vehicles.

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[28] For a detailed explanation see Karplus et al. (2010).

4.4 Summary and Extensions

This chapter has described a technology-rich approach to modeling passenger vehicle transport in a CGE model. This three-part approach could be applied, with some modifications, to model demand for any energy-intensive consumer durable product in a CGE framework.[29] Broadly, the three parts of this model development reflect three important generic considerations: 1) the relationship between total expenditures, expenditures on durable services, and the usage of the durable in physical units (miles-traveled for vehicles, load-hours for washing machines, or heating degree days for air conditioners), 2) representing capital stock turnover and vintage-differentiated opportunities for efficiency improvement, and 3) the availability and cost of substitute technologies with substantially different fuel requirements. Augmenting the model structure to facilitate a detailed engineering-based representation of the underlying physical system requires extensive and reliable data for calibration.

The new developments provide a platform that can be adapted depending on the purposes of the analysis. For instance, additional vehicle powertrain and fuel options could be easily added by expanding the number of technological substitutes included in the vehicle transport services nest. Other modifications could be undertaken as needed to address specific questions.

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[29] The approach described here for passenger vehicle transport can be readily adapted to models that disaggregate demand for transport services within the consumption function. With some additional effort passenger vehicle transport could be disaggregated from household consumption in most CGE models as needed (for more discussion see Paltsev et al., 2004).

Chapter 5: New Model Reference Case and Sensitivity Analysis

"Because things are the way they are, they will not stay the way they are."

Bertolt Brecht[30]

With new modeling capability in hand I now focus on developing the reference scenario for comparison with the policy scenarios in subsequent chapters. In this chapter, available data and previous studies are used to specify input assumptions for a new EPPA5-HTRN model baseline. The forecasted passenger vehicle fleet size, fuel use, CO_2 emissions, and adoption of plug-in hybrid electric vehicles (PHEVs, a representative alternative fuel vehicle) are shown for the United States. I then explore the sensitivity of model outputs for the United States to changes in a number of key assumptions: 1) relationship between per capita income and demand for vehicle-miles traveled (VMT), 2) the cost of powertrain efficiency improvements, and 3) the availability and cost of alternative powertrain technologies. The outcomes evaluated in the sensitivity analysis include fuel use, household consumption (a measure of economic welfare), and the technology adopted in the new and used vehicle fleets. These results provide a reference scenario for policy analysis and describe the influence of newly added parameters on the outcomes of interest. The main conclusion of this chapter is that in the absence of policy, petroleum use and GHG emissions from passenger vehicles in the United States will continue to remain above 2010 levels through 2050.

5.1 Introduction

A primary objective of this thesis is to evaluate the potential for several energy and climate policy approaches to reduce passenger vehicle petroleum use and greenhouse gas emissions through 2050. Before undertaking a comparison of policies, our analysis requires careful development of an appropriate baseline and a keen understanding of the sensitivities to the values of input parameters.

The new disaggregated structure of household vehicle transportation in the EPPA model is intended to capture a larger and more detailed set of technology and behavioral responses to policy. To provide a benchmark for comparison, it is important to understand how changes in this more comprehensive set of model parameters work (see **Table 5.1** for a list of parameters), alone or in combination, to drive outcomes under the reference scenario. This investigation uses assumptions informed by the literature to define ranges of input parameters and evaluates the range of expected outcomes in the absence of policy.

The sensitivity analysis performed here involves straightforward variation of key parameters—both one at a time as well as in select combinations. In **Section 5.2**, the inputs and

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[30] In Cook (2007).

outputs to the reference case are described. **Section 5.3** shows reference case forecasts. **Section 5.4** performs sensitivity analysis to identify how parameter changes affect refined oil use, CO_2 emissions, and technology adoption outcomes. **Section 5.5** summarizes the characteristics of the reference case and key sensitivities, and discusses their relevance for the policy analysis in subsequent chapters.

5.2 Reference Case Development for the United States

Model reference case development involved two exercises: 1) using data sources to describe the passenger vehicle fleet in the model in the benchmark year, and 2) choosing empirically-based values for the range of parameters that define how the system will respond to price and income changes, as well as policy interventions that act through price or income. I describe each of these exercises in turn.

Table 5.1 Parameter description and expected effect on outcomes of interest.

Parameter	In previous version of EPPA?	Description
Relationship between income growth and transport services demand	Yes – but equal to 1	Income elasticity of demand for vehicle transport services is calibrated to produce a high, reference, and low scenario for vehicle ownership growth as a function of per capita income.
Availability and cost of existing ICE vehicle efficiency	Yes – Not explicitly parameterized	Relates investment in energy efficiency technology to the price of refined oil used as transportation fuel.
Availability of PHEVs	No	Competes with efficiency improvements as a means to refined oil use (CO_2 emissions) in passenger vehicle transport.
Alternative fuel vehicle (AFV) powertrain cost	No	Defined as the percentage markup relative to the cost of the average existing ICE-only vehicle powertrain, calculated in 2004 USD. Cost will affect adoption of PHEVs, as well as the degree of efficiency improvements realized in existing ICE-only vehicles.

5.2.1 The U.S. Vehicle Fleet in the Benchmark Year

This section describes the how detailed physical data on the vehicle fleet, VMT, and fuel use were applied to represent the reference passenger vehicle fleet in the benchmark year. It should be noted that this analysis focuses on the effects of policies on vehicles owned by private households, which accounts for the vast majority of light-duty vehicles in the United States. Household-owned passenger vehicles accounted for around 82% of total VMT in 2004.[31] I focus primarily on passenger vehicles in part because of the structure of the EPPA model, which separates household consumption from government and commercial activities, but also because I am interested in assessing the effects of policies on household technology choices and travel demand explicitly.

Benchmark year 2004 values for number of vehicles, VMT, fuel use, and CO_2 emissions were obtained from the Residential Energy Consumption Survey (RECS), which reports on household transportation activity using data collected in the 2001 National Household Transportation Survey (EIA, 2001). To obtain estimates for 2004, I extrapolate from the 2001 values to 2004 using the overall rate of vehicle ownership and VMT growth from 2001 to 2005, which was 1.7% per year. The reported values for 2001 and the estimates values for 2004 are shown in **Table 5.2** below.

Table 5.2 Observed and extrapolated values for the passenger vehicle fleet in the benchmark year 2004.

Variable	2001 RECS/NHTS data	2004 Projected
Vehicles (millions)	191	201
VMT (billions)	2287	2406
Fuel (billion gallons)	113	119

These values are combined with economic data on expenditures related to passenger vehicle transport as described in **Chapter 4** and **Appendix A** to produce a model benchmark year consistent with the empirical data in both physical and value terms.

It should be noted that the values in Table 5.2 are equivalent to an average on-road (also known as "adjusted") fleet fuel economy of 11.4 L per 100 km (20.6 miles per gallon) in 2004.[32] The difference between a vehicle's rated (or test-cycle) fuel economy and its on-road fuel

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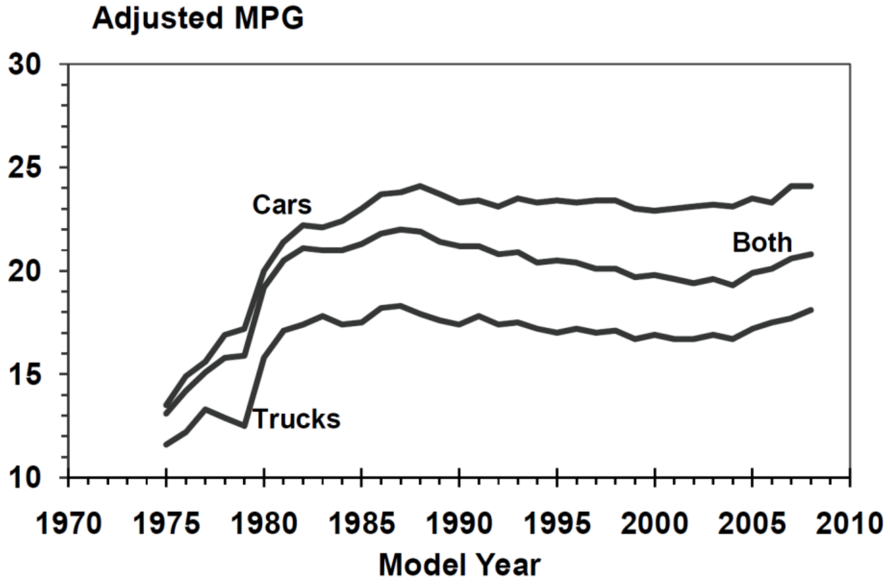
[31] This share is lower than the share of passenger vehicles in total light-duty vehicles because government- and commercially-owned vehicles average a higher number of miles per year relative to household vehicles. The share of passenger vehicles in total light-duty vehicles is around 86% (Davis et al., 2009).

[32] A useful rule of thumb for converting between miles per gallon (referred to as fuel economy) and liters per 100 km (referred to as fuel consumption) is to divide each quantity into 235 to achieve the target quantity in the alternative units.

economy is around 20%. Here I use the adjusted numbers to capture the energy and GHG emissions impacts of real-world driving. The efficiency of new and used vehicles in 2004 is roughly equal. Although fuel economy standards were slightly tightened and the remained steady for cars and light trucks over the past several decades, the new vehicle sales mix has evolved to include a higher proportion of vans, trucks, and sport-utility vehicles (SUVs) over time, offsetting any reductions in effective combined measures of fuel consumption. The shift toward heavier vehicles has offset increases in new vehicle fuel economy, as shown in **Figure 5.1**.

Fig. 5.1 Adjusted new vehicle fuel economy by model year in miles per gallon.



Source: EPA, 2008.

5.2.2 Parameter Values

The key parameter values for the reference case are shown in **Table 5.3** below. The sources of these values are also cited in the far right column. The rest of this section will provide a description of the baseline case outputs.

5.3 U.S. Reference Case Projection

The first task is to show projections of the physical quantities of vehicles, vehicle-miles traveled, fuel use, and CO_2 emissions. **Figure 5.2** shows the growth projection for the total number of passenger vehicles owned by private households from 2010 to 2050. The long-run fleet growth rate is 1.2% per year from 2010 to 2050. Part of the growth is due to a modest rebound in vehicle sales from 2010 to 2015, which offsets the effect of the global recession that started in 2008.[33] The total number of U.S. household-owned passenger vehicles rises from 200 million in 2005 to 257 million in 2030 and 317 million in 2050.

Table 5.3 List of the parameter values used in the United States in the reference case run.

Parameter	Value	Units	Source
PT elasticity (Elasticity of substitution between fuel and abatement capital – ICE)	0.75	Unit-less	From fuel price elasticity of demand for fuel economy – technology cost curves (see **Chapter 4**).
Income elasticity (Income elasticity of demand for vehicle-miles traveled)	0.70 (0.75 – high, 0.65 – low) through 2020, decreases by 0.01 every 5 years thereafter	Unit-less	Hanly et al., 2002
PHEV available?	Yes		Karplus et al., 2010
Incremental PHEV cost	25% (10%)	PHEV to ICE vehicle cost ratio	EPA, 2010b
EV available?	No (available in sensitivity analysis for policy cases)		Karplus et al., 2010
Incremental EV cost	60%	EV to ICE vehicle cost ratio	EPA, 2010b
Rate of PHEV, EV cost reduction	0. 5% reduction in markup every five years	Percent	Conservative assumption / consistent across cases
Advanced biofuels (CO_2 neutral) available?	Yes	EJ	(Not economic in reference case.)

Vehicle-miles traveled grow at a slightly faster pace, reflecting a very modest increase in demand for VMT per vehicle. Over the period 1970 to 2007, total VMT grew at 2.7% per year, but this rate of increase was only 1.4% from 2000 to 2007. Average VMT per vehicle has grown at the rate of 0.4% since 1970. However, at least one study has suggested that the growth rate asymptotes to zero or even decreases as per capita vehicle ownership increases (Meyer et al., 2007). The VMT projection for new and used vehicles is shown in **Figure 5.3**. Average annual growth in VMT in the model projection is equal to 1.3%.

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[33] The effects of the global recession are reflected in a slightly negative growth rate for GDP in the model from 2005 to 2010, which is paralleled by a drop in vehicle sales and close to zero growth over the same period.

Fig. 5.2 EPPA5-HTRN model projection of the total number of registered passenger vehicles in the United States, 2010-2050.

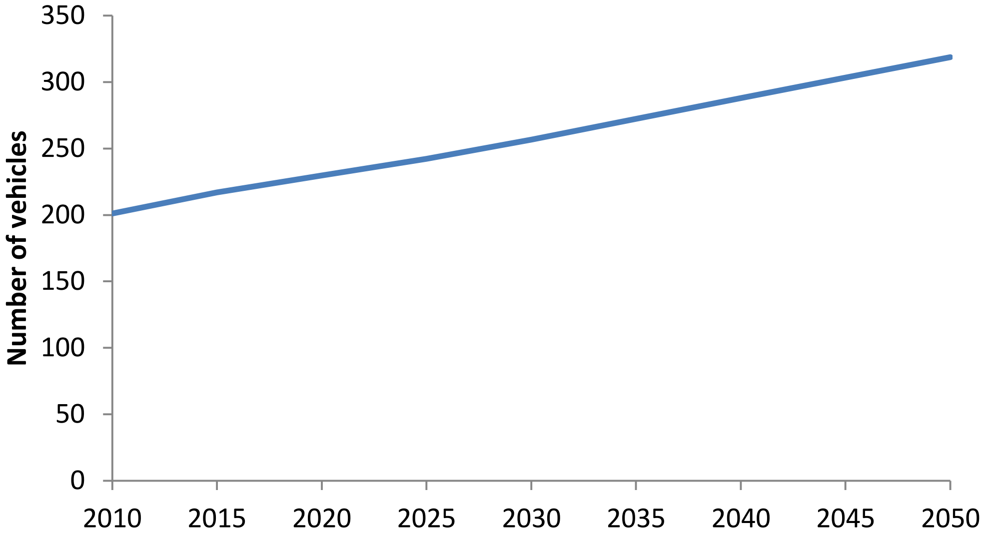
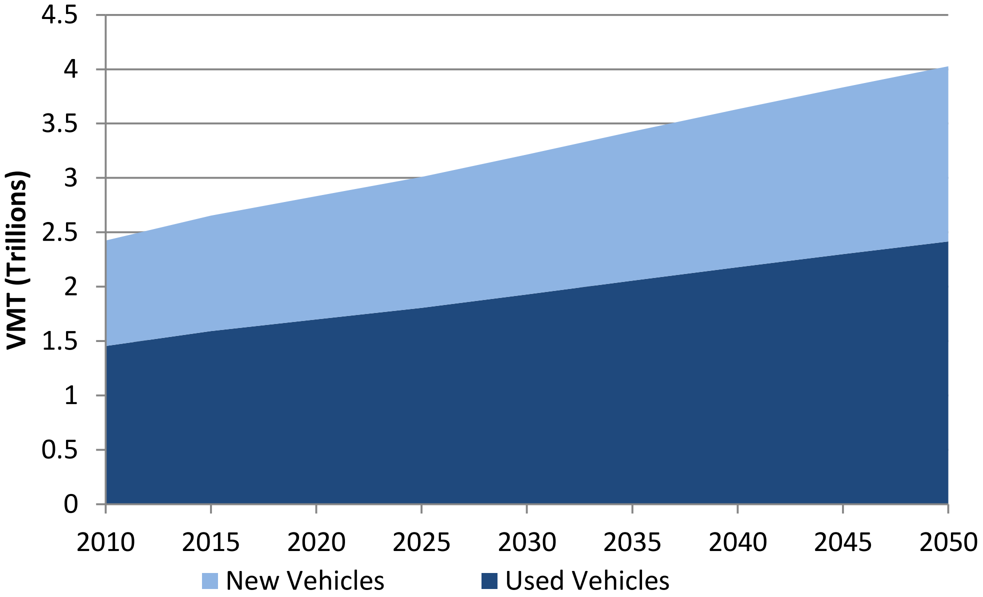


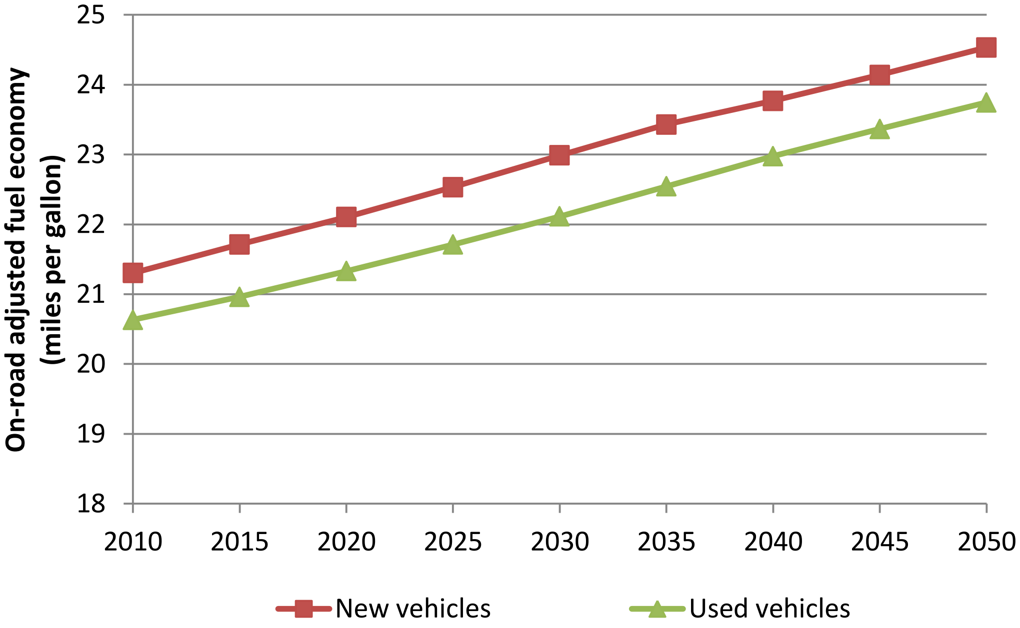
Fig. 5.3 EPPA5-HTRN model projection of the total vehicle-miles traveled by new (0-5 year old) and used (5-25 year old) vehicles in the United States, 2010-2050.



Fuel economy also improves over time in the absence of policy. The price of gasoline rises through 2050 as a result of growing demand and the rising cost of petroleum supply, inducing consumers to switch gradually to higher fuel economy vehicles. The on-road adjusted fuel consumption of vehicles drops at the average rate of 0.3% per year, which is far less than the reduction required to achieve a target adjusted fuel economy of 28 mpg in 2020 (equivalent to the 2007 U.S. Energy Independence and Security Act unadjusted fuel economy target of 35 mpg), which would require reductions in fuel consumption of 2.7% per year. The fuel economy trajectory for both new and used vehicles is shown in **Figure 5.4**.

The projected relationship between per capita income and household vehicle ownership in the reference case is shown below in **Figure 5.5**. The time progression of the data points proceeds from left to right, with per capita income rising over time in the model projection driven by the exogenously-imposed GDP forecast. Vehicle ownership rises more slowly than per capita income, and the growth is not uniform. A rebound in per capita income after the recession causes vehicle ownership to rise sharply from 2010 to 2015 before exhibiting slower growth in subsequent periods until it picks up again with larger increases in per capita income after 2025.

Fig. 5.4 EPPA model projection of a) on-road adjusted fuel economy for new and used passenger vehicles, 2010-2050, and b) adoption of PHEVs in the baseline scenario.
a)



b)

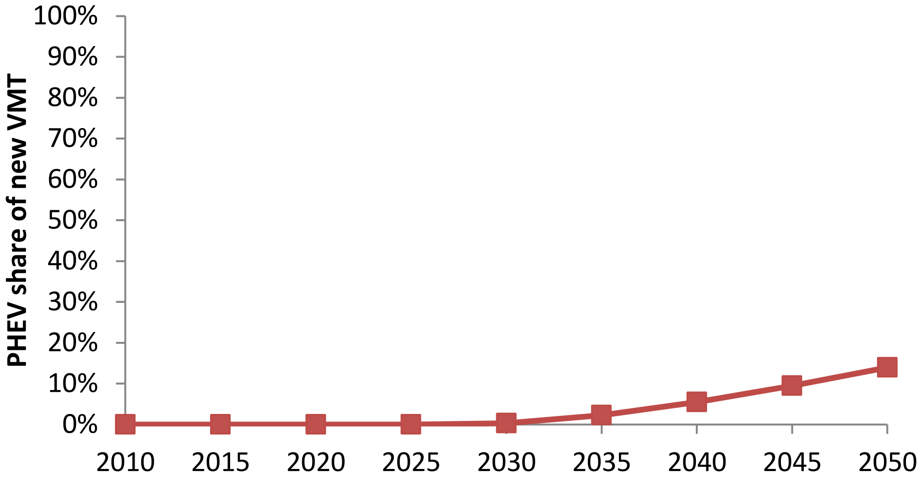
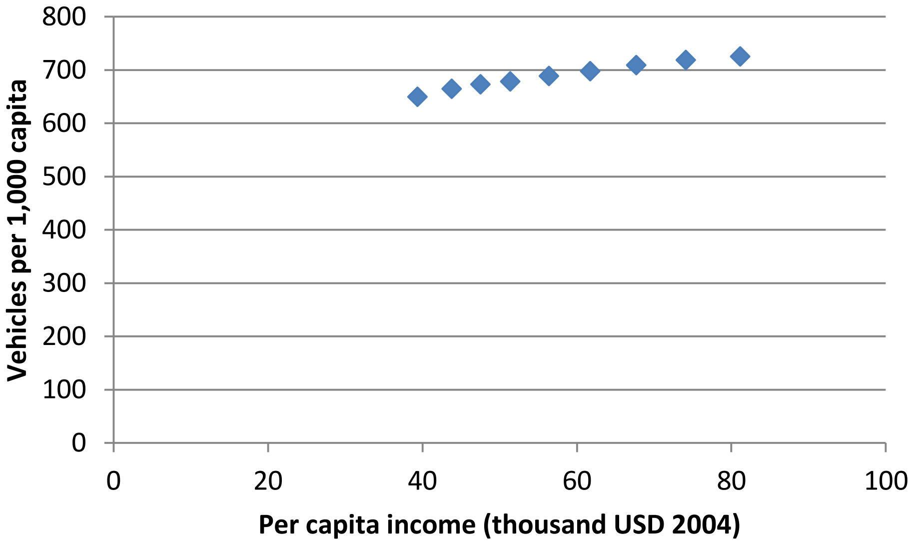
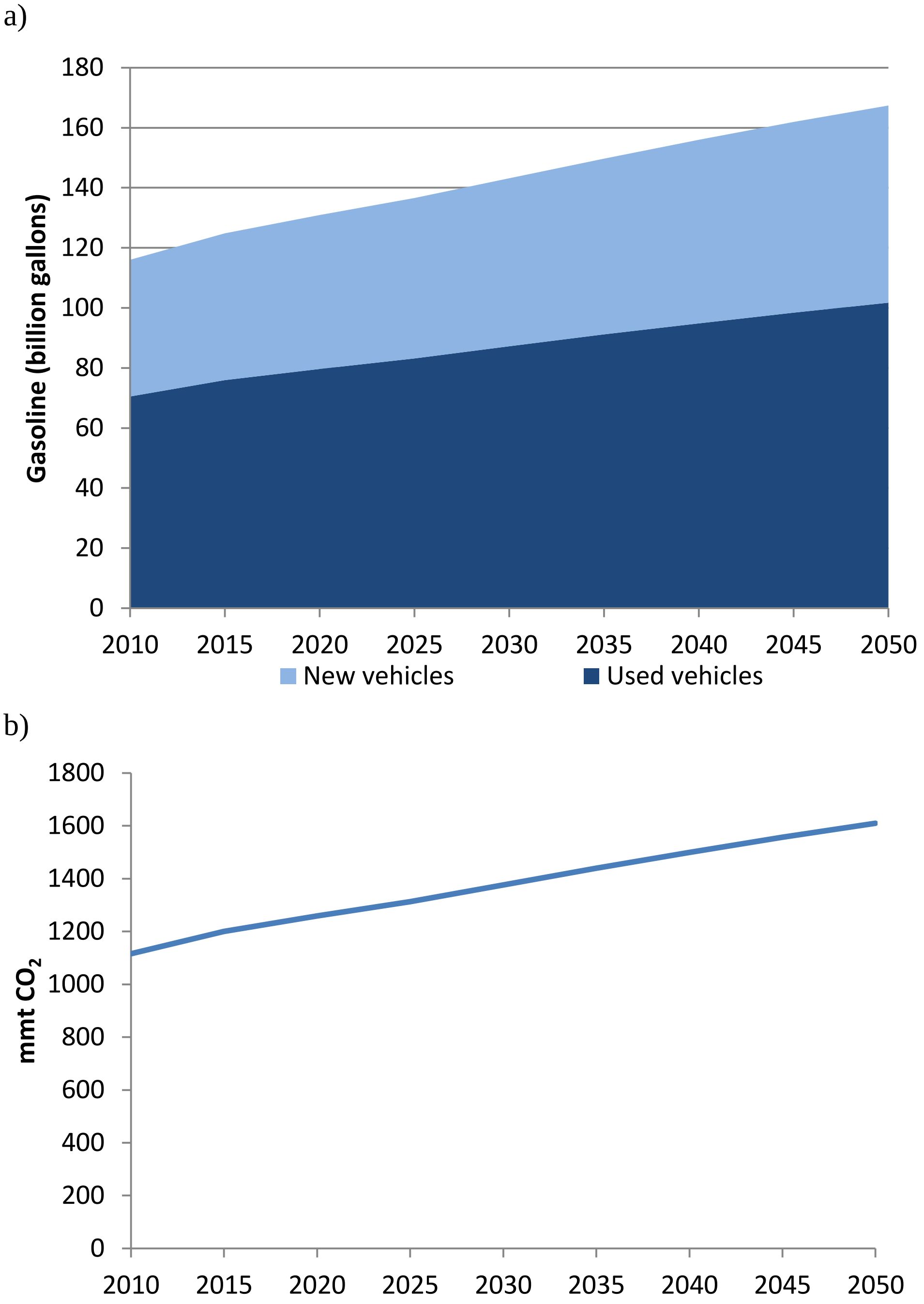


Fig. 5.5 Simulated relationship between per capita income and household-owned passenger vehicles per 1,000 capita in the United States in the EPPA5-HTRN model.



Finally, reference case projections for gasoline demand and tailpipe CO_2 emissions (**Figure 5.6**) are shown below. Gasoline demand and CO_2 emissions rise at 0.9% per year, more slowly than either vehicle ownership or VMT, reflecting a gradual reduction in new vehicle fuel consumption (an increase in vehicle fuel economy) over time. New vehicles drive more miles per year on average, and thus the contribution of new (0 to 5 year-old) vehicles to fuel use is substantial relative to used vehicles (>5 year old vehicles). The outputs of the reference case presented here are compared against projections by other agencies, including the International Energy Agency. The projections are included in **Appendix B**.

Fig. 5.6 Projected passenger vehicle a) refined oil demand and b) tailpipe CO_2 emissions.



5.4 Sensitivity Analysis

Sensitivity analysis of a newly constructed model is essential to understand the relationships between model inputs and outputs, and the elasticities that characterize these relationships in the absence of policy. A particular strength of the EPPA model is that its underlying structure captures non-linear responses and relationships among the key variables in the model, which can be further elaborated through the specification of time trends in key parameter values.

Two important new parameters were introduced into the model—the income elasticity of demand for vehicle-miles traveled and the elasticity of vehicle fuel economy in response to fuel price. These elasticities are described in **Chapter 4**. The first task for sensitivity analysis is to establish how significantly model outputs are affected by changes in these two parameters. I consider the effect of these parameters in two scenarios: the case in which no alternative fuel vehicles are available, and the case in which the PHEV is available as parameterized in the reference case.

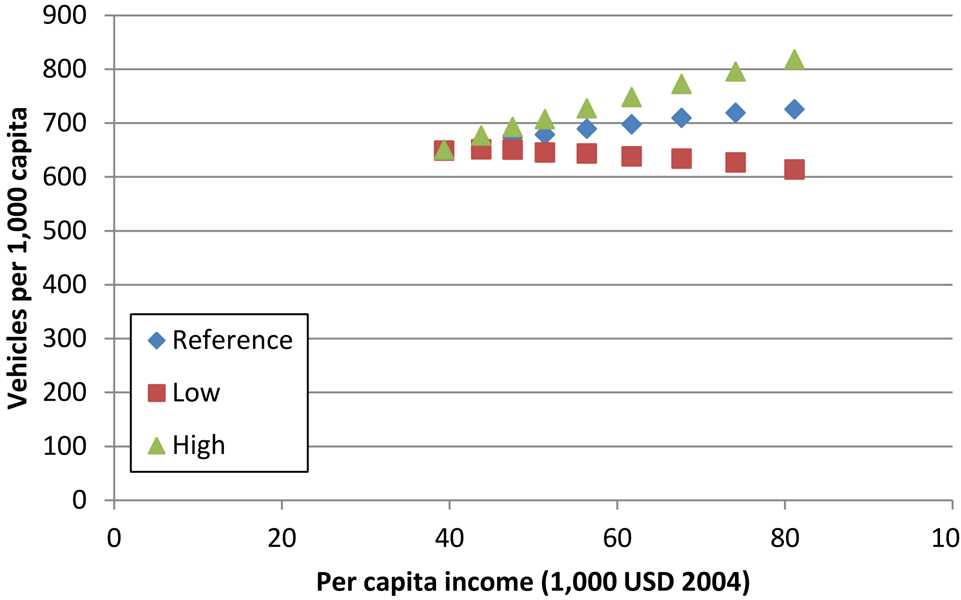
For each of the cases, I consider how increasing or decreasing these key elasticities by appropriately defined levels changes two representative output values: gasoline use by passenger vehicles, total CO_2 emissions, and consumer welfare relative to the base case assumptions.

5.4.1 Income Elasticity of U.S. Passenger Vehicle Ownership and Use

The future growth of the U.S. passenger vehicle fleet beyond 2010 is uncertain. The global financial crisis in 2008 was characterized by high gasoline prices, depressed vehicle sales, and reduced driving. Whether demand for vehicle transport services returns to pre-crisis levels or marks the beginning of a transition to slower demand growth (or even decline) remains an open question. To capture a reasonable range of potential growth patterns, I simulate high and low alternative fleet growth paths, which represent different levels of vehicle ownership (vehicles per 1,000 capita) by mid-century in the United States. The effect of changing income elasticity of demand is best visualized in terms of the relationship between per capita income and vehicle ownership over time. These paths are shown in **Figure 5.7** below, and based on the new model developments described in **Chapter 4**.

The three scenarios involve setting input elasticities to achieve the desired growth path in terms of vehicles per capita. The U.S. population grows over the period 2010 to 2050 at an average compound growth rate of 0.8% per year. Even in cases where the number of vehicles per capita decreases, the total number of vehicles in the fleet increases due to growth in the underlying population.

Fig. 5.7 Vehicle ownership projections used for sensitivity analysis at reference, high, and low elasticity values.



Comparing the outcomes in terms of fuel use, total fossil CO_2 emissions, and economic welfare suggest that income elasticity of demand for VMT is an important parameter. The effect of high and low vehicle ownership assumptions on cumulative quantities of gasoline use, GHG emissions, and household consumption is shown in **Table 5.4**. The trajectory of gasoline use and GHG emissions over time is shown in **Figure 5.8**.

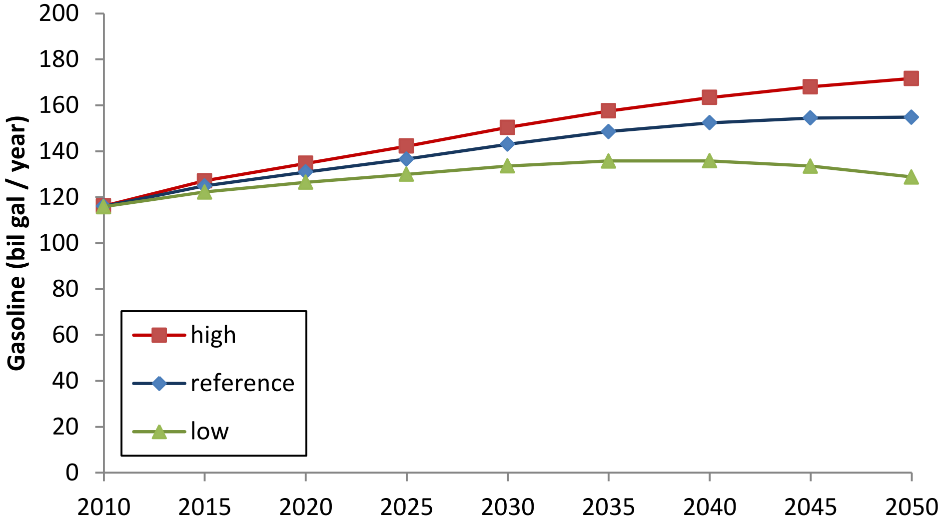
Table 5.4 The effect of changing assumptions about the relationship between per capita income and vehicle ownership in the United States through 2050 on cumulative fuel use, total fossil CO_2 emissions, and household consumption.

No PHEV	**High**	**Low**	**Reference**
Fuel use (billion gal)	5.9%	-7.1%	7,023
Total fossil CO_2 emissions (mmt CO_2)	1.1%	-1.3%	367,966
Consumption change (billion USD 2004)	0.7%	-0.8%	7,058
PHEV	**High**	**Low**	**Reference**
Fuel use (billion gal)	5.1%	-7.3%	6,898
Total fossil CO_2 emissions (mmt CO_2)	0.9%	-1.3%	366,844
Consumption change (billion USD 2004)	0.7%	-0.8%	7,058

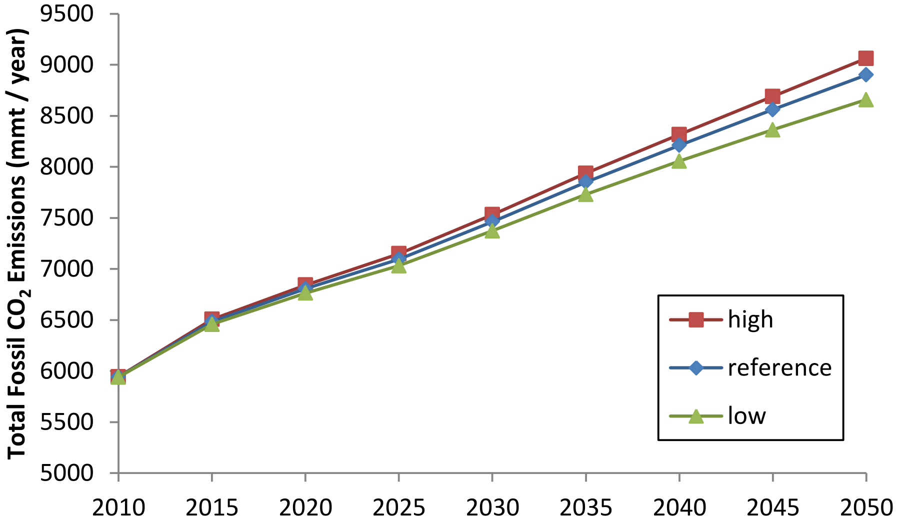
The largest effect of changing the income elasticity of demand for transport services is evident in the change in fuel use. The lower proportional change in fuel demand in the high elasticity case relative to the low elasticity case is a response to greater upward pressure on gasoline prices, which raises incentives to invest in vehicle fuel economy and offsets total gasoline demand in the high growth scenario.

Fig. 5.8 Projected a) gasoline use and b) GHG emissions through 2050 under different vehicle transport demand assumptions (PHEV is available).

a)



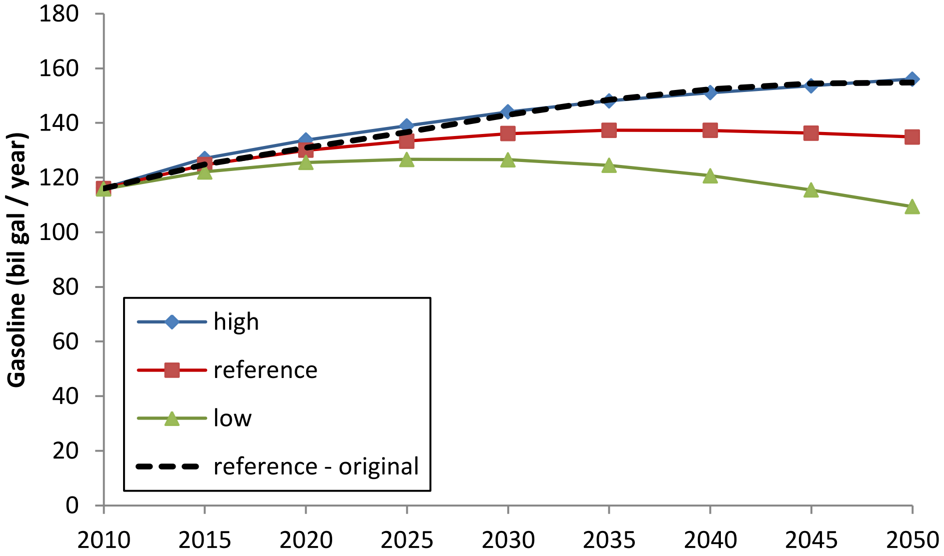
b)



If the PHEV is available, the outcomes of the scenarios change to reflect the fact that, in addition to incremental improvements in ICE technology, PHEVs offer another opportunity to reduce fuel use in response to fuel price increases. The main difference compared with the No PHEV case is the fact that fuel use only rises by 5.1% (from a lower baseline) relative to 5.9%, and total emissions only increase 0.9% relative to 1.1% in the high growth case (again, baseline emissions are slightly lower in the PHEV case). Although small in percentage terms, these changes are significant in absolute terms.

Finally, I consider the impact on gasoline use of a PHEV that is only 10% more costly (rather than 30% more costly) relative to an existing ICE vehicle in 2004. Instead of only 13.6% of new vehicle VMT in 2050, the PHEV is adopted more widely, reaching over 30% in 2050 (because it is cost competitive with ICE-only vehicles in the face of rising gasoline prices). The effect on gasoline use only (the most sensitive outcome) is shown in **Figure 5.9** below. The main result of higher PHEV adoption is to shift the reference fuel use projection down by around 20 billion gallons per year in 2050.

Fig. 5.9 The effect of changing the income elasticity on gasoline use in the absence of policy when the PHEV is available at a 10% premium over the ICE-only vehicle. Gasoline demand in the reference case with the PHEV available at a 30% premium is shown by the dashed black line.



5.4.2 Opportunities for ICE Efficiency Improvement

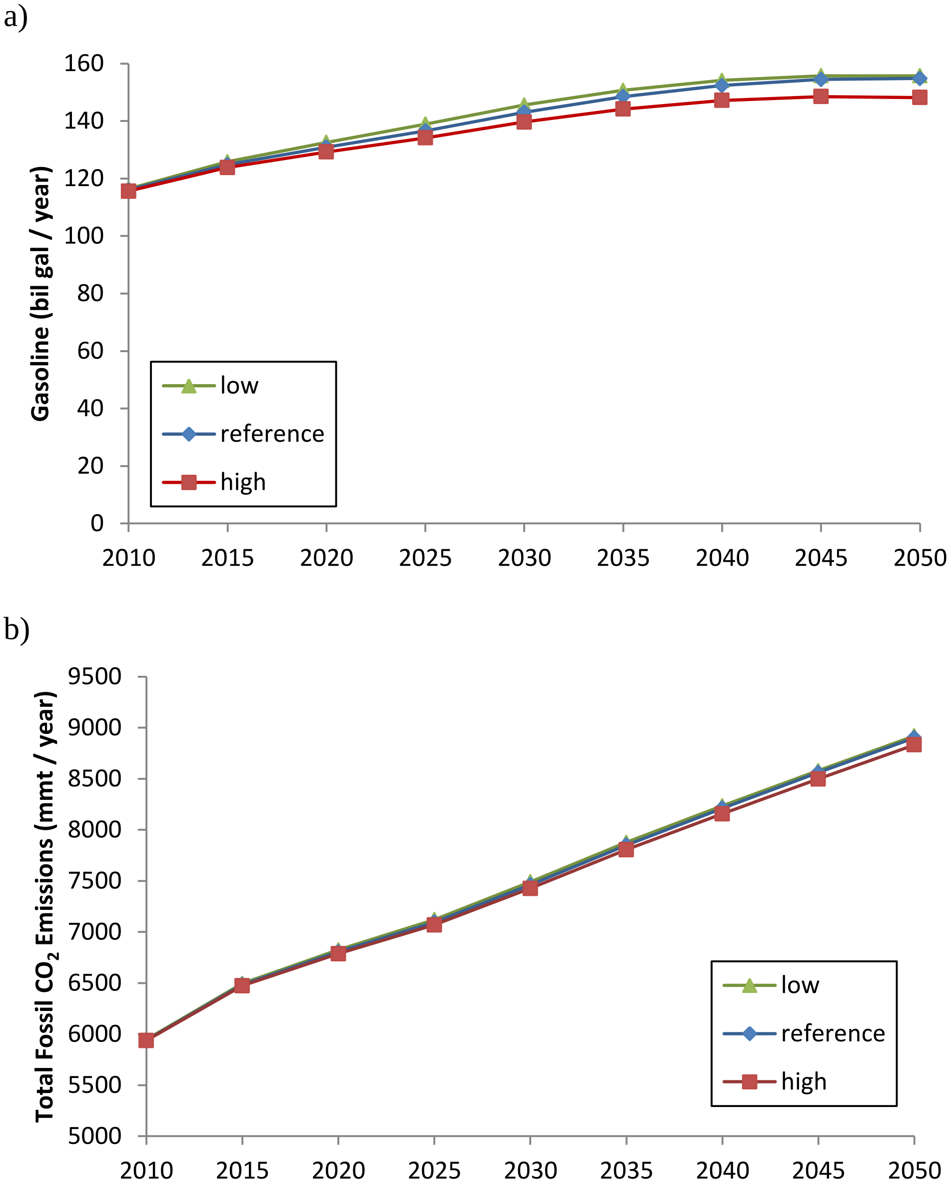
Given the inherent difficulty associated with the construction of an aggregate cost curve for gasoline use reduction from passenger vehicles, it is possible that the elasticity of substitution between fuel and vehicle efficiency capital discussed in **Chapter 4** and **Appendix A** does not perfectly capture the cost or availability of fuel use reduction opportunities in response to fuel price changes. This possibility grows more likely over time, as the cost of vehicle efficiency improvements and the realization of cost reductions in related technologies over time is uncertain. In this exercise I consider the effect of changing this key elasticity (referred to here as the PT elasticity) by plus or minus 25%.

Table 5.5 Effect of changing the PT elasticity on cumulative passenger vehicle fuel use, total CO_2 emissions, and consumption.

No PHEV	High	Low	Reference
Fuel use (billion gal)	-2.4%	2.3%	7,023
Total fossil CO_2 emissions (mmt CO_2)	-0.5%	0.5%	367,966
Consumption change (billion USD 2004)	0.0%	0.0%	7,058
PHEV	**High**	**Low**	**Reference**
Fuel use (billion gal)	-2.3%	1.0%	6,898
Total fossil CO_2 emissions (mmt CO_2)	-0.5%	0.2%	366,844
Consumption change (billion USD 2004)	0.0%	0.0%	7,058

The effect of changing the PT elasticity on fuel use, total CO_2 emissions, and consumption is shown in **Table 5.5**. Changes in the PT elasticity have the largest effect on fuel use, although this effect is relatively inelastic (elasticity of 0.09). The primary effect of making available the PHEV in these scenarios is to offset the increase in fuel use and CO_2 emissions (and associated economic cost) in the low PT elasticity case, because the PHEV can now provide reductions in fuel use that might have otherwise been provided by the ICE-only vehicle. The elasticity of fuel use with respect to changes in the PT elasticity is about half of the original value in the high demand case when PHEVs are available (0.04 versus 0.09). This result occurs because efficiency improvements in existing vehicles are more costly. If PHEVs are available, they will be adopted in lieu of (more expensive) efficiency improvements to ICE vehicles, offsetting the increase in fuel use that would have otherwise occurred. By contrast PHEVs do not play a role when the PT elasticity is high, because improvements in the ICE are the less costly way of undertaking fuel use reductions. In effect, the PHEV steps in as a “backstop” in the case where the efficiency improvements in the ICE-only vehicle are expensive. A less expensive PHEV has an even more pronounced effect (not shown). The gasoline use and fossil CO_2 emissions impacts are shown in **Figure 5.10**.

Fig. 5.10 Projected a) gasoline use and b) GHG emissions through 2050 under different assumptions about the cost of ICE vehicle efficiency improvements.



5.4.3 “Best” and “Worst” Case Scenarios: Interactions among Income Elasticity, PT Elasticity, and PHEV Availability

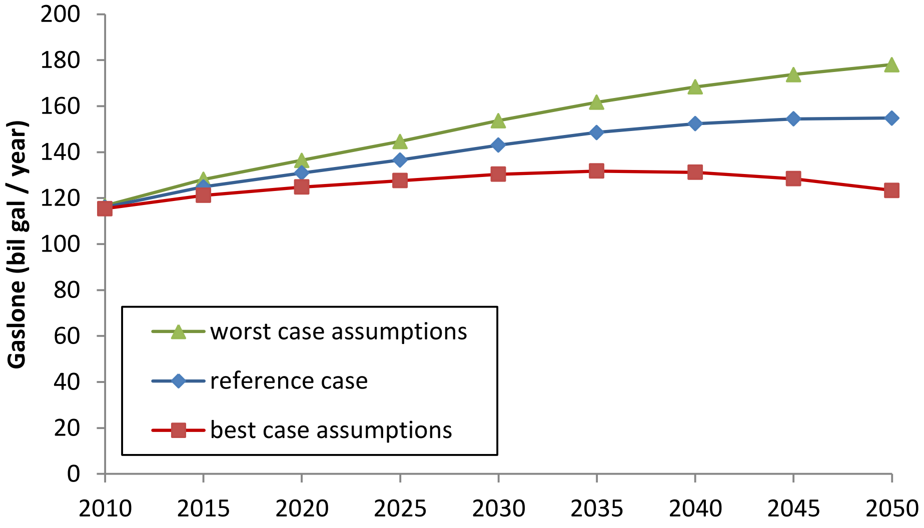
In order to understand how the three factors considered in this sensitivity analysis interact to affect the outcomes of interest, I consider both a best and worst case scenario. These are the combinations of inputs previously tested that are likely to produce the least or most fuel use and GHG emissions, respectively. The effects of the three factors are summarized in **Table 5.6** below. The trajectories for gasoline use and CO_2 emissions are shown in **Figure 5.11**.

Table 5.6 Sensitivity of outcomes to "best" and "worst" case assumptions.

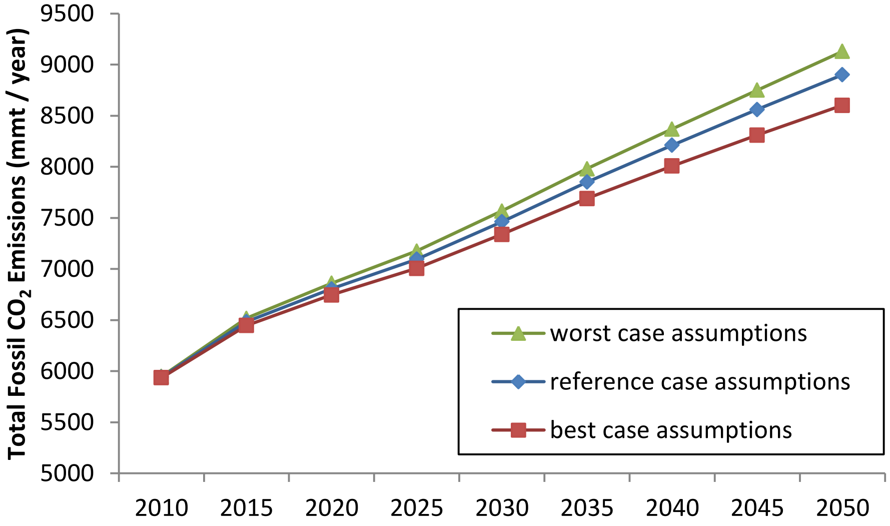
No PHEV	"best"	"worst"	Reference
Fuel use (billion gal)	-9.7%	7.3%	7,023
Total fossil CO_2 emissions (mmt CO_2)	-1.7%	1.4%	367,966
Consumption change (billion USD 2004)	-0.8%	0.7%	7,058

Fig. 5.11 Projected a) gasoline use and b) GHG emissions through 2050 under different assumptions about the cost of ICE vehicle efficiency improvements for the best and worst case scenarios.

a)



b)



5.5 Conclusions

This sensitivity analysis presents strong evidence that the U.S. will not achieve major reductions in GHG emissions or fuel use under a wide range of underlying conditions in the absence of policy. In the reference case scenario, the outcomes of the model are not very sensitive to changes in the underlying assumptions. The range of sensitivity considered for each of the parameters reflects careful consideration of a likely range of these parameters in terms of the physical system properties they represent. These results suggest that in the absence of policy, petroleum use and GHG emissions will remain very far from the levels policymakers have identified as necessary to achieve stated energy and climate policy goals. Even in the "best" case scenario gasoline consumption does not begin to decline before 2035, and after that, declines only modestly. Even availability of a PHEV with a low incremental cost of 10% does not significantly change this result. This sensitivity analysis is important to establish a baseline model response before undertaking policy analysis in the chapters that follow. With policy, the parameters considered—income elasticity of demand, PT elasticity, and PHEV availability—will exert influence on the magnitude of the policy response.

One source of sensitivity not presented was the effect of the availability of advanced CO_2 neutral biofuels. The reason for not considering this option in the baseline scenario is that these fuels are not economically viable at current estimated cost in the absence of policy. The policy analysis chapters will consider the role of this option under policies that require a fixed percentage of biofuels be added to the fuel supply, or policies that create favorable cost conditions for market entry.

Other parameters in the model that could influence the model outcomes include the rate of cost reductions for advanced powertrain vehicles, the maximum rate of deployment of alternative fuel vehicles, and elasticity values in other parts of the consumption structure unrelated to passenger vehicle transport. The assumption about the rate of cost reductions does not have a large effect on the relative timing of advanced vehicle adoption when comparing across cases, and therefore a single assumption is made and applied in all cases. Elasticities between purchased and household-owned passenger vehicle transport, as well as between household transport and other consumption, are set to low levels as described in Paltsev et al. (2005) and are also held fixed throughout the cases examined here. Revisiting these elasticities or other aspects of the broader model structure is left to future work.

Chapter 6: An Analysis of Climate and Energy Policies for Passenger Vehicles

A key contribution of economics has been the development of market-based approaches to environmental protection. These instruments are key to addressing the ultimate commons problem of the twenty-first century—global climate change.

Robert Stavins[34]

A new vehicle fuel economy standard (FES) and a renewable fuel standard (RFS) have been implemented in the United States with the aim of reducing gasoline use as well as, more recently, greenhouse gas (GHG) emissions. This work uses an economy-wide computable general equilibrium model with a detailed passenger vehicle transport sector to compare the effects of policy instruments. First, the cost of achieving a 20% reduction in cumulative gasoline use with each policy instrument is compared to the cost of a gasoline tax required to achieve an equivalent cumulative reduction. A tax is shown to be six to fourteen times less costly than either the FES or an RFS policy. Combining the FES policy and the RFS policy results in less than additive reductions in cumulative passenger vehicle gasoline use, relative to the sum of reductions taken under the policies implemented individually, while costs are nearly additive. The timing of the required reductions in fuel use affects the cost of the FES policy more than of the RFS policy, with a sharp path being significantly less costly relative to a gradual path in the case of the FES policy. I then analyze the effects of combining each of the two transport-focused energy policies with an economy-wide cap-and-trade (CAT) policy targeting GHG emissions. If adding a regulatory instrument results in additional gasoline reduction beyond the CAT policy alone, it also increases the cost of meeting the GHG emissions reduction target.

6.1 Introduction

Policymakers often claim that policies targeting reductions in petroleum-based fuel used in passenger vehicles (referred to here as transport-focused energy policies) achieve two goals: 1) reducing total petroleum use and 2) reducing total GHG (CO_2) emissions. It is therefore appropriate to evaluate these policies based on how cost-effectively, and under what conditions, these policies achieve these closely-related goals. Transport-focused energy policies may also be combined with an economy-wide market-based policies (such as a cap-and-trade (CAT) policy) to achieve additional reductions in gasoline use from passenger vehicles.

The two transport-focused energy policies evaluated in this chapter are a vehicle fuel economy standard (FES) and a renewable fuel standard (RFS). These policies primarily target petroleum-based fuel use. For passenger vehicles in the United States, this fuel is almost exclusively motor gasoline, and therefore I refer to gasoline throughout this discussion. Since

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[34] In Stavins (2011).

CO_2 account for nearly all of the contribution of passenger vehicles to GHGs, we focus on CO_2, although the economy-wide cap-and-trade policy considered later in this section targets other GHGs as well. This analysis begins by comparing policies designed to achieve a fixed reduction in cumulative gasoline use, while comparing the impact on total fossil CO_2 emission from the U.S. economy as well as economic cost, measured as cumulative consumption change over the period 2000 to 2050. I take a full life-cycle approach to quantifying CO_2 emissions reductions by focusing on the change in total CO_2 emissions across the U.S. economy, which includes the contribution of fuel production and use, as well as any offsetting effects on CO_2 emissions in other sectors.

This chapter is organized as follows. First, I briefly describe the policies and how each was implemented in the EPPA model. Second, I identify the cost of achieving a single cumulative fuel reduction target by applying each policy individually and compare the cost to a gasoline tax that achieves the same target. I also show how vehicle-miles traveled (VMT), vehicle efficiency, and alternative fuel vehicle adoption respond under each policy. Third, I show how combining an FES policy and an RFS policy produces a reduction in passenger vehicle gasoline consumption that is less than the sum of the reductions under each policy implemented in isolation. Fourth, I investigate the implications for cost, technology adoption, fuel use, and GHG emissions of combining the FES and RFS policies with a CAT policy.

6.2 Modeling a Fuel Economy Standard (FES) and a Renewable Fuel Standard (RFS)

The following section undertakes a comparison of an FES policy, an RFS policy, and a gasoline tax (with and without biofuels available).

6.2.1 Vehicle Fuel Economy Standard (FES)

A representative vehicle fuel economy standard was implemented in the model in order to simulate a policy constraint similar to that imposed by the U.S. Corporate Average Fuel Economy (CAFE) Standards, described in more detail in **Chapter 2**. First passed in 1975 and in effect since 1978, the U.S. CAFE Program has regulated the sales-weighted average fuel economy of new light-duty passenger vehicles, a classification which includes both cars and light-duty trucks. The program is designed to reduce passenger vehicle fuel use relative to a reference projection by increasing the efficiency of new vehicles sold.

A fuel economy standard is represented in the EPPA model as a constraint on the ratio of fuel use relative to vehicle-miles traveled in newly sold vehicles in each five-year time step. The model simulates modifications to the vehicle that reduce per mile fuel consumption, starting with the least costly opportunities.

The vehicle fuel economy constraint equation is shown in **Equation 6.1**. All future reductions are defined relative to the ratio of fuel, Q_{f,t_0}, to miles-traveled, Q_{VMT,t_0} , in the model benchmark year (t_0). Vehicle fuel economy in the EPPA model is based on the actual quantity of energy used and is expressed here as on-road (adjusted) fuel consumption in liters per 100 kilometers (L/100 km).[35] Targets set by policymakers are typically reported in the literature and popular press using unadjusted fuel consumption (or fuel economy) figures. Unadjusted fuel consumption refers to the fuel requirement per unit distance determined in course of laboratory tests, while adjusted figures reflect actual energy consumption on the road. To obtain adjusted fuel economy, I divide the unadjusted numbers by 0.8 (EPA, 2006). The trajectory A_t is a fraction that defines targeted per-mile fuel consumption relative to its value in the model benchmark year. The constraint requires that the on-road fuel consumption (FES_t) realized in each period remain equal to or below the target for that year by inducing investment in energy saving technology, which is a substitute for fuel. For instance, a value of A_t = 0.5 in 2030 means that fuel consumption relative to the model benchmark year must decline by half.

$$FES_t \leq A_t \, (Q_{f,t_0}/Q_{VMT,t_0}) \qquad \textbf{(6.1)}$$

For purposes of this analysis, I consider two policy trajectories through 2050, with the objective of exploring the long-term implications of continuing policies that have been set recently for 2012 to 2016, or have been proposed for the period 2017 to 2025. Due to the fact that the EPPA model forecasts in five-year time steps, the fuel economy standard in each time step was calculated to constrain fuel consumption to a level that reflects the stringency of the standard in each of the past five years, weighted by contribution of each year's new vehicles to VMT. The policy trajectories are shown in **Figure 6.1**. I choose two representative FES pathways. The FES-sharp policy is equivalent to halving on-road adjusted fuel consumption by

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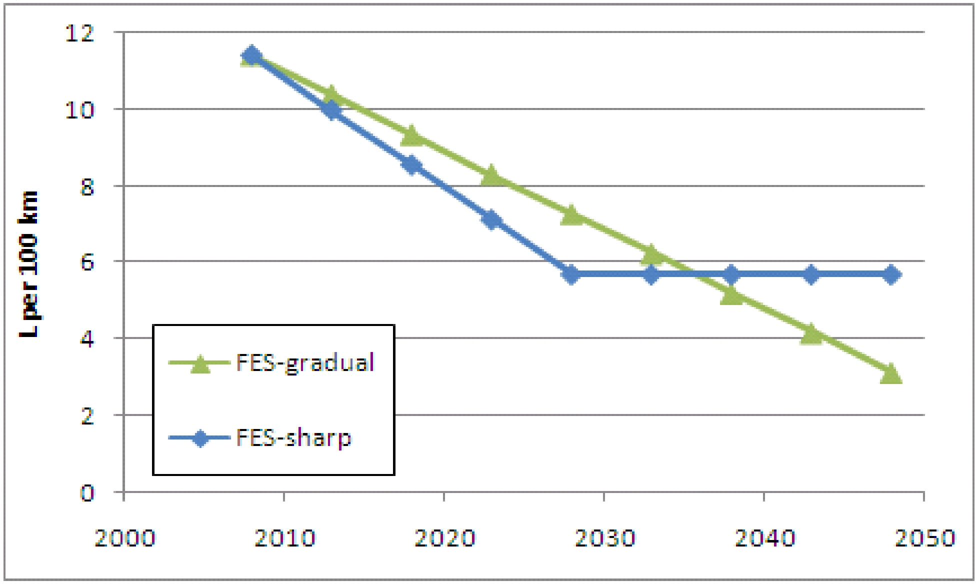
[35] Fuel economy targets are expressed here in L/100 km in order to preserve linear scaling in terms of the fuel requirement per unit distance traveled. To approximate the equivalent miles per gallon for targets expressed in liters per 100 km, the target quantity should be divided into 235.

2030 and holding it constant thereafter. The FES-gradual policy achieves the same cumulative reduction in passenger vehicle fuel use through steady incremental reductions through 2050.

Fig. 6.1 Adjusted (on-road) fuel consumption trajectories for three alternative FES policies shown a) graphically and b) numerically.

a)



b)

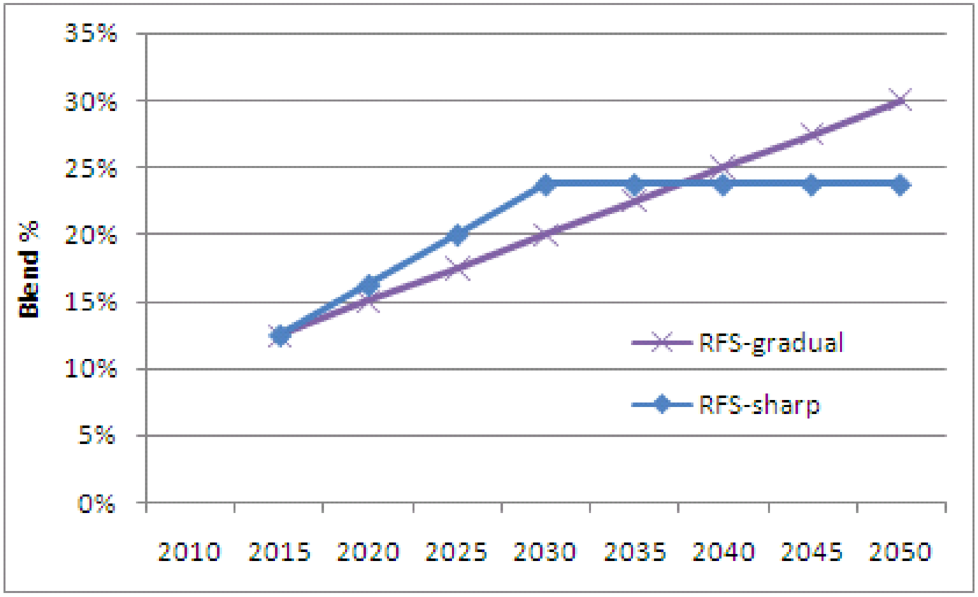
Year	FES 2050 – Gradual				FES 2030 – Sharp			
5-year average	% below 2010	UA L/100 km	A L/100 km	A mpg	% below 2010	UA L/100 km	A L/100 km	A mpg
2005-2010	0.0%	9.1	11.4	20.6	0.0%	9.1	11.4	20.6
2010-2015	9.1%	8.3	10.4	22.7	12.5%	8.0	10.0	23.5
2015-2020	18.1%	7.5	9.3	25.2	25.0%	6.8	8.6	27.5
2020-2025	27.2%	6.6	8.3	28.3	37.5%	5.7	7.1	33.0
2025-2030	36.3%	5.8	7.3	32.3	50.0%	4.6	5.7	41.2
2030-2035	45.3%	5.0	6.2	37.7	50.0%	4.6	5.7	41.2
2035-2040	54.4%	4.2	5.2	45.2	50.0%	4.6	5.7	41.2
2040-2045	63.4%	3.3	4.2	56.3	50.0%	4.6	5.7	41.2
2045-2050	72.5%	2.5	3.1	74.9	50.0%	4.6	5.7	41.2

Note: UA – unadjusted (regulatory target), A – adjusted (on-road fuel consumption)

6.2.2 Renewable Fuel Standard (RFS)

Another policy that targets reductions in petroleum use is the Renewable Fuel Standard (RFS), which is fully described in **Chapter 2**. An RFS mandates that a portion of the fuel supply be composed of an alternative fuel, in this case advanced biofuels.[36] The Energy Independence and Security Act (EISA) of 2007 set a national RFS policy that phases in biofuels in increasing volumes to reach 36 billion gallons by 2022. In the EPPA model the production of blended fuel required by the biofuels mandate is represented by an alternative production function for motor vehicle fuel characterized by a fixed percentage of biofuels and petroleum-based fuels defined by the policy in each model period.

Fig. 6.2 The targeted biofuels blending percentages under two representative RFS policies that achieve the same cumulative gasoline use reduction.



Biofuels are represented in the EPPA model as an advanced liquid fuel that has negligible life-cycle GHG emissions. While a biofuel with these idealized features is available today, research to reduce cost and GHG emissions (as well as to develop biofuel variants compatible with the existing fuel system—so called “drop-in” fuels) is ongoing. Today, biofuels blended into the fuel supply are far from carbon neutral and most can only be introduced up to a maximum “blend wall” before modifications in the vehicle’s fuel system are needed. The EPPA model does not represent these near-term (also called “first generation”) biofuels options explicitly, although in the base year a small fraction of the liquid fuel supplied at the pump is assumed to consist of first-generation biofuels (mainly ethanol from corn). Advanced “drop-in”

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[36] The Low Carbon Fuel Standard (LCFS) is related to the RFS in the sense that it requires changes in the composition of the fuel supply, but has included a broader selection of alternative fuels beyond advanced low carbon liquid fuels. The LCFS policy is discussed in more detail in Chapter 2.

biofuels are represented in the EPPA model, and their adoption is constrained by the availability and cost of land required to grow them (Paltsev et al., 2005). In the model, advanced low carbon biofuels are assumed to be available at a cost markup of 2.1 relative to conventional refined motor gasoline at the refinery gate. Since even first-generation biofuels did not 10% of the total fuel supply in 2010, the first blending target for advanced biofuels in the model is set for 12.5% in 2015.[37]

For this analysis, I consider two alternative paths for introducing biofuels. These paths are shown in **Figure 6.2**. Both RFS trajectories achieve the same cumulative fuel use reduction as the two FES policies described above. The RFS-gradual case involves a gradual increase from 12.5% in 2015 to 30% in 2050. The RFS-sharp case rises more quickly from 12.5% in 2015 to 23.75% in 2030, and then remains constant thereafter. The target blend percentage in the RFS-sharp case was chosen to produce the same cumulative gasoline use reduction, after constraining the starting point to the same level as the FES-gradual path.

6.3 Transport-focused Energy Policy Analysis

6.3.1 Which Policy Reduces Cumulative Gasoline Use by 20% at Lowest Cost?

The objective of this part of the analysis is to compare the regulatory policies described above in terms of their impact on GHG emissions and policy cost associated with achieving a 20% reduction in cumulative gasoline use between 2005 and 2050. These policies are then compared to a tax on gasoline (a constant *ad valorem* tax starting in 2010) designed to achieve an identical level of cumulative fuel use reduction over the same period. I compare the costs of the policies and the resulting technology outcomes associated with achieving the same level of fuel use reduction under six different policy paths (FES – sharp and gradual, RFS – sharp and gradual, and two gasoline taxes under different assumptions about the availability of advanced biofuels).[38] For the tax policy, the model was solved iteratively at different tax levels (effective in 2010) to find a level that produced the same reduction as the regulatory policies.[39] In all cases

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[37] Although first-generation biofuels represented less than 5% of the fuel supply in 2010, they are not considered advanced low carbon biofuels. The EPPA model defines the target in each period in terms of advanced low carbon biofuels only.

[38] The gasoline tax increases the pump price of gasoline in later periods to the point where biofuels become an economically-attractive substitute for gasoline (and market-driven adoption of biofuels reaches over 40% of the fuel supply by 2050).

[39] This tax is applied *ad valorem* before the application of refining and retail margins as well as per-gallon national average tax, and does not apply to any advanced biofuels blended into the fuel supply.

identical assumptions were made regarding the relationship between income and passenger vehicle demand, availability and cost of ICE improvements, and the availability and cost of alternative fuel vehicles as described in the reference case in **Chapter 5**. The resulting tax level (assuming biofuels are available) was an *ad valorem* rate of 45%.[40] If biofuels are not available, the required tax is to 75%.

Different gasoline reduction paths result under each of the policies. The gasoline reduction trajectories for each of the policy paths relative to the reference case are shown in **Figure 6.3**. In the FES policy cases (**Figure 6.3a**), it takes much longer to start achieving reductions in total gasoline use, primarily because the policy only affects fuel use in new vehicles. In the case of the renewable fuel standard (**Figure 6.3b**), both trajectories begin to reduce fuel use starting in 2015 when biofuels are first blended into the fuel supply. The reduction in gasoline use reflects both the gasoline displacement effect of introducing renewable fuel, and the consumer response to higher fuel prices (since the biofuels component is expensive, raising the total price of the blended fuel and reducing demand). If a gasoline tax is used and biofuels are available, the required tax is lower because biofuels start to displace gasoline completely as soon as they become cost competitive. As shown in **Figure 6.3c**, sharp reductions in gasoline use occur in 2045 and 2050, which are due to the market-driven introduction of advanced biofuels as they become economically attractive relative to gasoline. As a result, the reductions in distance traveled and investments in fuel efficiency do not need to be as aggressive in the earlier periods. In the absence of biofuels, the tax needs to be higher, incentivizing more significant gradual changes over the same period to make up for the reductions that biofuels would otherwise achieve.

I now report the simulated cost and CO_2 emissions changes associated with achieving the 20% gasoline reduction target using each of these policy instruments. Here, CO_2 is assumed to be the target of all policies as it is the main GHG associated with transportation. Cost is defined here as equivalent variation, which is an economic measure of the change in consumption relative to a reference (No Policy) case. Costs are expressed in present value using the 4% discount rate, which is also assumed in the EPPA model structure.

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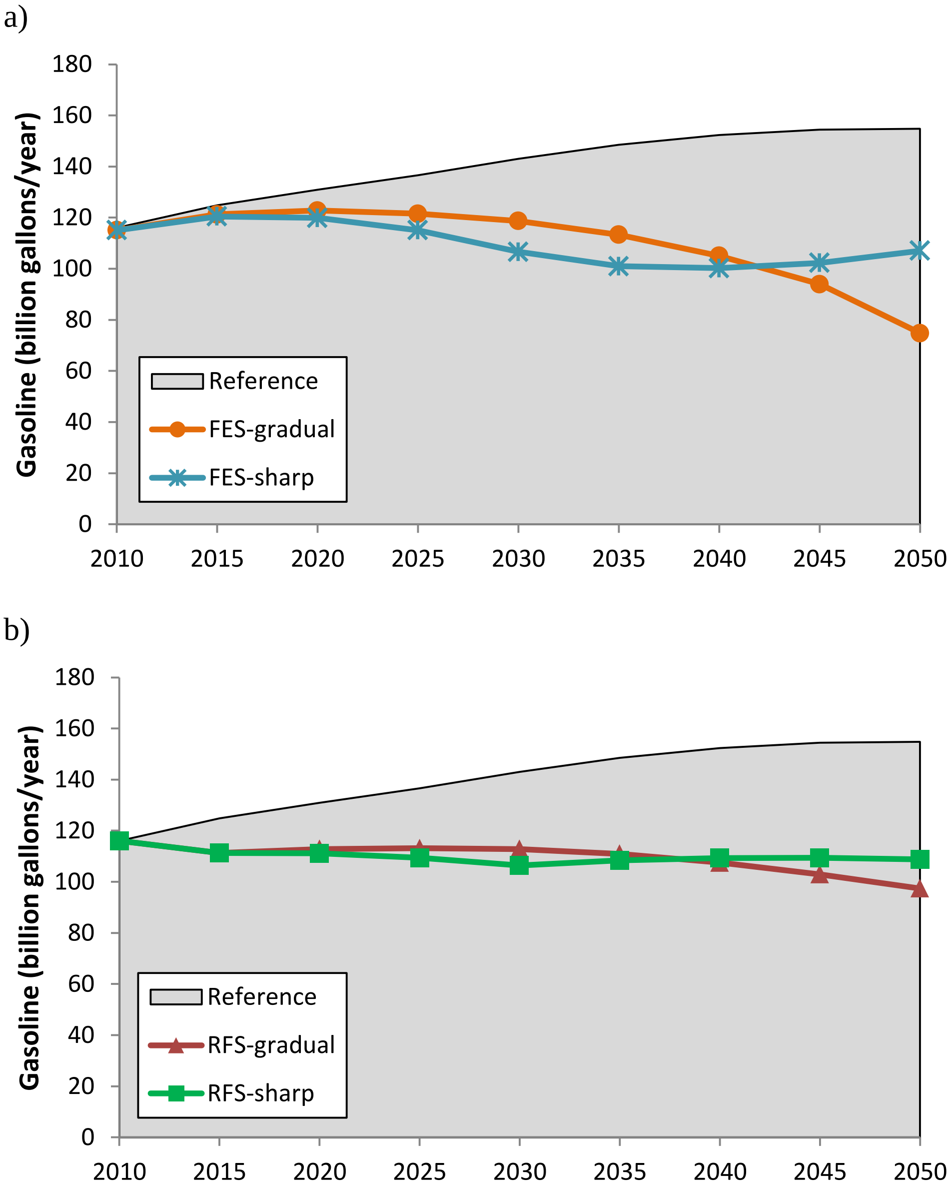
[40] The price of petroleum in the reference (No Policy) case rises over time due to the effects of rising demand and increasingly scarce supply, and as a result the constant tax is multiplied by a higher base gasoline price, increasing the amount of the tax in absolute terms. The retail gasoline price increase includes refining and distribution margins.

Fig. 6.3 Gasoline reduction trajectories for a) the fuel economy standard, b) the renewable fuel standard, and c) the gasoline tax (with and without biofuels) that achieves a total cumulative reduction in gasoline use of 20% relative the reference (No Policy) case.



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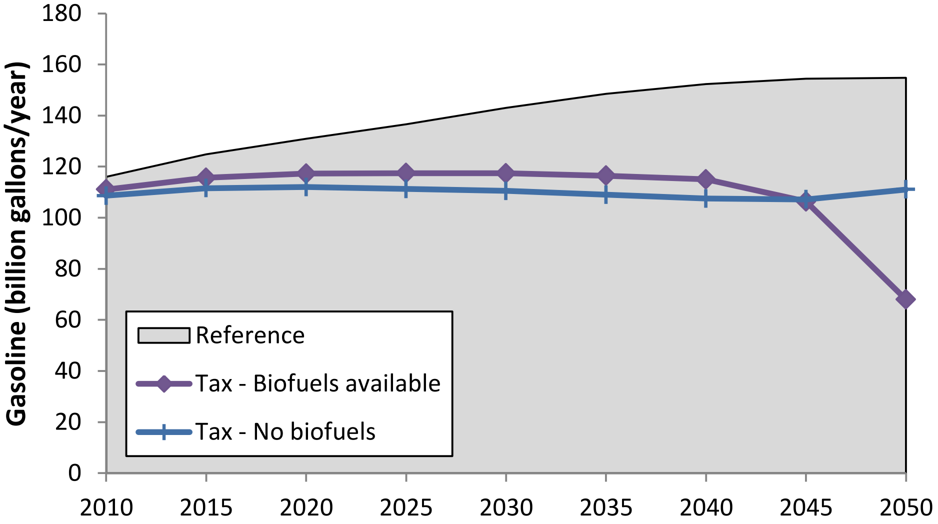
c)

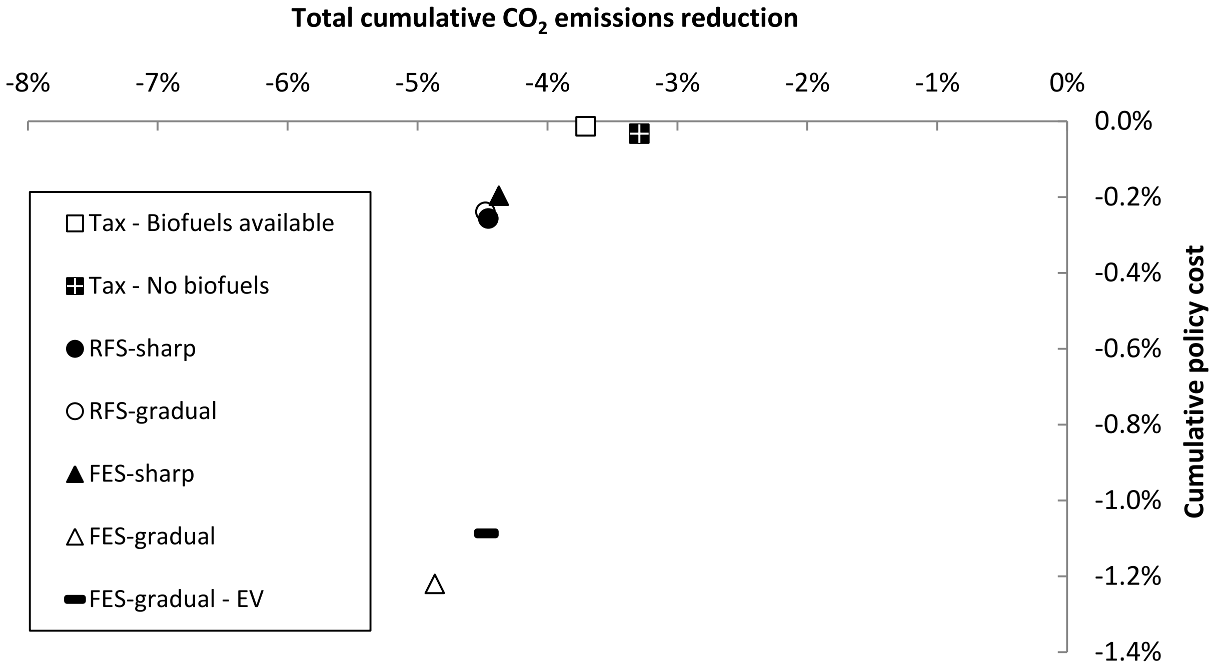


The costs and associated GHG emissions reductions under each of the policies are shown in **Figure 6.4**. The first observation is that for the same cumulative gasoline reduction, the FES and RFS policies are at least six to fourteen times more expensive in than under the gasoline tax, with the relative cost advantage depending on the availability of advanced biofuels in the tax cases. Comparing the two fuel economy standards, the gradual path is much more expensive than the sharp path. To understand why, it is important to consider how the policy operates. Its mandate is limited to increasing the efficiency of new vehicles, while its impact on gasoline use depends on how intesively the vehicles are driven. In order to achieve significant reductions in gasoline use, the higher efficiency vehicles must be driven on the road over multiple years. Thus for a linear path to achieve the same reduction in gasoline consumption, the target in the final compliance year must be very tight in order to compensate for the effects of the more relaxed standard in earlier periods. The marginal cost associated with obtaining additional reductions from advanced internal combustion engine (ICE) vehicles and plug-in hybrid electric vehicles (PHEVs) to produce a five-year new vehicle fleet average fuel consumption of lower than 2.5 L per 100 km (unadjusted fuel consumption) increases non-linearly and is very high at these low fuel consumption levels. If the electric vehicle (EV) is available at a markup of 60% (and assumed to offer an equivalent range and other functionality as an ICE vehicle or PHEV), the cost of achieving this tough target is reduced by more than half, demonstrating the importance and sensitivity of this result to the cost and availability of advanced vehicle technology and fuels.

Figure 6.4 compares the cost and the CO_2 emissions impacts of the two FES policies, the two RFS policies, and the two taxes. The results are shown in **Figure 6.4**. The results indicate that for a fixed level of cumulative gasoline reduction (20%), the cost and CO_2 emissions impact varies. A fuel tax is the lowest cost way of reducing fuel use, with a total cumulative discounted cost of $1.7 or $0.7 billion, respectively. The impact on CO_2 emissions is slightly less under the tax because the tax has the effect of increasing the relative price of fuel used in passenger vehicles relative to fuel used in other non-covered transportation modes, and fuel demand (as well as CO_2 emissions) from these related sectors increases slightly relative to the reference case. Both the RFS-sharp and RFS-gradual cases have a cost and CO_2 emissions impact slightly higher than the FES-sharp cases but much lower than the FES-gradual cases, which has the highest cost of all.[41] In the FES-gradual case the cost is sensitive to the availability of EVs (which, if available, result in a reduction in cost from $63 billion to $56 billion).

Fig. 6.4 A comparison of the cumulative change in total fossil CO_2 emissions and household consumption in a) graphical and b) tabular form from 2005 to 2050 for the two FES policies, the RFS policy, and the gasoline tax that achieve the same level of cumulative gasoline reduction from passenger vehicles.

a)



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[41] The fact that the FES-gradual case has the highest cost is related in part to the recursive-dynamic structure of the model, which does not allow expectations about standard stringency to influence the response of manufacturers in earlier periods. To investigate this issue further, a forward-looking model would be preferable. Banking and borrowing of fuel economy reduction credits is also not modeled in this analysis.

b)

Policy	Change in fuel use (billion gallons)	Change in Emissions (bmt)	Change in cost (billions/ year, DR = 4%)	% Fuel	% Emissions	% Cost
FES-sharp	-1370	-16	10	-20%	-4.4%	-0.20%
FES-gradual	-1375	-17.8	63	-20%	-4.9%	-1.22%
FES-gradual - EV	-1361	-16.4	56	-20%	-4.5%	-1.09%
RFS-sharp	-1357	-16.3	13	-20%	-4.5%	-0.26%
RFS-gradual	-1383	-16.4	12	-20%	-4.5%	-0.24%
Tax – biofuels	-1385	-13.6	1.7	-20%	-3.7%	-0.01%
Tax – no biofuels	1363	-12.1	0.70	-20%	-3.3%	-0.03%

Each of the regulatory policies achieves reductions in GHG emissions relative to the baseline case, although these reductions are relatively modest. Cumulative fossil CO_2 emissions reductions are less than 5% in all cases, with the smallest reductions achieved under the two tax policies. Part of the reason why the tax policies result in lower cumulative reductions is due to the combination of a large increase in the relative price of petroleum for passenger vehicles relative to other sectors. By increasing the retail price of gasoline, the gasoline tax has the effect of reducing total petroleum demand, which results in lower relative prices of petroleum in sectors excluded from the tax. This larger relative price difference has the offsetting effect of increasing fuel demand and associated CO_2 emissions in these sectors.

6.3.2 Policy Design and Technology Adoption

The model forecasts how each policy design affects the combination of gasoline reduction opportunities pursued as a result of the regulation. The scope and target of each policy has a large impact on the opportunities chosen. For example, a policy focused on reducing gasoline use by expanding the contribution of a renewable fuel to the fuel supply will overlook other low cost gasoline reduction opportunities.[42] By contrast, policies that act through the price of new vehicles or fuels may trigger a multi-faceted response, inducing shifts to alternative vehicle technologies or fuel types, or incentivizing investments in efficiency.

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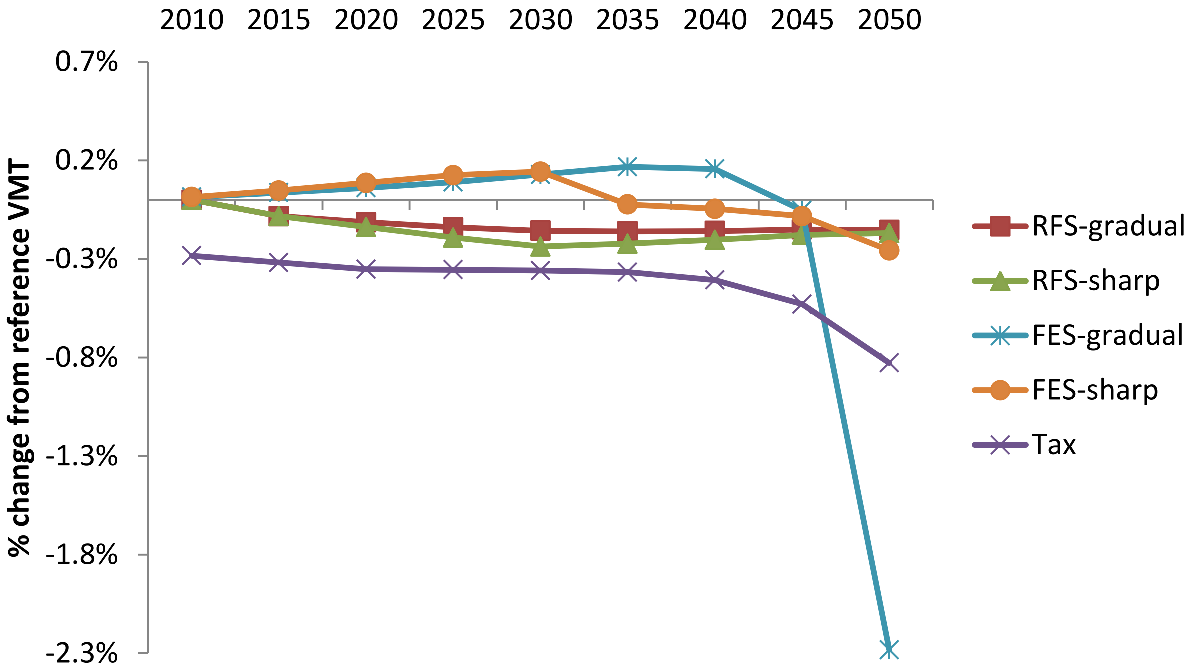
[42] The RFS policy does have some indirect effects on vehicle efficiency and PHEV adoption because it causes an increase in the gasoline price, incentivizing above-reference levels of investment in reducing fuel consumption.

Fig. 6.5 Changes in VMT relative to the reference case when policies are applied.



The EPPA model captures several avenues for reducing gasoline use: 1) increasing ICE vehicle fuel economy, 2) reducing vehicle-miles traveled, 3) switching to alternative liquid fuels, and 4) introducing advanced powertrain types such as the plug-in hybrid electric vehicle (PHEV). For each of the policies described above, a different combination of these strategies is employed in response to the policy signal. Here I briefly describe the responses under each policy, which are illustrated in terms of the effects of each of the policies over time.

Figure 6.5 illustrates the effect of each of the policies on total passenger vehicle VMT, relative to the reference case. In both of the fuel economy standard cases, total VMT actually increases slightly through 2030 above reference in response to a decrease in the fuel cost per mile of driving. After 2030, VMT declines, either moderately through 2050 (in the FES-sharp case) or more dramatically (in 2050 in the FES-gradual case) as the efficiency improvements required in vehicles cause the price to rise so dramatically that it discourages new vehicle purchases, which is reflected in reductions in VMT. Both RFS policies induce a reduction in VMT relative to the reference case because the blending requirement for biofuels increases the fuel cost, which scales with the required blend percentage. Finally, the tax acts earliest to produce an immediate reduction in VMT by increasing the fuel price to higher levels relative to the RFS or FES cases. The tax bears on both the consumer’s extensive (vehicle purchase) as well as the intensive (vehicle use) margin, encouraging immediate, sharp reductions in VMT that are not incentivized under the other policies. Moreover, this price signal affects drivers of both new and used vehicles, resulting in reductions in fuel use in both the new and used fleets.

Fig. 6.6 The ICE-only vehicle fuel consumption trajectories under different policy scenarios.

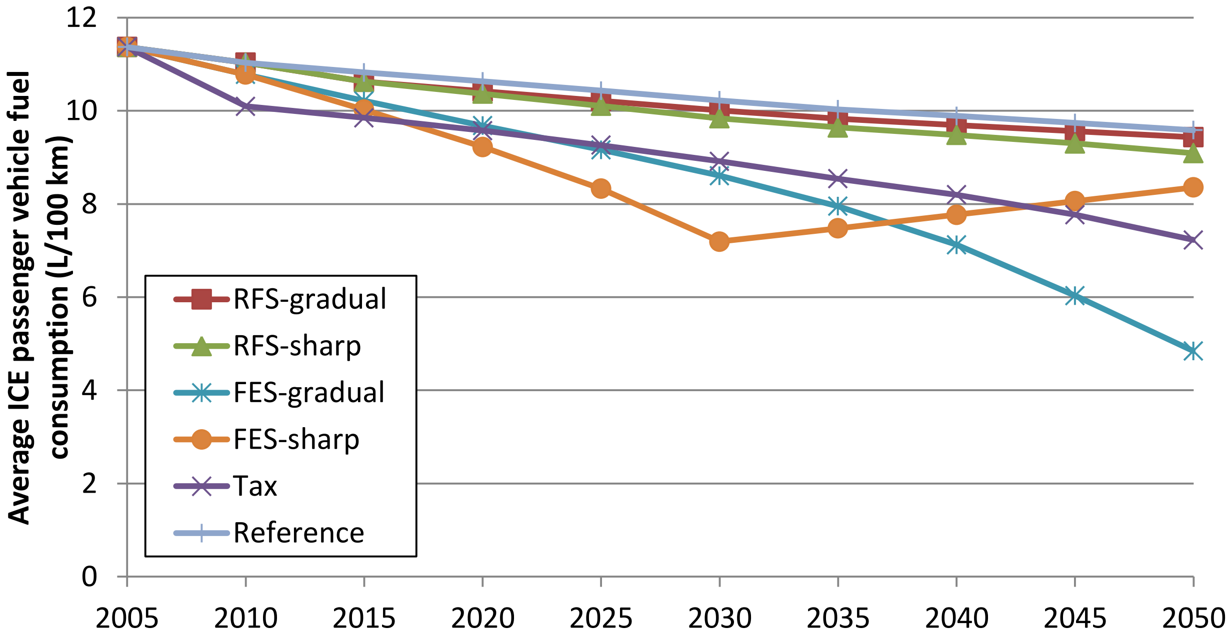


Figure 6.6 shows the impact of the policies on the fuel consumption of new ICE-only passenger vehicles over time. The fuel consumption for ICE vehicles does not necessarily follow trajectories because the PHEV is also counted towards meeting the standard. In fact, without the PHEV, the 2030 target in the sharp reduction path would be very difficult to meet, even with off-grid hybrid electric vehicle (HEV) technology applied across much of the new vehicle fleet. The fuel economy standards require the most aggressive reductions in vehicle fuel consumption, with the FES-sharp policy requiring large changes by 2030, while the FES-gradual policy requires significant increases through 2050. To be consistent with such dramatic reductions in fuel consumption as observed under the FES-sharp case, ICE-only vehicle fuel consumption would have to be reduced by more than half by applying aggressive hybridization, turbo-charging and downsizing, and weight reduction across the new vehicle fleet. Manufacturers would also likely reduce production of vehicles with high fuel consumption under these circumstances in order to achieve such an aggressive target. Both RFS paths do not result in significant changes in ICE-

only vehicle fuel consumption relative to the reference case, with only modest additional reductions due to gasoline prices that are slightly higher relative to the reference case. The tax has a pronounced but relatively steady effect on fuel consumption starting in the first compliance year (2010).

Fig. 6.7 PHEV adoption trajectories that result from applying policies.

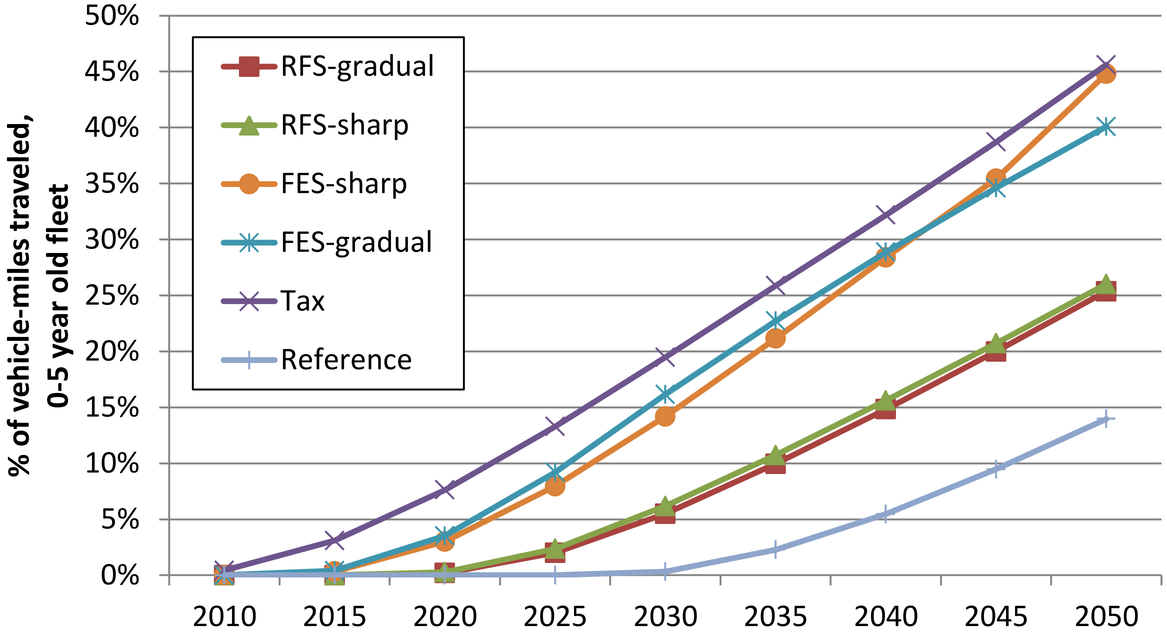


Figure 6.7 shows the impact of the different policies on the adoption of PHEVs, in terms of the share of VMT by zero to five-year-old vehicles. The PHEV is assumed to cost 30% more than the comparable ICE vehicle, and is also subject to initial adoption constraints as described in **Chapter 4** and **Appendix A**. A comparison of the two FES policy paths indicates that PHEVs play an important role in both cases, once they become the most cost-effective option for meeting the constraint. The tax, by contrast, induces adoption by acting through the fuel price, and as a result adoption proceeds slightly faster since there is an economic motivation for consumers (in the case of the FES policy manufacturers must cross-subsidize high fuel efficiency vehicles in order to meet the program’s targets, in the absence of price-driven consumer demand).[43] Finally, even in the reference case, rising fuel prices over the period of interest lead

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[43] This cross-subsidizing behavior is not modeled explicitly in EPPA but is assumed to be reflected in the retail price of the representative vehicle.

to an increasing contribution from the PHEV, although it accounts for only 13% of VMT by zero to five year old vehicles by 2050.

Table 6.1 Summary of forecasted travel demand and technology response under policies.

Scenario	ΔVMT in 2030	ICE fuel cons. 2030 (L/100 km)	ICE fuel cons. 2050 (L/100 km)	% PHEV in new VMT 2030	% PHEV in new VMT 2050	Cost ($ billion / year USD 2004)	Loss (%) relative to reference
Reference	N.A.	10.2	9.6	0%	14%	N.A.	N.A.
Gasoline tax (biofuels)	-0.36%	8.9	7.2	19%	46%	0.70 *No biofuels: 1.7*	0.01% *No biofuels: 0.03%*
FES-sharp	+0.13%	7.2	8.4	14%	45%	10	0.2%
RFS-gradual	-0.16%	10	9.4	16%	25%	12	0.2%
RFS-sharp	-0.24%	9.8	9.1	6.1%	26%	13	0.3%
FES-gradual	+0.14%	8.6	4.8	5.5%	40%	63	1.2%

The above trajectories describe more fully the way policies act in the model to incentivize reductions in gasoline use. A summary of the effects of each policy on VMT, fuel economy, and PHEV adoption is shown in **Table 6.1**. An important result of this analysis is to show exactly how a tax acts most efficiently to achieve the policy's goal: it incentivizes changes across many parts of the vehicle-fuel-user system according to least cost. The ICE-only vehicle fuel economy improves modestly and PHEVs grow as a share of vehicle VMT through 2050. A modest reduction in demand for VMT from all vehicles also contributes to the reduction in gasoline use. Finally, if available, biofuels are introduced in 2045 and 2050 only. Under a tax, fuel economy improvements ramp up more quickly in the earlier model periods, while biofuels only play a role in the later periods, when they are adopted in response to market signals. The fact that fuel economy increases in early periods translate into a reduced requirement for biofuels in later periods further reduces the cost of the policy.

6.4 Combining a Renewable Fuel Standard and a Fuel Economy Standard

Under the least costly policy above (the gasoline tax), vehicle fuel economy improvements and demand response (VMT reduction) begins in earlier periods, while biofuels play a role in later periods if they are available. Policymakers may instead prefer to achieve this type of multifaceted response using separate, targeted policy instruments that bear on different parts of the system. An example of this type of policy approach involves combining a vehicle fuel economy standard with a renewable fuel standard. Regulatory impact assessments typically focus on one policy at a time, making assumptions about the energy efficiency or carbon intensity of related parts of the system. However, there may be overlap in the gasoline reduction strategies an RFS and FES policy motivate, and so it is worth considering whether the magnitude of reductions under a combined policy will be equivalent to the sum of the policies implemented in isolation, or not.

Table 6.2 A comparison of cumulative change in gasoline use, total fossil CO_2 emissions, and household consumption from 2005 to 2050 for the four RFS and FES policy combinations.

a)

Scenario	Average change in gasoline use (billion gallons/year)	Average change in total CO_2 emissions (Mt/year)	Average annual policy cost (billion USD/year)	% change gasoline	% change CO_2 emissions	% change cost
RFS-gradual, FES-gradual	-44	-550	67	-32%	-7.5%	-1.3%
RFS-gradual, FES-sharp	-44	-520	20	-32%	-7.1%	-0.39%
RFS-sharp, FES-gradual	-44	-550	69	-32%	-7.5%	-1.3%
RFS-sharp, FES-sharp	-44	-520	21	-32%	-7.1%	-0.41%

b)

Scenario	Average gasoline use (billion gallons/year)	Average CO_2 emissions (Mt/year)	Average annual consumption (billion USD/year)*	% change gasoline	% change CO_2 emissions	% change cost
Reference (annual average)	*138*	*7,300*	*14,120*	*N/A*	*N/A*	*N/A*

For the comparison here, I consider four possible pairings of the FES and RFS paths from the analysis above. For each policy type, I consider a sharp and a gradual reduction path. As before, all policies implemented individually achieve the same cumulative gasoline use reduction. As before, all cumulative quantities correspond to the period from 2000 to 2050.

The results of the comparison are shown in **Table 6.2**. One important point to note is that the reductions under the combined policies are less than the sum of reductions taken under each of the policies individually (each policy individually achieves a reduction of 20%). Each of the combined regulatory policy approaches achieves a reduction in cumulative gasoline use of approximately 32%, or around 20% less than the expected sum of reductions under each policy implemented in isolation. Total reductions under each policy are because each policy has an offsetting effect on the ability of the other policy to achieve its target. For example, improving vehicle efficiency, all else equal, leads to increases in total VMT, and thus greater biofuels volumes are required to meet the mandate. The discounted cost of the policies implemented in combination, however, is roughly equal to the sum of the discounted costs of the policies individually.

6.5 Combining Transport-focused Energy Policies with an Economy-wide Cap and Trade (CAT) Policy

At the national level U.S. policymakers have considered a range of policies targeting petroleum use and GHG emissions. Any comprehensive policy to address GHG emissions will require reductions in GHG emissions from the transportation sector, and from passenger vehicles in particular. However, the role that passenger vehicles will play in achieving GHG emissions reductions has been subject to debate. Reducing passenger vehicle fuel use is generally considered one of the more costly sources of GHG emissions reductions relative to other sectors of the economy. In the previous section I showed how reductions of CO_2 emissions, the major GHG associated with transportation, were modest under each of the transport-focused energy policies (and combinations), in part because the policies induced shifts to uncovered sectors as well as alternative vehicle and fuel types that were not in fact carbon-free, and in part because a 20% reduction in passenger vehicle fuel use is, at most, equivalent to approximately 5% of total cumulative economy-wide CO_2 emissions. Focusing again on CO_2 emissions, here I explore the effects of combining a fuel economy standard (FES) or a renewable fuel standard (RFS) with an economy-wide cap-and-trade (CAT) policy targeting CO_2, with the objective of describing the trade-offs between cost and favoring reductions in passenger vehicle fuel use under a CO_2 emissions constraint.

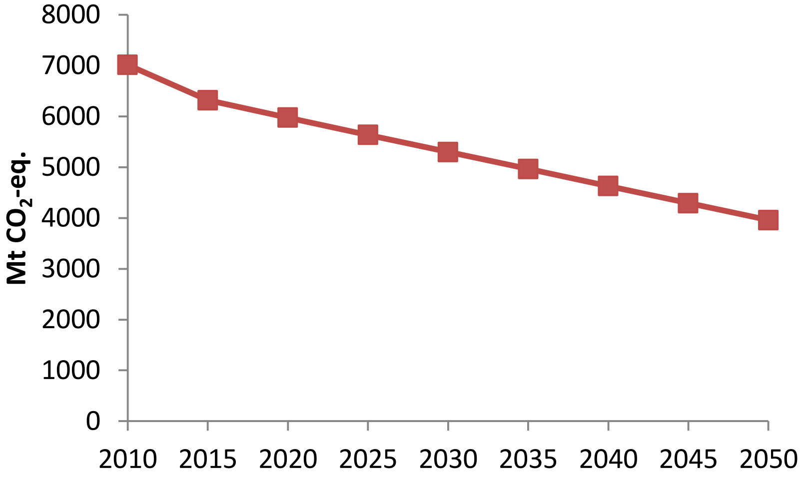
This chapter is organized as follows. First, I describe the CAT policy as implemented in the EPPA model, and the adjustments in energy use throughout the economy that occur in response to a representative CAT policy through 2050. Second, I describe the results of combining a CAT policy with an FES policy and RFS policy in terms of the impact on cumulative fuel use, GHG emissions reductions, and cost. A sensitivity analysis using the model indicates that the magnitude of fuel reduction under a CAFE standard in both the presence and absences of an economy-wide CO_2 constraint is sensitive to the assumed consumer payback period.

6.5.1 Description of the CAT Policy in the EPPA Model

A cap-and-trade (CAT) policy is a constraint on GHG emissions from covered sectors across the economy. Regulated sources then engage in trade that results in the allocation of reductions to emitters with the lowest marginal cost of abatement. The CAT policy instrument is a longstanding feature of the EPPA model and was adapted for this analysis (for more information, see Paltsev et al., 2005; Clarke et al., 2007). A CAT policy is defined by the sources covered, the stringency of the constraint over time, and a reference baseline relative to which GHG emissions reductions are measured.

The CAT policy represented in this analysis is based on policies recently proposed in the U.S. Congress. The policy considered is defined by a GHG emissions target with gradually increasing stringency, reaching a reduction of 44% of GHG emissions in 2030 relative to 2005. The GHG emissions reduction targets are consistent with the Waxman-Markey proposal that passed the House of Representatives in 2009, which includes a modest amount of international offsets (ACES, 2009).[44] The policy trajectory is shown in **Figure 6.8**.

Fig. 6.8 CO_2-equivalent emissions path under the CAT policy considered in this analysis.



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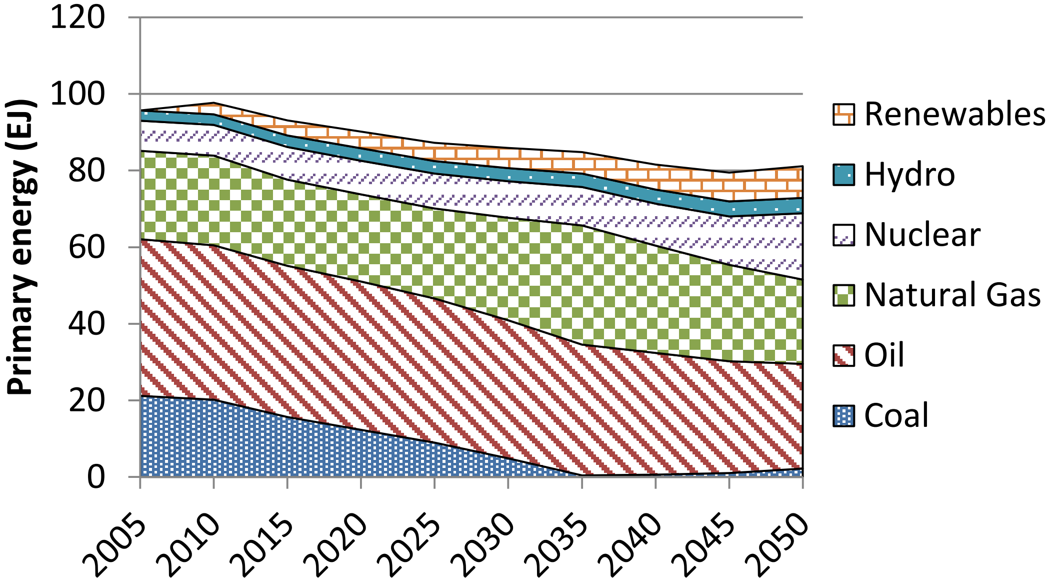
[44] International offsets are reductions that are taken from emissions sources not covered by the policies, but once certified by an appointed authority reductions can be used to meet some fraction of the GHG emissions reduction obligations of covered sources. Offsets are expected to reduce the cost of the CAT policy.

The unmodified version of the EPPA model gives a projection for primary energy use in the United States shown in **Figure 6.9** below. Under this representative CAT policy, coal (used primarily in the electricity sector) is phased out in favor of nuclear, natural gas, and renewable sources. Most of the changes in energy use occur in the electricity sector, while petroleum (refined oil) use, including use by passenger vehicles, does not decline as significantly. The model also produces a GHG emissions price in dollars per ton CO_2 equivalent, which rises under the model assumptions used in this analysis to around $200 per ton CO_2-equivalent by 2050 as the cap tightens.

Fig. 6.9 Total primary energy use by type in the United States under the CAT policy.



The impact of the CAT policy on passenger vehicle fuel use, CO_2 emissions, and PHEV adoption in the absence of additional regulation is shown in **Table 6.3** below.

Table 6.3 The impact of a CAT policy on passenger vehicle gasoline use, total CO_2 emissions, and the new VMT driven by PHEVs in 2050.

Scenario	Gasoline – passenger vehicles (billion gal)	Total CO_2 emissions (Mt)	% PHEVs in new VMT, 2050	Gasoline – passenger vehicles (% change)	Total CO_2 emissions (% change)
Reference	6,900	370,000	14%	N.A.	N.A.
CAT Policy	3,800	230,000	42%	-45%	-38%

It is important to note that the availability of advanced biofuels with negligible CO_2 emissions affects the role that passenger vehicles will play under the GHG emissions constraint.

If advanced GHG neutral biofuels are available to be used in passenger vehicles, they are introduced widely during the period from 2030 to 2050.

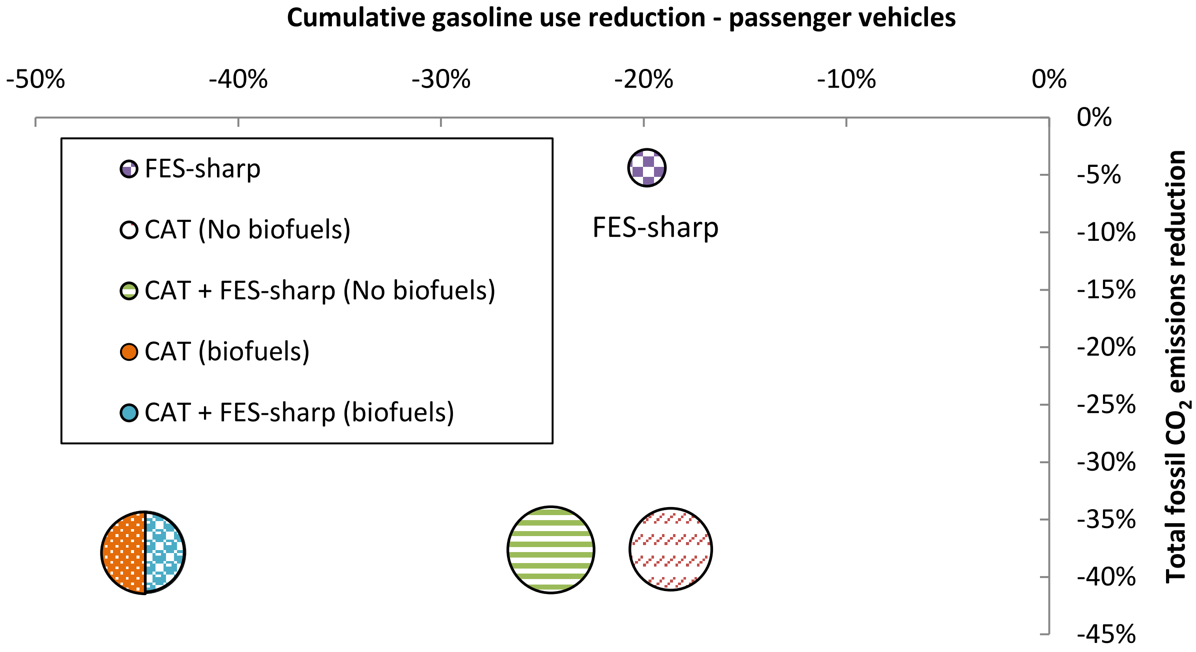
6.5.2 Combining Transport-focused Energy Policies with a CAT Policy

I now consider the impact of combining a CAT policy with each of the transport-focused energy policies described in the previous chapter.

6.5.2.1 CAT Policy and FES Policy

An important question for policymakers involves determining the impact of adding a regulatory policy that targets reductions in gasoline use to a CAT policy that targets economy-wide reductions in GHG emissions. First, I consider the effects on policy cost, gasoline use reduction, and economy-wide fossil CO_2 emissions reduction. For simplicity and because the FES-gradual policy is much more costly, I consider only the sharp reduction path as described in **Section 6.2** in combination with the CAT policy. In the absence of advanced, carbon-neutral biofuels, model results show that combining the FES-sharp with the CAT policy results in additional reductions in gasoline use, but also increases the cost of the policy (**Figure 6.10**). The total reduction in CO_2 emissions does not change, because that reduction is set by the cap. It is interesting to compare the implied costs of displacing gasoline and GHG emissions (which are joint products) that result from the policy analysis. Assuming that the goal of the FES-sharp policy was solely to reduce gasoline use, the discounted cost per gallon of displacing gasoline is \$0.37. If reducing GHG emissions were the only goal, the implied cost would be \$31 per ton. Under a CAT policy, reducing gasoline use is not the primary target of the policy; nevertheless, if reducing gasoline was the only goal, it would be achieved at \$2.00 per gallon. Under a CAT policy, GHG emissions reductions are achieved at an average cost of \$18 per ton. When the FES-sharp is added to the CAT policy, additional cost of the gasoline reductions beyond those that would occur under the CAT policy only is \$0.68 (per additional gallon displaced). If biofuels are available, significantly greater reductions in gasoline use are cost-effective under the CAT policy, and the FES-sharp does not change the magnitude of the reductions achieved. As long as advanced biofuels with negligible GHG emissions are available, they are the preferred abatement option in the later model periods. The cost, cumulative fossil CO_2 emissions reduction, and cumulative gasoline use reduction remain unchanged with the addition of the FES policy, because the cap determines GHG emissions and the FES policy is not binding.

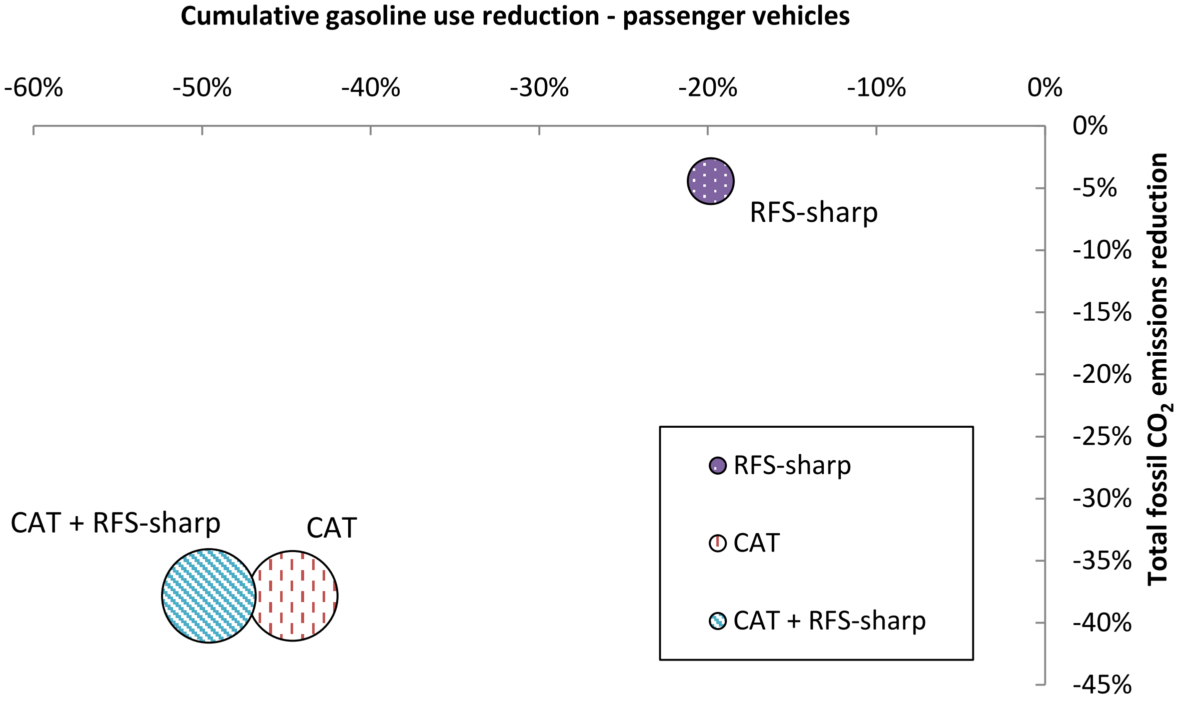
Fig. 6.10 A comparison of the cumulative change in gasoline use, total fossil CO_2 emissions, and household consumption from 2005 to 2050 under a FES and CAT policy with and without advanced biofuels available.



6.5.2.2 CAT Policy and RFS Policy

I now consider the consequences of combining an RFS policy with a CAT policy, focusing on the RFS-sharp (**Figure 6.11**). In the scenarios considered the RFS policy increases the reduction in cumulative gasoline use relative to the CAT policy alone, and also results in a slight increase in cost (-1.6% relative to -1.5% change in consumption relative to the No Policy baseline). The implied price of gasoline displaced beyond what occurs under a CAT policy alone is $0.63 per gallon. In these cases it is important to distinguish between biofuels that are introduced in compliance with the regulation and biofuels that enter once prompted by market signals. In this case, I do not consider a case without advanced biofuels (because it is assumed that if biofuels are available to meet the mandate, they could also be encouraged by market signals).

Fig. 6.11 A comparison of the cumulative change in gasoline use, total fossil CO_2 emissions, and household consumption from 2005 to 2050 under a RFS-sharp and CAT policy.



6.6 Conclusions

This chapter has compared a set of policies in terms of their impact on passenger vehicle gasoline use, total economy-wide fossil CO_2 emissions, and household consumption (economic cost). By focusing on policy paths that achieve the same cumulative reduction in gasoline use through 2050, it is possible to identify how policies lead to different technological and behavioral outcomes (where behavior refers here to demand for vehicle-miles of travel).

The main findings of this chapter can be summarized as follows. First, the model results indicate that the regulatory instruments (FES and RFS policies) considered would be at least six to fourteen times as costly as the tax. In the case of a fuel economy standard, the FES-sharp path in which the policy ramps up rapidly through 2030 is preferred to the FES-gradual path that requires large reductions in later periods, in part because under the gradual policy more vehicles with a relatively higher efficiency must be added in later periods to achieve the required cumulative reduction. The effects of the RFS in terms of gasoline reduction, GHG emissions reduction, or costs did not differ substantially between the gradual and sharp trajectories, because adding biofuels to the fuel supply allowed greater reductions from both new and used vehicles (relative to a fuel economy standard) and did not depend on fleet turnover to phase it in gradually over time. Obviously, the effects of an RFS would be limited if the advanced biofuels considered here were not a perfect substitute for gasoline.

Second, it was shown that all policies achieved comparable, albeit relatively modest (<5%), reductions in cumulative total economy-wide CO_2 emissions, with the tax achieving the lowest reduction of all the policies considered in part due to offsetting effects on petroleum use in unconstrained sectors.

Third, I show that when an FES and RFS policy are implemented in combination, the reduction is around 20% less than the sum of the reductions under the policies individually, while costs are nearly additive.

Fourth, I show that when an FES or RFS is combined with a cap-and-trade system, any additional reductions beyond what would have been achieved by the cap come at a cost. The cost of these additional reductions depends on the availability and cost of alternative fuel vehicles and fuels. In general, it is less costly to take additional reductions from passenger vehicles by introducing biofuels into the fuel supply (rather than raising new vehicle fuel economy) because biofuels introduction affects gasoline use and emissions across a larger share of the total fleet, not just new vehicles.

Additional work could be usefully focused on testing the sensitivity of GHG emissions reductions and technology outcomes under alternative assumptions about the GHG emissions footprint associated with biofuels. Also, the gasoline tax cases used for comparison made the assumption that the *ad valorem* tax rate was applied uniformly over the period of interest. Finally, it would be interesting to compare the results from EPPA5-HTRN, the recursive-dynamic model used here, with a forward-looking model to consider the effects of the FES-gradual path on the timing of investment in abatement technology in earlier model periods, and its effect on the total cost of the policy.

Chapter 7: Political Analysis

"Never mistake motion for action."

Ernest Hemingway[45]

Previous analysis in this thesis has established why a price instrument (gasoline tax) is most cost-effective policy approach to reduce petroleum use from passenger vehicles. However, in the United States, less cost-effective alternative policies, including a fuel economy standard and renewable fuel standard, have been preferred in practice. This chapter investigates additional considerations beyond cost effectiveness that have influenced policy outcomes. I argue here that in the case of passenger vehicle policy, often the attributes that make policies cost effective also reduce their political feasibility, and vice versa. I place the U.S. case in international context, showing how the policy path the U.S. has taken may make moving directly to a gasoline tax particularly difficult. Using the model results in earlier chapters, I use evidence of the distributional impacts across sectors to show how modifications to existing policies can be evaluated both in terms of cost effectiveness as well as stakeholder support. This approach can help policymakers identify politically feasible near-term actions that will help to establish the support necessary to move to more cost-effective policies over time.

7.1 Introduction

Economic analysis offers a few clear principles for policy decisions. Tailor policy interventions to target undesirable outcomes directly, remaining mindful of the effects of interactions with closely related policies. Price the adverse impact of use into the product, ensuring that the premium scales with the harms. Include, to the extent possible, all the sources, as well as all the abatement opportunities, within the scope of the policy, so that the targeted parties will face incentives to employ the least-cost solutions.

However, the public debate over how to regulate petroleum use and greenhouse gas emissions from passenger vehicles in the United States is only partially about the economics. The issue of whether a gasoline tax achieves policy objectives at the least aggregate cost to society is often a sideshow in national debates. Instead, a range of non-economic factors—ideology, the distribution of policy impacts, the ease of implementation, and political process constraints—seem to be just as important, if not decisive, to the policy outcomes we observe. What, then, does this reality mean for the role of economic analysis, and the prospects for economically "optimal" policies?

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[45] In Venstra (2008).

The economic analysis in previous chapters demonstrates that out of the policies considered, a gasoline tax is the least costly policy alternative for reducing petroleum use. However, in the United States, it seems that policies currently in effect represent everything but the tax option. The case for a gasoline tax appears all the more compelling when viewed in an international context. Indeed, the taxes on petroleum-based transportation fuel in the United States have remained the lowest of any advanced industrialized nation. This divergence suggests that trade-offs between economic efficiency and political feasibility on gasoline tax policy have played out differently in various national contexts.

In this chapter, I argue that in the policy-making arena, sharp tensions often arise between the prescriptions of economic analysis and the characteristics of policies, aside from cost, that make them politically workable in a particular national context. First, I develop a list of several factors that contribute to a policy's political feasibility, including ideological appeal, incidence of impacts, ease of implementation, and political process considerations. Second, I show how political feasibility considerations in these broadly defined categories often clash with economic prescriptions in several respects—at the level of policy justification, policy type, and design choices within policies—for the case of passenger vehicles. I argue that these tensions make it difficult or potentially impossible to implement economically-optimal passenger vehicle energy and climate policy designs in the U.S. context. Observations of these tensions in automotive energy and GHG emissions regulation help to explain some of the policy outcomes of the past, and provide the context for policy decisions in the future. Given that strong tensions arise and create trade-offs for policymakers, first-best policies from an economic standpoint are unlikely to be implemented in practice. Third, I position the U.S. policy situation in an international context, and offer several explanations for why gasoline taxes have been much harder to legislate in the U.S. relative to other advanced industrialized countries. This section also explores the trade-offs policies impose at the level of individual stakeholders.

This chapter concludes by suggesting that decision makers must remain keenly aware of the relative costs of policies today, as well as the impact that a chosen policy will have on underlying conditions that will affect support for more cost-effective policy designs in the future. This emphasis on actively evolving incentives should be combined with a mechanism for revisiting and adjusting policies over time in response to changing conditions.

7.2 Defining Political Feasibility

The security and environmental impacts associated with passenger vehicle fuel use arise because these impacts are not priced into the fuel itself—in other words, they are externalities. These externalities over time will result in degradation of two public (non-excludable, non-rival) goods—the atmosphere and national security. In order to protect and provide an optimal level of each of these goods to citizens, barriers to collective action must be overcome (Olson, 1971). One widely-recognized function of government is to act on behalf of the public interest in ways that overcome these barriers, because the market alone will fail to result in optimal stewardship of these common resources. Yet the policymaking process is fraught with its own requirements, including the need to satisfy powerful, often concentrated, interests. These constituencies tend to be vocal in shaping the policies that affect them (Stigler, 1971). The skeptical analyst might ask, for any particular policy choice, which course of action is preferable—reliance on the unconstrained market, or a policy intervention that has survived the scrutiny of the political process. The following paragraphs define in detail what is meant here by these potentially divergent alternatives.

In order to develop an argument that the economics and politics are in tension, I first define a set of factors that affect political feasibility. To this end, I have identified a set of conceptual policy characteristics or aspects of the policy process that influence a policy's endorsement and, ultimately, its passage into law. Here I focus on four factors that have characterized the political process with respect to regulation of passenger vehicles as well as other environmental issues: ideology, the distribution of impacts, ease of implementation, and political process constraints.

7.2.1 Ideology

The political process is fraught with the influence of ideology, which is perhaps most prominent in the espoused positions of political parties. Ideologies may also be reflected in more nuanced positions, such as fiscal conservatism or issue-based stances related to freedom of speech, energy independence, environmentalism, or the welfare state. These are ideals that may resonate with particular interest groups, stakeholders, or political parties in ways that determine the acceptability or unacceptability of policy proposals. For example, in the case of passenger vehicles, over the course of its history the car has alternatively served as a symbol of freedom of mobility, technological progress, and industrial strength. Meanwhile, energy security and energy independence have remained on the list of public priorities, and addressing it would mean potentially sacrificing one ideology—freedom of mobility—in favor of another.

7.2.2 Distribution of Impacts

How the impacts of policies are distributed—or perceived to be distributed—is an important determinant of support. Distributional issues are important in passenger vehicle policy in primarily two ways. First, impacts of policy are distributed across the population, depending on individual as well as household vehicle ownership and use patterns. For instance, the work in **Chapter 3** has shown how increases in fuel prices elicit different responses depending on income, urbanization, vehicle ownership, and other factors. One avenue to overcome equity-based objections is to redistribute the revenue collected to reduce the impact on vulnerable groups, however they are defined. The design of a revenue recycling scheme requires understanding which groups of the population are hit hardest, and then successfully selling the program, which could be tricky if redistribution schemes do not satisfy the most vocal groups (which may not be equivalent to those most harmed).

Second, impacts are distributed across sectors, which differ from individuals in that they represent foremost a particular productive activity in the economy, have larger resource bases, and may enjoy greater direct political influence. To the extent that a policy is either financially harmful or ideologically unpalatable to influential stakeholders, that proposal could be at a disadvantage relative to policies that do not harm, or possibly reward, their interests. Firms typically have more information about the costs of compliance than policymakers do, and this information asymmetry leaves regulators reliant on firms to inform the regulatory process.[46] Stigler (1971) asserts that regulated parties face strong incentives to exact favorable provisions in the process of informing regulations. By similar logic, the re-distribution of impacts through stakeholder negotiations shapes policies in ways that could improve prospects for implementation but, without oversight, may dilute potency.

Third, impacts may be distributed in time. Policy decisions reflect an implicit rate of time preference, that is, the value of money in the present relative to the future. The choice of the

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[46] One example is the case of regulation of diesel emissions in Europe, the United States and Japan, in which it was shown that automotive firms would deliberately withhold information or would flaunt regulatory procedures in order to gain competitive advantage (Ng, 2006).

discount rate in evaluating policies is often subject to debate, and for policy evaluation purposes the choice of discount rate may be tied to ideology.[47] The way the impacts are spread over time can have large effects on stakeholder attitudes toward them. Postponing stringent or costly action further into the future is one way for a policymaker to speak to two audiences—those that want strong action (eventually), and those who want little cost (now). One example in vehicle policy is the case of the FreedomCar program, which focused on research and development of hydrogen fuel cell vehicles in order to address dependence on foreign petroleum imports and climate change concerns over the long term, despite the fact that at the time experts believed the costs to be ten to 100 times as high as conventional vehicles (Sandoval et al., 2009). A key critique was perhaps not the fact that it existed but that it seemed to exist in lieu of measures to address the problem in the short term. The fact that postponing pain may be a politically powerful way to sell policy is at odds with the notion that large benefits may accrue to action in the near term. For example, as discussed in **Chapter 6**, increasing the stringency of a fuel economy standard early on can reduce the total discounted cost of the policy over the compliance period.

It is worth noting that it is not just the distribution of impacts, but their visibility, that strongly affect a policy's prospects in the political arena. A dollar of tax on each gallon at the pump may be significantly more visible than a modest change in the price of a new vehicle at the dealership, since consumers purchase new vehicles far less frequently. To the extent that visibility of a policy's impacts is greatest for a vocal set of a policy's opponents, it may have difficulty gaining traction as a politically viable proposal. This resistance may be especially strong if low gasoline prices over an extended period corresponded to ever greater reliance on vehicles, especially if alternative transport modes are not readily available.

7.2.3 Ease of Implementation

Policies may gain little traction if they require collaboration across stakeholder groups or sectors that have disparate interests, autonomous (and potentially conflicting) oversight and enforcement capabilities, and scant history of cooperation. For instance, when reducing a target substance would require the cooperation of multiple interacting sectors, it may be more straightforward and less costly to draw up regulations that affect one sector and make

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[47] For different positions on the discounting issue, see for example discussions in Ackerman and Heinzerling (2004) and Viscusi et al. (2001).

assumptions about how other sectors (uncovered by the regulation) will respond. If assumptions about the response of uncovered sector(s) prove wrong, the regulation could be far less effective than intended. However, representatives of the covered sector would be acting in their own interest if they tried to avoid being held responsible for the effects of actions taken by the uncovered sectors, since otherwise they would be running the risk of incurring costs they could not control.

A policy approach might also be judged based on the complexity of procedures required for its effective implementation. One example is the choice of regulatory designs for nitrogen oxide, in which a cap-and-trade system that created separate trading regimes for individual detectors was arguably the most efficient design (Atkinson & Tietenberg, 1982). Under such a system, however, regulators have to determine and update initial permit allocations frequently, and firms must manage the complexity of holding permits in multiple emissions markets (Martin, 2007).

7.2.4 Political Process Constraints

Election cycles, institutional structures, and policy processes for decision-making can place constraints on the type of policies that get passed into law. For instance, the timing of events in the political process can be very important to constituents' perceptions and their resulting support for policies. It may be easier to get a gasoline tax passed in the wake of an oil embargo, while climate legislation may find more supporters after a heat wave or several devastating hurricanes. Such events exert their impact on the policy process by raising political will and creating “windows of opportunity” (to borrow from the innovation and security studies literatures), but proposals must then surmount other barriers created by the political process (Sartorius & Zundel, 2005; Van Evera, 2001).

The height of these barriers depends on the type of process that must be employed in order to implement a policy, as well as the extent of consensus required. In the case of legislative action (which is required for the passage of new taxes or new large initiatives to be carried out by the government agencies), the status of other ongoing legislative priorities and the availability of decision makers could have a large effect on whether or not new laws can be passed, or whether the issue will even find its way onto the agenda. Another distinction of the legislative process is its visibility and importance in determining the balance of political power between the two major political parties as well as among coalitions of political actors representing specific interests. When a vote is required, voters, political analysts, and journalists may pay more attention than they would to a court decision or agency rule-making, given that the latter institutions are focused on interpreting the law rather than establishing it.

Another barrier is the simple fact that consensus is important for a policy to succeed. The degree of consensus required varies depending on a country's political institutions. A policy cast only in terms of catering to a single cause may fall flat while one that appeals to multiple constituencies may stand a better chance of success. Combining agendas may also have advantages from the perspective of the political process, because multiple priorities combined into a single policy need only be sold to decision makers once as a complete package, rather than requiring multiple votes or prolonged discussion.

A final barrier is germane to highly technical issues that require assessment of specialized knowledge as part of the policy process. This specialized knowledge extends to the natural and social sciences as well as to the engineering details that characterize the problem. This process is often undertaken in-house or by external consultancies. Knowledge must also be made available in a timely manner and presented in a way easily understood by decision makers (Stokey & Zeckhauser, 1978). One challenge that emerges is that the advocates most likely to commission a knowledge assessment are also those most likely to have an interest in shaping the policy, perhaps in their own favor. Factual discrepancies that arise in the course of legislative design or agency rule-making may reflect the biases of experts commissioned by parties with opposing views. Economic analysis is likewise at risk of being drawn into the fray to serve positions on either side of a debate.

This section has outlined several (though not all) important influences that can affect a policy's political feasibility. I now consider how these considerations align (or not) with economic efficiency imperatives in the case of passenger vehicle transportation in the United States.

7.3 Tensions between Economic Efficiency and Political Feasibility

This section applies the framework developed above to the case of policy options for regulating petroleum use from passenger vehicles. The analysis in earlier chapters began with a comparison of policies that address fuel use, focusing on the renewable fuel standard (RFS), fuel economy standard (FES), and gasoline tax (tax). For the RFS and FES policies, I considered both sharp and gradual reduction paths. Here I discuss the relationship between the results that emerge from the economic studies and the political feasibility considerations outlined above. I argue that strong tensions between the economic prescriptions and the determinants of political feasibility help to explain the adoption of more technology-specific regulatory policies (such as an FES or RFS policy) for the purpose of reducing gasoline use by passenger vehicles.

To focus the discussion of tensions between the economics and politics, I define three levels of the policy design process where political considerations become particularly important, and tend to trade off with economic considerations. The first is the level of policy justifications—in other words, how a policy is sold to lawmakers, industry, and the public. The second is the level of policy type—the choice of a policy tool for a specific job, such as a gasoline tax for gasoline use reduction. The third is the level of design choices within policies—the timing of policy targets, the coverage of emissions, and the types of compliance strategies allowed or incentivized. Different types of political considerations become important at these different levels, as illustrated in **Table 7.1**, which has been filled out based on the policy cases considered here. For each level, the argument will be fleshed out with both historical as well as contemporary examples from policy to illustrate the origins and consequences of these tensions.

Table 7.1 Role of political considerations at different levels of the policy process.

Stage in policy design process	**Political considerations**			
	Ideology	**Distribution of impacts**	**Ease of implementation**	**Political process constraints**
Policy justification	X			X
Policy type	X	X	X	X
Policy design choices		X	X	

7.3.1 Tensions at the Level of Policy Justification

How a policy is justified to the affected parties can determine whether or not it finds support, as well as who supports it. The connection between the justification given for the policy and what the policy achieves in practice may not be obvious or precise, but can nevertheless be politically powerful. The ability to link a proposed policy to current, often rapidly changing political priorities can affect its prospects for passage into law. In this section I draw on historical examples of justifications for passenger vehicle policy intervention that are closely related to the policies studied in earlier chapters. I use these examples to illustrate the role that policy justification has played in the success or failure of policies, arguing that a convincing justification—and not necessarily one related to a policy's primary target—has been necessary, even if not sufficient, for policy success. The focus of the discussion then shifts to contemporary policy, to consider how recent policy designs have been justified. Reviewing the list of historical and contemporary political influences described above, the roles of ideology and political process constraints seem to clash most strongly with economic prescriptions to pursue policies tailored to particular goals. This section concludes by arguing that the examples provided reveal a tension between the economics and politics at the level of policy justification.

7.3.1.1 Historical Examples

Two historical policies for passenger vehicles provide insight into the role of policy justification in the determinants of policy success: the federal gasoline excise tax and the Corporate Average Fuel Economy (CAFE) standard. In order to avoid selecting on the dependent variable—policy success—I consider instances where increases in the gasoline tax as well as the CAFE standards were unsuccessful. Moreover, I have selected the historical policy analogues closest to proposals considered in the economic analysis in previous chapters. Although these policies are described in detail in **Chapter 2**, a brief description follows here. First imposed in 1932, the federal gasoline excise tax is a levy per gallon of gasoline sold.[48] The Energy Policy and Conservation Act (EPCA) in 1975 established the CAFE standards, which starting in 1978 required that each manufacturer must achieve an average regulated fuel economy in the mix of new vehicles sold (EPCA, 1975).

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[48] State gasoline taxes preceded the excise tax on gasoline at the federal level. The first state to pass a gasoline tax was Oregon in 1918.

Table 7.2 Attempts to change the Federal Excise Tax on gasoline and justifications.

Rate of the Federal Excise Tax on Gasoline in cents per gallon (or proposed increase)	Dates	Successful?	Justification
1	June 21, 1932, to June 16, 1933	Yes	Rectify depression-era budget imbalances
1.5	June 17, 1933, to December 31, 1933	Yes	Rectify budget imbalances
1	January 1, 1934, to June 30, 1940	Yes	Prohibition ends, providing alternative revenue source
1.5	July 1, 1940, to October 31, 1951	Yes	Raise revenues to support World War II expenditures
2	November 1, 1951, to June 30, 1956	Yes	Raise revenues to support Korean War expenditures
3	July 1, 1956, to September 30, 1959	Yes	Raise revenues for highway expansion and repair
4	October 1, 1959, to March 31, 1983	Yes	Increase federal highway aid under existing programs
(15)	1973-1975	No	Initially studied as brake on inflation / response to Arab oil embargo
(50)	1977	No	Energy security
9	April 1, 1983, to December 31, 1986	Yes	Expansion / completion of interstate highway system / job creation
9.1	January 1, 1987, to August 31, 1990	Yes	Leaking underground storage tank (LUST) fund re-established
9	September 1, 1990, to November 30, 1990	Yes	LUST fund target reached and tax terminated
14.1	December 1, 1990, to September 30, 1993	Yes	Infrastructure funding and deficit reduction, LUST tax reinstated
18.4	October 1, 1993, to December 31, 1995	Yes	Deficit reduction
18.3	January 1, 1996, to September 30, 1997	Yes	LUST tax terminated
18.4	October 1, 1997, to March 31, 2005	Yes	LUST tax reinstated

Sources: Talley, 2000.

Justifications for the gasoline tax have varied over time, with the most successful justifications including lowering the federal deficit and spending on infrastructure improvement, as shown in **Table 7.2**. Initially, the gasoline tax was justified as a way to rectify budget imbalances caused by reduced revenues due to the depression in the 1930s and subsequent government expenditures on public works programs (Talley, 2000). By contrast, energy security or environmental justifications have been less successful, although until the 1970s these concerns were also arguably less salient. Nevertheless, two attempts to introduce gasoline taxes in the 1970s based (at least in part) on energy security arguments were unsuccessful, perhaps in part because the proposed increases were dramatic relative to existing levels of taxation.

Ideology has affected the justification of gasoline taxes in several ways. Efforts to raise the gasoline tax in the 1970s ran aground in part due to conflicts with political ideologies on both sides of partisan lines. The Ullman plan introduced in 1975 proposed to increase the gasoline tax by 10 cents per gallon per year for four years, and included equity-enhancing provisions such as coupons for a fixed number of tax-free gallons per week (Sullivan, 2008). The proceeds were to be used to finance development of alternative energy sources. However, some democrats opposed the program because they viewed consumption taxes as regressive, while republicans opposed the taxes on principle, all the more so because they would have been highly visible to consumers while gasoline prices were also rising (Sullivan, 2008). It was only with a return to the original justification of interstate highway expansion did an increase in the gasoline tax (albeit more modest than prior proposals) gain traction.[49] As the episodes in the 1970s indicate, debates over the gasoline tax have often divided along partisan lines. The later success of efforts in the 1980s to justify taxes as “user fees” to support infrastructure projects is perhaps not surprising, given that those most affected by the tax—drivers, particularly over long distances—also benefit directly from infrastructure investments. The purpose of the tax as a source of infrastructure funds had also long been established, so that it was arguably easier to obtain a doubling of the tax by justifying it on historical precedent.

The success of the gasoline tax in the 1980s required its proponents to surmount several political constraints. The gasoline tax introduced into Congress in 1983 narrowly survived a filibuster in the Senate, and broad bipartisan support helped to overcome opposition, in part because the bill was sold as both a jobs bill and a roads bill (Sullivan, 2008). Whether or not these justifications were tightly correct appeared to be a secondary consideration. The president’s chief economic advisor even pointed out at the time that as a result of the policy jobs could

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[49] The proposal was also justified in Congress as a jobs bill, a rationale later denied by Reagan (Sullivan, 2008).

decrease in the near term (Cowan, 1982). However, this case highlights the advantages of appealing to multiple causes in order to mobilize the necessary bipartisan support.

Historically, the CAFE standard has also relied on a combination of justifications to enhance support. Part of the Energy Policy and Conservation Act of 1975 (EPCA), the CAFE standard was in many ways viewed as an alternative to a gasoline tax as a way to respond to the Arab oil embargo and the resulting first energy crisis in 1973. Over the previous decades, automobile ownership had been increasing apace, while the fuel economy of new vehicles was actually declining. Raising the efficiency of the vehicle fleet was largely viewed as necessary to offset this trend and was expected to have the effect of offsetting growth in gasoline demand, which would in turn reduce upward pressure on oil imports. Unlike the gasoline tax, the CAFE standard has a shorter history and a narrower set of goals has been used to justify it. Here I consider how combined justifications for the CAFE standard made it more palatable than using a gasoline tax to achieve the same purpose.

It is interesting to consider the arguments put forward on behalf of the CAFE program since its inception. The justification during the 1970s was primarily to reduce gasoline use by raising the fuel efficiency of the passenger vehicle fleet, and indeed reducing gasoline use has always been the primary goal from the standpoint of policy coverage and target. However the objectives of the policy have shifted over time. Environmental appeals only increased over the 1990s amid greater global attention to climate change in the policy debate.

The increased focus on an environmental rationale occurred despite the fact that environmental goals were arguably not being addressed in an economically efficient way, given the scope and metrics of the CAFE policy, a topic that will be discussed later at the level of policy design choices. A National Academies report in 1992 stated: "…replacing the cast iron and steel components of vehicles with lighter weight materials (e.g., aluminum, plastics, or composites) may reduce fuel consumption but would generate a different set of environmental impacts, as well as result in different kinds of indirect energy consumption" (NRC, 1992). Another study conducted by the Office of Technology Assessment around the same time suggested that the GHG emissions benefits would be small: "A 40 percent increase in fuel economy standards would reduce greenhouse emissions by only about 0.5 percent, even under the most optimistic assumptions" (OTA, 1991). Including environmental concerns did draw greater support for the policy, which may have become especially important as the energy crises of the 1970s faded further from political memory. Environmental justifications for increasing CAFE did not succeed in bringing about a tightening of the policy during the 1980s and 1990s. Only with the Clinton administration in the 1990s did both President Clinton and Vice President Gore publicly announce support for the policy on both energy security and environmental grounds. A U.S. Congressional Budget Office Study in 2003 referred to CAFE standards as an environmental program (CBO, 2003). The environmental rationale for a CAFE standard is also cited in articles before climate justifications were officially included in cost-effectiveness estimates for the program (Austin & Dinan, 2005).

7.3.1.2 Contemporary Examples

Recent examples of energy policies for passenger vehicles have simultaneously been advertised as climate policies explicitly, even if their primary goal is not to reduce GHG emissions. Policy examples examined in this thesis include the latest round of CAFE standards and the Renewable Fuel Standard (RFS). Additional examples include stimulus programs aimed at increasing the production of alternative fuel vehicles, creating an infrastructure for alternative fuels, and providing consumer tax credits for alternative fuel vehicle purchases.

Given the number of references to the potential of CAFE standards to serve as an effective environmental program, it is perhaps unsurprising that when the standards were finally revisited in the late 2000s and substantially tightened, environmental metrics were included alongside the effects on gasoline use. The Energy Independence and Security Act of 2007 included reference to reducing GHG emissions as well as improving vehicle fuel economy, and mandated under the fuel economy heading that federal vehicle purchases must be certified as “low greenhouse gas emitting” vehicles (EISA, 2007). In the CAFE regulations for Model Year 2011, GHG emissions impacts were required to be reported alongside gasoline use reduction in cost-effectiveness calculations.

The explicit addition of environmental goals to the CAFE standards did not happen until the standards set under the 2007 EISA for vehicle fuel economy were superseded by the 2010 CAFE standards. In late 2009 the EPA was required to rule on whether or not GHG emissions endangered human health and the environment. At this point, pressure on the U.S. government to take action on climate change was increasing. Prior to the economic downturn in the second half of 2008, gasoline prices had hit record levels, public concern in the United States over the climate issue was high, and the Copenhagen conference on a global climate treaty was approaching. In 2009 a comprehensive climate bill (H.R. 2454 or the Waxman-Markey Act of 2009) passed the U.S. House of Representatives (ACES, 2009). Climate goals in the form of per-mile GHG emissions targets were included under a new "National Program" that created harmonized fuel economy and per-mile emissions targets. This program is jointly administered by the U.S. Environmental Protection Agency (EPA) and Department of Transportation's National Highway Traffic Safety Administration (NHTSA) (DOT & EPA, 2009).[50]

The 2010 CAFE rulemaking for 2012 to 2016 model year vehicles represents an instance where a second policy goal was added to an existing program to create a new regulatory function. However, this harmonized program may not be comparably cost effective in achieving gasoline use and GHG emissions reductions. First, the program does not consider GHG emissions associated with fuel production upstream for a wide variety of fuel types, which would reward producers for switching to technologies that displace gasoline use but do not necessarily result in GHG emissions reductions. Second, the program allows automotive manufacturers to meet the per-mile emissions standard in part through changes in the air conditioning system, which lowers the actual fuel economy target that manufacturers must meet. Verifying that these different reductions have in fact been achieved is likely to require new testing procedures, as well as harmonization of penalties for non-compliance, increasing the complexity of implementation (GAO, 2010). Third, the program gives special treatment to vehicles that are classified as advanced technologies (such as PHEVs, EVs, or FCEVs) as well as vehicles that run on high percentage blends of advanced fuels (flex-fuel vehicles or FFVs), which may further increase the distortions associated with excluding upstream emissions from the coverage of the regulation (EPA, 2010b). As this analysis shows earlier, if combined with a cap-and-trade system, the fuel economy standard (and its equivalent per-mile emissions standard) will not increase emissions reductions beyond the level achieved under the CAT policy alone.

A second contemporary policy example I consider here is the renewable fuel standard (RFS) included as part of the Energy Independence and Security Act of 2007 (EISA, 2007). The

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[50] The "National Program" was a compromise worked out after California released its own ambitious per-mile emissions targets for vehicles. Starting in 2009, the U.S. Environmental Protection Agency was charged with oversight of the per-mile GHG emissions program under the Clean Air Act (after finding that GHGs endanger human health and the environment), while NHTSA retained responsibility for the CAFE program administration. Prior to the National Program, NHTSA administered the CAFE program, while the EPA was charged only with oversight of the fuel economy test procedures.

RFS policy calls for the blending of 36 billion gallons of biofuels into the fuel supply by 2022. The justifications provided for this policy are the promotion of renewable fuel, both to displace gasoline and to reduce GHG emissions. Beyond 2016 all increases in biofuels supplied must come from "advanced biofuels," which are defined as cellulosic biofuels and fuels from feedstocks other than corn (EISA, 2007). Renewable fuels produced by bio-refineries must reduce the life-cycle GHG emissions footprint by 20% relative to conventional fuels in order to be counted (EISA, 2007). The appeal to both environmental and energy security goals, as well as agricultural interests, was important to mobilizing support for the policy, irrespective of its cost effectiveness relative to other options.[51]

In both the cases of the FES and the RFS, ideological opposition is less strong relative to the case of taxes. Making vehicles more efficient or encouraging introduction of gasoline substitutes in the fuel supply do not impose highly visible costs at the pump or require behavioral changes, which may partly explain why these policies have been legislated successfully. In neither case are the costs as visible to the consumer as the case of a gasoline tax. A fuel economy standard might increase the price of new vehicles on average, but households buy new vehicles infrequently and also have used car options to choose from. While an RFS that requires biofuels be blended into the fuel supply may have the effect of raising the price of the fuel (assuming biofuels are not receiving other subsidies, which could help to keep the price low), the analysis in previous chapters has shown that fuel prices will rise. However, the connection between higher pump prices and the availability of alternative fuels is not a link that consumers are likely to make as easily as that between pump prices and a recently announced tax.

Beyond the policies considered in detail here, it is worth noting that the range of incentives that have been announced to support the introduction of alternative fuel vehicles and alternative fuels have been justified using a combination of goals as well—enhancing energy security, the environment, job creation, and national competitiveness, among other rationales. The role of far-reaching justifications for specific interventions is prevalent here, and probably helps to explain why—at a time when worries over recession and security are strong—the government has succeeded maintaining support for these programs.

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[51] GHG emissions reductions under an RFS will be modest especially if reductions in motor gasoline demand reduce the price and result in higher demand for these fuels in other sectors, or if indirect land use-related emissions are not counted.

7.3.2 Tensions at the Level of Policy Type

Tensions between economic and political considerations also occur at the level of choosing a type of policy to address a particular goal. Even if a policy may be justified for many reasons, it usually has a primary target. This primary target could be achieved with multiple different policy types—for the example of gasoline use reduction, policy options could include a tax, a vehicle efficiency standard, or policies that promote alternative fuel use. In this section I show how choices among policies have tended to favor those where the costs of the policy are less obvious, the features of the policy can be altered to serve re-distributional ends or to carve out provisions favorable to sectoral interests directly affected by the policies, and the political processes—both formal and informal—required to pass legislation are likely to encounter the least resistance. Political considerations, which reflect the influences of ideology, distributional impacts, ease of implementation, and political process constraints, can affect the choice of policy type. The following discussion illustrates how often the features that make a policy attractive from each of these perspectives may be the same features that reduce the cost effectiveness of policies, producing tensions alluded to above. I focus again on the same set of historical and contemporary cases of regulations that target reductions in vehicle gasoline use—the gasoline tax (past and present), the fuel economy standard (past and present), and the renewable fuel standard (present).

7.3.2.1 Historical Examples

Returning to the case of the gasoline tax, I consider only instances when increasing it was considered as a means of reducing gasoline use.[52] A gasoline tax has never been successfully sold as a gasoline reduction policy. Despite several failed attempts to pass gasoline taxes on energy security grounds under the Nixon and Carter administrations, only under the Regan administration did a small increase in the gasoline tax gain traction when once again justified as a road infrastructure "user fee" and deficit reduction tool (Sullivan, 2008). This is partially due to the political difficulties associated with obtaining support for a tax among groups that are

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[52] In earlier sections I considered a broader set of instances when increases in the gasoline tax were considered in order to understand how the policy was sold to the public. It could be argued that the primary mechanism of a gasoline tax is to discourage gasoline use by increasing its price to consumers (and thus infrastructure provision and deficit reduction constitute additional purposes that could potentially be addressed better through more targeted policies). However, the inelastic consumer response to small changes in the gasoline price and the ease of revenue collection has made raising the gasoline tax attractive for purposes other than the goal of reducing gasoline use. Gasoline use reduction did not become a major policy concern until the 1970s.

ideologically opposed. The efforts to implement a gasoline tax during the Nixon and Carter administrations did not overcome these ideological (often partisan) divides. That the concept of a tax, independent of its purpose, the size of the burden, or its distributional implications, can draw strong opposition (especially if rejecting it offers visible political gains) is one illustration of how the politics of taxation are in conflict with the economically efficient policy choices.

The prospects for a particular policy type are intertwined with external circumstances as well as the status of efforts to address the same problem through other forms of policy. It is important to note here that the inclusion of fuel economy standards in the Energy Policy and Conservation Act of 1975 likely reduced pressure to address energy security concerns through gasoline taxation in subsequent years. With oil prices remaining low in the 1990s and earlier energy crises fading into the past, support for higher taxes to reduce gasoline use all but disappeared.

Concerns over the distributional impacts of policies have also made it more difficult to mobilize support for taxes. Objectors to gasoline taxes have cited the visibility of the tax to consumers, particularly certain groups such as low-income drivers, or rural residents that travel long distances. How consumers respond to gasoline taxes in terms of their vehicle purchase and usage decisions is also less clear, creating uncertainty for fuel providers and vehicle manufacturers, which are large employers and contributors to economic output in the United States. Alternative policies that provide certainty about what targets will have to be met, and provide for flexibility in meeting them, may be more acceptable to these influential stakeholders.

Political process constraints have also affected the prospects for a gasoline tax. Given the political challenges associated with obtaining broad bipartisan support for new taxes, proponents have sought alternative channels for implementing them, including working outside traditional legislative processes. As part of his broader energy policy, in 1979 President Carter rejected a gasoline tax as part of his broader energy policy and instead used his authority to implement an oil import fee, which was later struck down by the courts and rejected by Congress (Sullivan, 2008). Since new taxes almost always require a vote by Congress, which can be logistically difficult and require its proponents to wager political capital, it is perhaps not surprising that the President resorted to alternative channels, and that the gasoline tax has found few champions in Congress over the past several decades. These difficulties exist despite the fact that a gasoline tax is widely recognized as the most efficient policy.

The success of vehicle fuel economy standards, in contrast to a tax, can be likewise linked to ideological and distributional considerations that affected the passage of policies aimed at reducing gasoline use. Since fuel economy standards both look and act differently from taxes, proponents of the standards approach may not face the same level of entrenched resistance, and thus may not have to concede as much in the course of negotiations in order to mobilize support. Taxes, by contrast, have remained a political "third rail" (Levine & Roe, 2009).

Beyond ideology, fuel economy standards have historically been accepted by consumers and interested stakeholders because they offer real or perceived benefits to each. Consumers may perceive that the burden of fuel economy standards most directly falls on industry, which is responsible for producing a sales-weighted mix of vehicles that complies with the standard. Even if consumers are required to pay more on average for new vehicles, these purchases are infrequent relative to refueling, and the policy does not incentivize a reduction in driving. In fact, consumers have been observed to drive more as per-mile fuel costs decline (Small & Van Dender, 2007). However, the fact that the fuel economy policy targets only the vehicle (the extensive margin), and not its usage (the intensive margin), that makes it less efficient from an economic standpoint. Even though the automotive industry bears perhaps the greatest burden under the policy, it arguably benefits from the opportunities to influence the way regulations are written, based on its internal knowledge of what is technologically possible as well as what is likely to be profitable.

7.3.2.2 Contemporary Examples

More recently policies designed to address energy security concerns have expanded to include fuel economy standards and renewable fuel standards, while a gasoline tax has only recently been revisited as a deficit reduction tool (Przybyla & Faler, 2010). As explained above, the conspicuous absence of a gasoline tax as a tool of energy policy can be attributed to the factors outlined in historical cases above as well as a general view that, especially in the face of economic downturn starting in 2009, new consumption taxes would be handily rejected. Here I focus on policy actions to increase the fuel economy standards in 2007 and again in 2010 as well as the renewable fuel standard, drawing attention to attributes of the policies that made them attractive relative to the most economically defensible option.

A revitalized Corporate Average Fuel Economy Standard found favor in Congress in 2007 as a tool for reducing gasoline use, with a target of 35 miles per gallon (combined fleet average) set for 2020 (EISA, 2007). At this point, reducing GHG emissions was not a direct focus of the policy. Nevertheless the policy gained traction as an energy policy tool, for perhaps many of the same reasons that proponents had historically supported it: the compliance burden falls mostly on industry, its direct impacts are limited to the new vehicle fleet, and consumers face lower per-mile costs of driving. Hidden burdens, such as a shift to used vehicles that in turn raises vehicle prices for lower income buyers, rely on more complex causal chains of reasoning that were largely overlooked (CBO, 2002).

The fact that both the 2007 and 2010 CAFE regulations were amenable to the inclusion of “flexibility provisions” further helped them to gain the support of the most affected parties. Flexibility provisions, which will be discussed in **Section 3.3** under the heading of policy design variables in more detail, can be more easily incorporated into some policy types than others. Congressional decisions over arcane details of how the standards would apply across vehicle models or manufacturers largely escaped the public spotlight. Just like the costs of the policy, the exceptions (and the political processes through which they can be included) are also less visible with a fuel economy standard relative to a tax. This is another example of the influence of the relative visibility of policy costs on political viability.

The fact that the CAFE policy affects only a relatively small fraction of the vehicle fleet every year in order to achieve the required changes is perhaps one of the sharpest illustrations of why it is politically palatable but economically inefficient. Economically efficient policies provide significant flexibility to allow reductions to be taken starting with the least-cost solutions. By forcing the solutions to come from a limited part of the passenger vehicle transport system, the costs will necessarily be higher (at best, they will be identical, if the least-cost options are also contained in the targeted sector).

In the case of an RFS policy, costs are less visible to consumers (especially if the renewable fuel is subsidized), while potential producers of advanced renewable fuels stand to gain significantly from its implementation. The Renewable Fuel Standard in the EISA of 2007 did not encounter strong opposition in part because it directly carves out a role for a particular advanced technology—biofuels. Supporting a particular technological solution is one way a policy can create winners and losers, and in this case, appeal to popular support for “advanced fuels" (which carries connotations of supporting technological progress without targeting behavioral change, e.g. mileage reduction, on the part of consumers). Meanwhile requiring biofuels carves out a role for their suppliers—including large integrated energy companies, new specialized refiners and producers, as well as farmers responsible for growing the feedstock. The fact that an RFS is popular with both influential constituencies as well as large concentrated interests makes it more politically saleable. However, the aspects of the policy that favor these constituencies also reduce the scope of potential solutions that could be used to achieve the goal. A low carbon fuel standard (LCFS) that allows a wider range of renewable or low carbon fuels to meet the stated target would not guarantee a similarly large role for biofuels, which would in turn reduce support for the policy from interested constituencies.

The RFS also faced fewer political process constraints, given the longstanding history of government subsidies for ethanol in the fuel supply. It is interesting to contrast the case of the RFS with a renewable electricity standard that did not make it into the final version of the bill (EISA, 2007). A renewable electricity standard did not benefit from the same concentrated constituency as an RFS (which through 2015 allowed increases in the required biofuels blend levels to be met with corn-based ethanol if substitutes were not available, gaining the support of corn producers). Renewable electricity producers span a wide variety of technologies—wind, solar, geothermal, hydro—that were arguably not as tightly organized as the renewable fuels (essentially biofuels) lobby, given little precedent for cooperation (subsidies until that time had been directed at specific applications individually, such a tax credits for solar).

This discussion of past and contemporary examples of policies designed to reduce gasoline use by passenger vehicles (and the associated security externalities) illustrates that tensions exist between economic prescriptions and political realities. Policies that share the general features of having less visible costs, limit those costs to a particular part of the system, generate certainty about actions required for compliance, or enable policymakers to compensate or favor concentrated interests in less visible ways seem to have gained the most traction politically. By contrast, these exact features erode the economic efficiency of policies by focusing on limited parts of the system or reducing overall flexibility to meet targets at least cost.

7.3.3 Tensions at the Level of Policy Design Variables

Policy design choices, such as the timing of reduction targets or the scope of actions counted towards compliance, can make a particular policy type more or less efficient from an economic standpoint, or make it more or less attractive to a particular constituency. This section provides a detailed discussion of policy design variables that can be altered within each policy type. Policy design variables can lead to outcomes that are more or less economically efficient; they can also affect the level of support a policy receives. Tensions between these two ends at the level of policy design variables emerge clearly from this discussion, which draws examples from both historical as well as contemporary experience in passenger vehicle regulation.

The number of design choices for a particular policy type is virtually limitless, so it is worthwhile to first mention the concrete examples to be considered in this analysis. As in previous sections, I focus on policies aimed at reducing gasoline use. Here I consider policy design choices that affect the timing of required reductions, the coverage of road transportation fuels and associated GHG emissions, provisions that constrain or incentivize the types of compliance measures that can be employed, and rules about redistributing the costs or benefits generated by the policy intervention. Where relevant, I discuss trade-offs inherent in these choices between economic cost effectiveness and political feasibility.

7.3.3.1 Historical Examples

I revisit the historical cases of the gasoline tax and fuel economy standard in order to understand the importance of, and tensions surrounding, choices over policy design variables in terms of their economic and political advantages. In the case of the gasoline tax, several possible policy design choices were considered. First is the initial level of the tax and whether or not it would increase over time. Second is how the revenues would be used. Third is whether or not, and how, certain groups would be excluded from the tax. I consider each of these design choices in turn.

One feature of the history of the federal excise tax on gasoline is that high taxes (at least double the pre-existing tax level) have been consistently rejected. Under the Nixon Administration, the idea of a 5 to 10 cent per gallon tax was rejected by Congress. President Ford dismissed his federal energy administrator when he described a plan for a 10 to 30 cent per gallon gasoline tax (*Time*, 1974). The Ullman plan in 1975 involved 10 cent per year increases in the price per gallon over four years. Carter later proposed increasing the gasoline tax by five cents per gallon per year for every percentage point that gasoline use exceeded stated national targets. This plan was also rejected.

The way tax revenues were to be used also provided another route to make taxes more politically palatable, but these efforts were not sufficient to overcome broader opposition to the tax option. Gasoline taxes that would have supported goals closely linked to energy security did not gain much traction. Even a gasoline tax of three cents that would have supported public transport, energy research, and conservation was rejected (Sullivan, 2008). Meanwhile, using revenues to improve road infrastructure or reduce the deficit did not meet with such opposition—possibly because the taxes were lower, but also possibly because the goals of the tax related to tangible or pressing concerns.

Third, provisions to ease the burden on vulnerable groups have played an important role in attempts to make gasoline taxes more palatable. The Ullman plan excluded a fixed amount of gasoline per vehicle from taxation, and also excluded gasoline used for farming and commercial aviation. When Carter constructed his "oil import fee" using executive powers (with the motive of restraining inflation), he excluded heating oil and other petroleum products used by households. These provisions have constituted attempts to win the support of vulnerable groups in exchange for some modest loss of economic efficiency.

Historically, the fuel economy standard has—purposely or inadvertently—contained provisions that have eroded the potential for fuel use reduction. When it was first established, the vast majority of light-duty vehicles were passenger cars. Congress set a standard for passenger cars of 27.5 miles per gallon, but delegated the task of setting a separate fuel economy standard for light-duty trucks (which include SUVs, minivans, and pickup trucks) to the Department of Transportation, which was required to assign a "Maximum Feasible Level." This standard for light-duty trucks was set at 20.7 mpg and remained unchanged through 2007. This distinction under the standard had the perverse effect of rewarding manufacturers who increased their sales of light-duty trucks, particularly sport-utility vehicles, which consumers eagerly bought as long as gasoline prices remained relatively low.[53] Over this same period, the stringency of the fuel economy standard did not increase, while a shift to light trucks actually had the net effect of

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[53] In the 2000s and especially 2008 SUV sales dropped sharply and the market share of smaller cars increased in response to increasing gasoline prices.

reducing the average fuel economy of the light-duty vehicle fleet overall (An & DeCicco, 2007). The differentiation of the standard for cars and light-duty trucks actually reduced the relative economic efficiency of the policy.

Fuel economy standards have also historically contained provisions that have helped reduce the burdens on manufacturers by allowing them to comply early, reducing the compliance burden in later years. This type of banking provision would be expected to both increase the economic efficiency and the political acceptability of the CAFE policy, which rewards but does not require earlier compliance. Another mechanism that provides additional flexibility in compliance is credit trading. A credit trading program across manufacturers was introduced into the CAFE program in 2007 for model year 2011 vehicles, allowing those firms facing high abatement costs to instead purchase credits from firms facing lower abatement costs, reducing the total cost of compliance (EISA, 2007). Although it entails additional administrative costs, both the banking and the credit-trading program were nevertheless incorporated, providing examples of a policy design choice that improved economic efficiency (by taking advantage various sources of flexibility) in a way that was also attractive to affected stakeholders.

7.3.3.2 Contemporary Examples

Recently passed fuel economy standards (2007 and 2010) and renewable fuel standards (2007) provide additional examples of how policy design choices embody trade-offs between economic efficiency and political feasibility. In the case of the 2007 fuel economy standards, a recognition that applying standards differentially to cars and light-duty trucks perversely resulted in a decrease in overall fleet fuel economy led policymakers to abolish this distinction in favor of an “attribute-based” standard. An “attribute-based” standard requires fuel economy improvements in vehicles belonging to all weight classes, but sets different standards depending on the size of the wheelbase. These standards are still set separately for cars and light-duty trucks. The purpose of these standards is threefold: first, it is designed to mitigate concerns that manufacturers will meet the standards through changes in vehicle size that might reduce vehicle safety; second, it ensures that manufacturers will continue to make available a diverse selection of vehicles to consumers; and third, it is intended to spread compliance costs more equitably across manufacturers with diverse production portfolios. However, some have argued that the attribute-based standard will prevent manufacturers from pursuing low cost weight reduction strategies, further reducing the set of options available to achieve compliance.[54] Attribute-based standards are an example of a policy design choice that, by reducing the compliance options available to manufacturers, increases the cost of the policy in order to address stakeholder concerns, improving acceptability. A related feature of the CAFE standard is its emphasis on technology adoption, rather than technology allocation, in assessing compliance costs. Critics of this approach have emphasized that reallocating technology—for instance, to emphasize fuel economy over performance—within the vehicle would enable manufacturers to meet the standard at a much lower cost, but that the way the CAFE standard is written effectively discourages manufactures from taking advantage of these opportunities (MacKenzie, 2009).

Another aspect of particularly the 2010 CAFE standard (which applies also to GHG emissions) is the exclusion of upstream fuel-related emissions from coverage under the regulation. This provision is particularly relevant in the case of electric vehicles, in which case increased adoption and use will not translate into actual reductions in overall emissions (especially relative to advanced ICE vehicle technologies) unless emissions from the power grid are also significantly reduced. At present, upstream electricity-related GHG emissions from the first 200,000 electric vehicles produced by each manufacturer are not counted under the standard (EPA, 2010b). In an early version of the rule, these vehicles are also subject to an “advanced technology credit” under which every electric vehicle produced counts as two zero-emission vehicles under the standard. These provisions make it highly attractive for manufacturers to produce vehicles the run on electricity. Similar provisions are given to vehicles produced with flex-fuel capability, which means the vehicles can run on ethanol blends of up to 85% or higher, whereas most existing vehicles are only certified to accept blends of 10% or in some cases up to 15%. Flex-fuel vehicles are treated as if they only use about 40% the gasoline of regular vehicles. Introducing flex-fuel technology particularly into large vehicles where compliance with the standard would otherwise be more costly or difficult has proven a popular option for automakers as they complied with 2007 to 2010 model year CAFE standards. Meanwhile, evidence suggests that flex-fuel capable vehicles are rarely driven on the alternative fuel. The treatment of electricity-related emissions from electric vehicles as well as the fuel use profile assumed for flex-fuel vehicles at the same time provides incentives for manufacturers to

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[54] There is debate over whether or not heavier vehicles are necessarily safer. A range of new materials available are claimed to be lighter without compromising strength (Cheah, 2010).

introduce these technologies into the fleet, providing them with cost-competitive strategies for compliance with the new standard based on a misrepresentation of their impact on gasoline use and GHG emissions. However, this type of partial or misrepresentative coverage of the policy will reduce the cost effectiveness of the policy even further relative to an economically-optimal (tax) policy.

An interesting aspect of recent increases in the CAFE standards is the aggressiveness of their targets, despite the fact that many studies assert that achieving compliance on such a short time frame presents automakers with a major challenge. If the goal of the policy is to achieve a certain reduction in cumulative fuel use over a fixed time period, then an economic analysis would suggest that starting earlier is a wise approach, because the cumulative reduction achieved depends both on the fuel economy of new vehicles as well as the number of miles they drive. It is not clear if this rationale lies behind the ambitious targets set by the new standard. It may be that the standards, while ambitious on paper, are actually much less ambitious once the flexibility provisions are considered.

Renewable fuel standards also include provisions that are advantageous to affected stakeholders, but may change (or detract from) the cost-effectiveness of the policy. A first example is the volumetric (as opposed to percentage) targets for biofuel blending written into the standards. Volumetric targets require a fixed volume of biofuels be added to the fuel supply, irrespective of total demand for fuel. While this provides suppliers with certainty over the volumes that will need to be produced, it provides little certainty over the average blend level that will have to be achieved in the fuel supply. If other policies such as the fuel economy standard result in a reduction in overall gasoline demand as projected, the blend levels that would need to be achieved would need to be much higher to accommodate the mandated volumes. Handling higher fuel blends would be costly for vehicle manufacturers as well as for fuel providers, who would need to install specialized equipment for storage and fuel handling.

Another feature of the renewable fuel standards is the timetable for phasing required volumes of biofuels, and the type of biofuels required, into the fuel supply. Today, virtually all of the ethanol blended into the fuel supply is produced from corn as a feedstock. While they displace petroleum, corn-based biofuels offer few, if any, GHG emissions benefits. As a result, the legislation requires that starting in 2016 the increases in required biofuels volumes must be met by advanced biofuels, preferably cellulosic biofuels made from feedstock other than corn.[55] However, even these advanced biofuels may have associated GHG emissions impacts due to required changes in land use, direct or indirect, and how these emissions are counted has important implications for the GHG emissions as well. By failing to define the standard in a way that considers the potential for offsetting or adverse GHG emissions impacts, the architects of the policy have simultaneously made it easier to meet the standard and reduced its cost-effectiveness with respect to one of its stated goals.

As these examples have demonstrated, in multiple cases for each of the policies, past and present, that have been considered or implemented, design variables have provided policy architects with a mechanism for reducing the burden on regulated parties or spreading it over time. In cases where design variables have been set to produce outcomes in line with economic recommendations (for instance, in the case of the aggressive increases in fuel economy standards) the teeth of these provisions have often been blunted by additional provisions that hold regulated parties to standards more lax than they appear on paper. These provisions include partial (instead of full life-cycle) emissions accounting as well as special treatment of advanced technology vehicles.

7.4 Politics in Passenger Vehicle Policy: International Context and Path Dependency

The low level of gasoline taxes makes the United States an outlier among advanced industrialized countries. **Table 7.3** shows a comparison of average gasoline taxes per gallon in six countries, with the Germany's per gallon tax over twelve times as large as the gasoline tax in the United States. Although an exhaustive cross-national comparison is left to future work, this section focuses on developing hypotheses to explain the exceptional policy situation in the United States. First, I briefly review the politics of gasoline taxes in several advanced industrialized countries, and provide evidence that institutional, geographic, and ideological differences help to explain how countries have resolved differently the tensions between the economics and politics on gasoline tax issue. Second, I rely on the economic modeling results to identify sector impacts and combine them with observations about the influence of these sectors in the U.S. political process to develop hypotheses about which policies find the greatest support.

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[55] If required volumes of biofuels are not available, the U.S. EPA administrator is permitted to adjust the standard.

7.4.1 Relating Gasoline Tax Levels to Political Considerations

Table 7.3 clearly illustrates that the U.S. is an outlier among advanced industrialized countries when it comes to gasoline taxation. Asking why is a complex task, and must be undertaken with caution. This section offers an initial assessment of why vehicle policy has evolved so differently in the United States. My argument draws on the political feasibility considerations discussed earlier, support from the literature, and empirical evidence of national transport system evolution to develop the argument that policy decisions are path dependent—the set of alternatives available tomorrow, and their political viability, will depend on decisions made today. I develop two explanations for these divergent policy outcomes, focusing on the case of the United States as compared to the cases of the France, Germany, Japan, and the United Kingdom. One explanation relates to the influence of ideology and political process constraints in shaping historical policy outcomes at key decision points, and the second argues that initial policy decisions changed underlying conditions in ways that altered the acceptability of alternative (potentially more cost-effective) policy choices several decades later.

Table 7.3 Gasoline and diesel fuel taxes in cents per gallon.

September 2010 (Cents per Gallon)

COUNTRY	GASOLINE	DIESEL
Belgium	455	283
France	443	328
Germany	471	354
Italy	425	334
Japan	254	161
Netherlands	518	334
United Kingdom	338	298
United States*	39	46
*Includes the weighted average of state taxes plus the federal tax.		

Source: FHWA, 2009c.

First, it is worth asking why a gasoline tax initially was more possible in many European countries but not in the United States, despite multiple attempts to introduce it. These explanations include ideology (in this case, related to the appropriate role of government), the institutional thresholds that must be overcome to pass policy, and existing infrastructure and settlement patterns. Arguably no single factor was responsible, but these factors, when considered in concert, may help us to understand why policy outcomes have diverged.

Ideological opposition to taxation can be found everywhere. Although gasoline tax outcomes in the U.S. reflect the interaction of ideology with other the factors to be explored in the next several paragraphs, it is worth noting that the strength of opposition to taxes in the United States is perhaps especially strong, and can be traced back to the philosophies of its founders. This initial antipathy towards big government and taxation has persisted most strongly in the political positions of the ideological right. Without an existing strong tendency to oppose taxes, the other factors—which are related to political and physical system characteristics—might not have been strong enough to lead to repeated rejection of gasoline taxes aimed at reducing gasoline use, although it is impossible to know for sure.

Features of the political process affect the chances of passing into law a proposal facing a fixed level of opposition in the broader populace. In the United States, distrust of concentrated power led at the outset to the adoption of a three-branch governing system with built-in checks and balances, distinguishing it from its European counterparts, then and now. It is possible to imagine that taxation proposals advanced by U.S. presidents would have encountered less opposition had they not had to win a majority vote in both the House of Representatives and Senate, one or both of which was often controlled by a party different from the executive. I argue that this political reality has made it easier to adopt policies that target a narrow, well-defined stakeholder group, while benefiting (or at least not visibly harming) politically powerful interests or constituencies. It also allows a small but strong group of opponents to defeat a policy that otherwise may have enjoyed broad support.

With regard to automotive policy in particular, the U.S. and European nations have also faced very different starting points. Many European cities developed long before the invention of the automobile, and have been generally characterized by a higher population density and shorter intercity transit distances. Moreover, roads for moving people and goods between cities were already in place in many parts of Europe, whereas the large distances in the United States meant that equivalent coverage required more effort. A massive investment in the 1920s and 1930s in the construction of President Eisenhower's National System of Interstate and Defense Highways offered plenty of spare capacity for both passenger and freight traffic. In the 1970s when attention turned to ways of reducing dependence on petroleum-based fuels, this infrastructure was being well utilized and new settlements had become reliant on it, particularly in less populated areas of the country. Despite low population density, states that spanned these areas held considerable power in the Senate, creating a constituency with few substitutes to vehicle transport that would also be strongly affected by a tax, given lower incomes and longer average driving requirements. One hypothesis is that the concentrated opposition of these constituencies was particularly successful at advancing their interests in a political system set up to maximize checks on majority or individual power, and that already had a strong ideological propensity to oppose taxes in the first place.

Second, given that different energy policy choices were made in the 1970s, I now argue that the changes induced by these policies made it more difficult to change course later on. In the mid-1970s, vehicle ownership, annual miles traveled per vehicle, and fuel consumption per mile were higher in the United States than in Europe, which had more densely populated cities and more public transport options. Vehicle ownership and operation was a relatively large share of the average household budget. Oil supply disruptions during the 1970s provoked different policy responses across the globe, with the United States implementing a relatively aggressive fuel economy standard but no increase in the federal excise tax on gasoline. The effect of the standard was to bring on-road vehicle fuel consumption closer to European levels (low fuel consumption in Europe also reflects increasing reliance on diesel vehicles) (Schipper, 2008). By contrast fuel taxes in many European countries increased, and were coupled with efforts to develop more inter-city high speed rail infrastructure and other public transport options.

Now fast forward to the present. Interestingly, as shown in **Table 7.4**, studies have recorded that elasticities in the United States are lower than those recorded in the 1970s by statistically significant levels (Hughes et al., 2006). In other words, U.S. drivers appear to be less responsive to price signals today than they were several decades ago. Meanwhile, no such structural break has been recorded in other countries, including those with high gasoline taxes. Explanations given for this structural break in the United States include the increasing efficiency of the vehicle fleet over time (affected by the CAFE program) and the proliferation of low-density settlement patterns.

Stepping back, it is possible to interpret ever-growing U.S. demand for vehicles, miles-traveled, and fuel as evidence in support of the argument that a gasoline tax may be even less politically feasible today than it was in the 1970s. It is perhaps no surprise that policy proposals have tended to favor changing the composition of the fuel supply, or raising the efficiency of vehicles, rather than taxing petroleum-based fuel. This trend would not be so worrisome, were it not for the fact that relative to a tax, alternative policies are very costly to society as a whole. Today, policymakers are discussing much more aggressive policy targets than have been pursued under fuel efficiency or renewable fuels mandates prior to 2005. The danger of focusing on too narrow a target is that much of the low-hanging fruit may be quickly exhausted, with compliance costs growing non-linearly with incremental gasoline use reductions. The challenge then becomes: what politically saleable policies can we enact in the present to create conditions that will allow a transition to more cost-effective policies over time? I revisit this question in the final section and in the conclusion

Table 7.4 Short-run price elasticities of gasoline demand in the U.S.

Years	Short-run price elasticity of gasoline demand
1975-1980	-0.21 to -0.22
2001-2006	-0.034 to -0.077

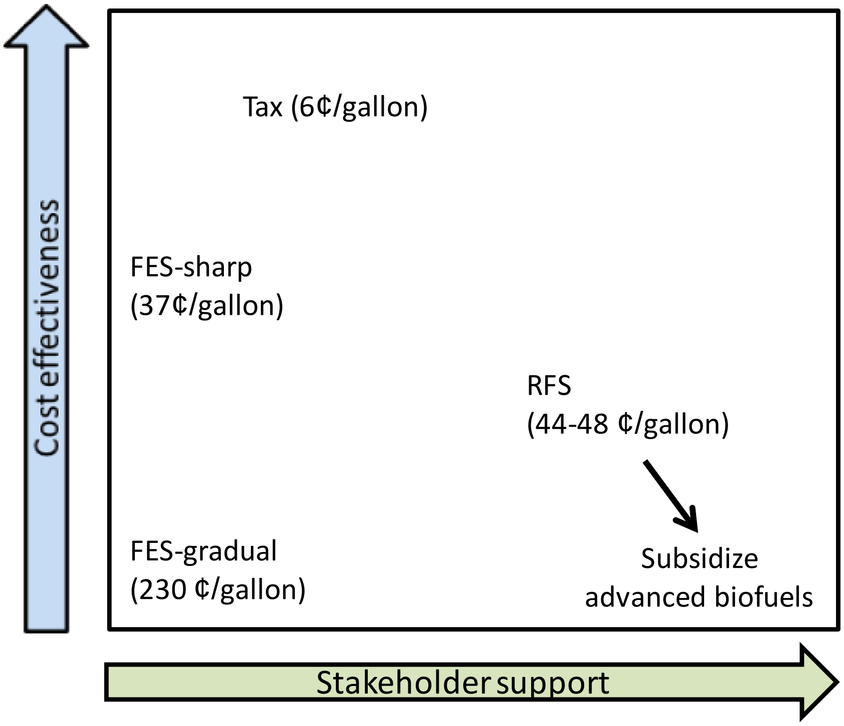
Source: Hughes et al. (2006).

7.4.2 Sectoral Interests and Policy Support in the United States: A Few Hypotheses

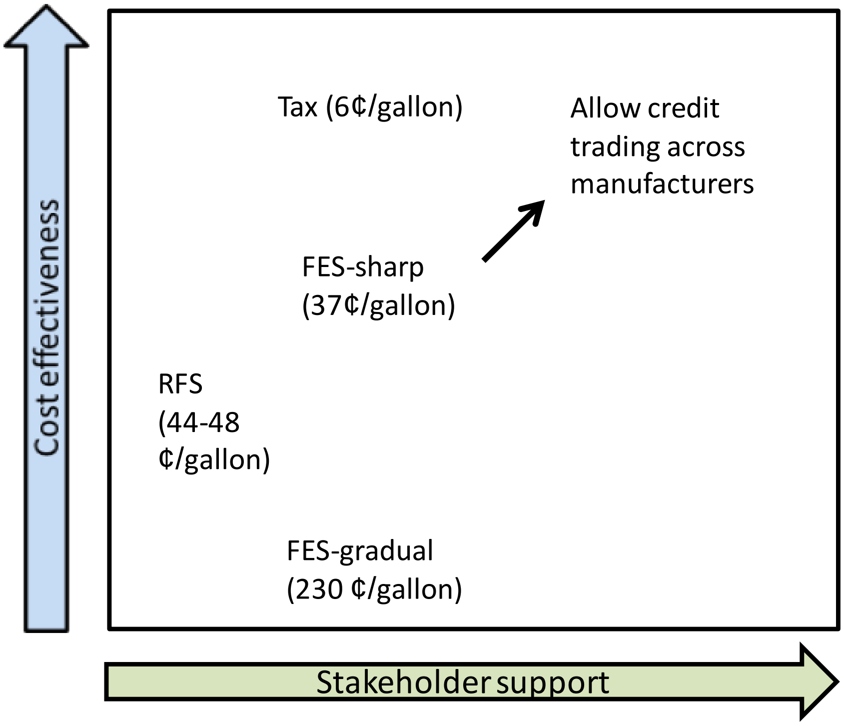
One means to explore current policy outcomes in the United States is to examine how stakeholder interests do, or do not, align in support of particular policy options. In **Figure 7.1** I show how cost effectiveness (which can be captured in the implicit cost per gallon of gasoline displaced) at the aggregate level does not necessarily translate into—and is often at odds with—the interests of particular influential stakeholders. In each case the interests of stakeholders are defined as the policies that offer them the greatest economic gains through sale of their primary product, as predicted by the modeling analysis in prior chapters.

Fig. 7.1 The inverse relationship between political considerations and policy support (which depends on political feasibility considerations) as shown for the case of a) biofuels producers, b) automotive manufacturers, and c) electric sector suppliers.

a)



b)



c)

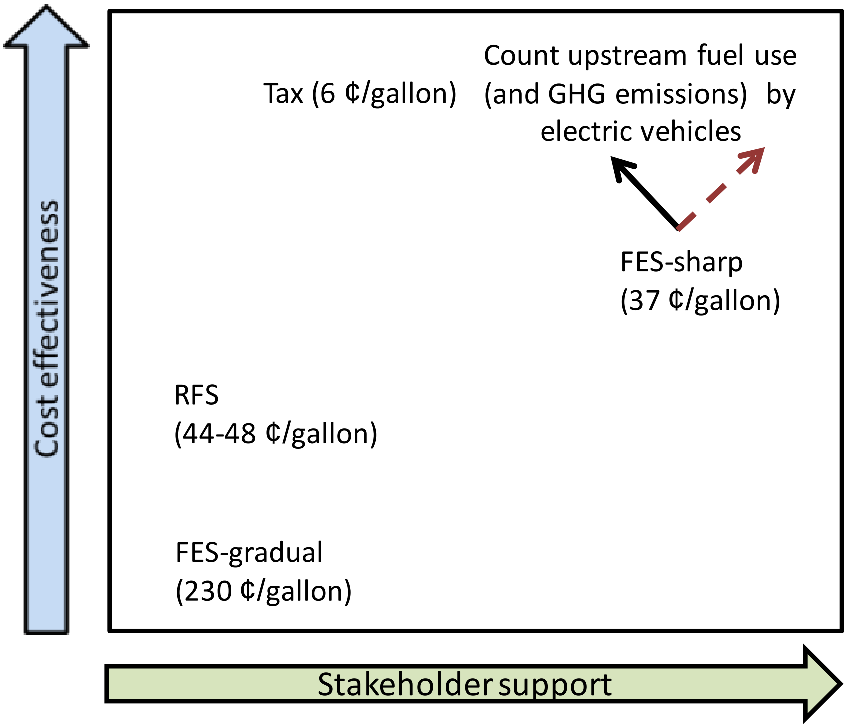


Figure 7.1a shows the relationship between policies ranked on aggregate cost effectiveness and the policies expected to be preferred by biofuels producers. These important stakeholders (which are linked to powerful agricultural interests and the ethanol lobby) would prefer any policy that increases the role of biofuels. The fuel economy standard policies are not favored because they would actually decrease the overall demand for petroleum-based fuel as well as its substitutes. By contrast, a tax would encourage fuel substitution, but would also encourage many other mechanisms of fuel use reduction including conservation and investment in vehicle fuel economy. Perhaps most attractive to biofuels producers is a mandate that requires that certain volumes of advanced biofuels be introduced into the fuel supply, which provides certainty that a market will exist and, if volumetric targets are set, guarantees the precise volumes required. As modeled in the analysis in previous chapters, a renewable fuel standard would raise the cost of the blended fuel at the pump, unless the more expensive component fuel is subsidized (as is currently the case with the blender’s credit in the United States). Eliminating this subsidy would remove any price signal to consumers, which would have otherwise further encouraged reductions in fuel use, making the policy less efficient. The existence of the subsidy (shown by the arrow in the figure) would make the policy more attractive to stakeholders but

lower its cost effectiveness. By the same token, reducing the subsidy would make an RFS policy more cost effective overall, illustrating the trade-off inherent in designing cost effective policies and securing support for them.

The case of the automotive industry is shown in **Figure 7.1b**. Automakers' profitability depends on whether or not they manufacture vehicles that consumers will buy. Automotive companies also face long product development cycles and thus require significant lead times to introduce new technologies into their produce lines. When it comes to policies that reduce fuel use, these companies are likely to favor policies that provide both certainty in addition to opportunities for financial gain. Although rising gasoline prices have been shown to increase demand for high fuel economy vehicles, rapid fluctuations in prices can create headaches as consumer demand shifts along with prices. It is also not clear how consumers will respond to various gasoline taxes over longer periods in terms of their valuation of fuel economy. As a result, these firms are perhaps most likely to favor policy that creates clear rules that apply equally to all automotive manufacturers, and that they are able to influence in ways favorable to their own interests. Again, it is possible to view the relative positions of these policies on both axes as dynamic, depending on how specific policy design variables are chosen. In the case of a fuel economy standard, both automotive industry support and cost effectiveness could be increased by allowing credit trading across manufacturers, leading to an equalization of marginal abatement cost over the longer term.

Finally, **Figure 7.1c** shows the policy options from the perspective of the electric power industry and their supplies, which in the realm of transportation policy are motivated primarily by the impact of policy on vehicle electrification. Similar to the impact of a tax on the automotive industry, a tax would incentivize adoption of grid-connected vehicles, but it would also incentivize many other solutions, creating uncertainty for generation companies, especially around long-term capacity planning. A fuel economy standard (especially an aggressive standard), by contrast, would favor adoption of PHEVs and EVs at the expense of changes in the fuel supply. This case also provides a good illustration of how the incentives for an industry to support cost-effective policies may change over time. In the near term, the electric power industry and its suppliers may be reluctant to count upstream GHG emissions from grid-connected vehicles under the standard, since it could discourage adoption of these vehicles and the grid upgrades that would boost their bottom line. However, if electricity producers are required to reduce their GHG emissions under other complementary policies, they may have an incentive to seek credit for these modifications under an existing fuel economy standard policy. This example suggests the importance of designing a policy or set of policies with the flexibility to incorporate more cost-effective features, or move to new, more cost-effective substitutes, as underlying conditions change.

7.5 Trade-offs Inherent in Climate and Energy Policy for Passenger Vehicles: Policy Implications

The examples discussed above provide concrete illustrations of the tensions that arise between economic efficiency and political feasibility when it comes to justifying policies, choosing among policy types, and setting internal policy design variables. **Table 7.5** summarizes the evidence for these tensions, drawing on both historical and contemporary cases. This section first briefly summarizes the evidence for these tensions, reflects on the cross-national and stakeholder analyses, and discusses the implications for policy.

As illustrated in the earlier discussion, how a policy is justified to affected parties can significantly affect its political feasibility, but may be unrelated to its mechanism of action and its associated economic efficiency. In the cases considered here, the regulatory policies (fuel economy standard and renewable fuel standard) are both more amenable to being sold on the basis of their perceived benefits to consumers (lower cost of driving), the environment, and technology development as well as the primary goal of reducing fuel use, relative to a gasoline tax. However, the actual aggregate economic cost of a fuel economy standard was shown to be more than an order of magnitude above the cost of a gasoline tax. By contrast, a gasoline tax has never succeeded when being sold as an energy security policy tool—only when justified to support a war effort, close a budget gap, or improve national road (and public transit) infrastructure has a (very modest) increase has the tax proposal met with limited success.

At the level of policy type, more targeted policies that affect very specific parts of the overall system have gained more political traction than those that incentivize changes across the system as a whole. Narrowly tailoring a policy to focus on a particular part of the system reduces resistance from those not covered by the policy, while parties that fall under the regulation have a strong incentive to carve out favorable provisions. As shown in the economic analysis in **Chapter 6**, implementing a policy focused on one part of a large, complex, interconnected system can result in unintended or offsetting effects in other parts of the system, reducing the efficiency of the policy. In the case of passenger vehicles policy, these offsetting effects are evident in the rebound effect (increase in driving under the policy) due to a fuel economy standard or an increase in overall fuel efficiency (including PHEV adoption) in response to blending expensive biofuels into the fuel supply.

Finally, perhaps the sharpest contrast between economic efficiency and political feasibility imperatives occurs at the level of policy design variables. The above discussion gave multiple examples of how fuel economy standards (past and present) and renewable fuel standards offered a range of provisions for altering the stringency and timing of targets, the extent of policy coverage, the allowed compliance strategies, and the metrics for assessing progress. In most cases it was shown that policy design choices preferred by regulated parties clashed with principles of life-cycle emissions accounting, flexibility in terms of compliance strategies, and robust policy target design.

Given the tension between economics and politics on multiple levels in the case of energy and climate policy for passenger vehicles, what is an earnest policymaker to do? Clearly it is in the collective interest of society to choose policies that minimize overall costs. Distributional concerns, according to the second welfare theorem, can then be addressed through redistributive mechanisms that compensate the most vulnerable groups. The fact that we do not observe these economic "first-best" policies gaining political traction is disturbing to scholars keenly aware of the relative costliness of alternative paths. Yet if these policies consistently prove politically impossible, is it even worthwhile to keep considering them? Should we not be asking where on the trade-off frontier between economic efficiency and political feasibility policy proposals stack up, and then choosing the best feasible option? An impossible first-best policy, pragmatists might argue, is no better than business as usual.

Table 7.5 Tensions between economic efficiency and political feasibility for passenger vehicle policy.

Level of Analysis	Time Frame	Policy	Considerations	
			Economic efficiency	Political feasibility
Policy Justification	Historical	Gasoline Tax	Tax is the most cost-effective way to reduce gasoline use and clearly linked to energy security goals	Ideological opposition to taxes Successfully sold as a road "user tax" or deficit reduction tool
		Fuel Economy Standard (FES)		FES sold as energy policy favorable to consumers, most of burden on industry
	Contemporary	Fuel Economy Standard (2007 and beyond)		Increasing emphasis on energy security as well as environmental goals
		Renewable Fuel Standards		RFS justified as addressing both energy security and environmental goals
Policy Type	Historical	Gasoline Tax	Tax is the most cost-effective way to reduce gasoline use because it incentivizes a wide range of changes across the vehicle fleet and fuel supply	Ideological opposition to taxes Taxes are highly visible to consumers when refueling Re-distributional mechanisms of policy also highly visible, difficult to manipulate
		Fuel Economy Standard (FES)		Cost less visible to consumers Modifications affect a narrowly-defined part of the system Policy is easy for affected stakeholders to manipulate
	Contemporary	Fuel Economy Standard (2007 and beyond)		Covering GHG emissions under existing CAFÉ policy easier than new regulations Ease of adding "flexibility provisions"
		Renewable Fuel Standards		RFS costs less visible to consumers (ethanol subsidies), burden falls on fuel suppliers
Policy Design Variables	Historical	Gasoline Tax	Most cost-effective policy designs are technology agnostic and cover full life-cycle GHG emissions	Redistributive mechanisms not enough to overcome opposition Large gasoline tax increases consistently rejected
		Fuel Economy Standard (FES)		Focus on technology adoption rather than (re-)allocation
	Contemporary	Fuel Economy Standard (2007 and beyond)		Well-to-tank emissions excluded from FES policy coverage Advanced technology credits favor expensive solutions
		Renewable Fuel Standards		Volumetric standard creates certainty for biofuels suppliers Reductions in GHG emissions though advanced biofuels delayed and uncertain

Studying the success of taxes in other national contexts as well as the alignment of sectoral interests in the United States can aid in generating new, potentially more promising policy strategies. The comparison with other nations with high gasoline taxes highlights the role of path dependence—in other words, the observation that a policy can provoke responses (in terms of physical investment or changes in the alliances or incentives of stakeholder groups) that change in turn the future policy calculus. Unfortunately, since 1975 incentives in the United States have evolved away from the gasoline tax solution and toward policies compatible with an ever more motorized society. This reality suggests a need to identify ways that existing policies can shift toward more cost-effective designs, whether through spatial or temporal flexibility mechanisms, credit trading, or even periodic comparisons to alternative policy instruments combined with formal referenda on existing policies. These proposals should be made with attention to their palatability to sectoral interests that are highly influential in the policy process.

Proponents of the economic approach might quickly answer in defense of first-best policies, that even if they are never implemented, they provide an important waypoint in an otherwise disoriented political debate. Indeed, comparisons to first-best instruments are needed to provide a metric of how far second-best policies fall short.[56] The "penalties" of incorporating certain politically palatable features into policies could then be made more transparent to policymakers.

The trade-offs inherent in obtaining economically optimal policies, however, points more broadly to the need for a different approach to policy design in the case of energy and climate policy for passenger vehicles. This approach would assess policies not only relative to the economic first-best (which remains important), but also search for solutions at the other end of the spectrum, starting with what is politically feasible and ranking them based on a broader set of criteria. In addition to the economic attractiveness of a policy in its static form, a broader definition could give weight to the trajectory a policy establishes, and the extent to which it provides opportunities for adaptation over time as its impact and future needs become clear. The conclusion of this thesis (**Chapter 8**) recommends several approaches.

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[56] Of course, if economic models are used to develop comparisons of this kind, the role of underlying model assumptions related to consumer behavior (e.g. inter-temporal optimization, access to information, etc.) should be carefully considered to the extent that they could affect the rankings of policies. Disagreements over the suitability of particular models, and recommendations of how to improve the realism of their assumptions and outputs, are an important, though separate, area for future work.

Chapter 8: Conclusions

I have been impressed with the urgency of doing. Knowing is not enough; we must apply. Being willing is not enough; we must do.

Leonardo Da Vinci[57]

This chapter summarizes the findings from earlier chapters and highlights the conclusions for research and public policy. It then describes how the findings from the different sections can be synthesized to draw insights for policy going forward. Policymakers should start from today's most politically feasible policies and attempt to introduce provisions that will both increase cost effectiveness and simultaneously alter underlying conditions in ways that increase support for more cost-effective policy types over time.

Policies designed to reduce petroleum use and greenhouse gas (GHG) emissions from passenger vehicles affect the decisions of firms and households, which inevitably react to changing constraints and incentives. Alternative policy designs incentivize different technological and behavioral responses, which in turn influence the cost and effectiveness of achieving stated goals. Understanding on one hand how signals created by policies affect decisions at the micro level, while on the other hand comparing the macro-level cost effectiveness and political feasibility of candidate interventions, are important agendas for both research and policy.

This thesis is comprised of four parts, each of which contributes to the overarching question of how to design of climate and energy policy for passenger vehicles. The first contribution is to the econometrics literature on household energy use behavior, and involves an analysis of the household vehicle use response to gasoline prices. The second contribution is to the field of energy-economic modeling. Specifically, an approach was developed to represent the engineering and fleet detail of passenger vehicles within a computable general equilibrium (CGE) model, helping to fill the gap between bottom-up technology-rich models dependent on exogenous macroeconomic assumptions and simplified top-down macroeconomic models that fail to capture important physical system constraints. The third contribution is to economic analysis of passenger vehicle policy. Policies were compared, alone and in combination, in terms of their cost effectiveness in reducing petroleum use and GHG emissions. The fourth contribution is to the political economy of regulation. This part of the work shows how sharp tensions exist between economic efficiency and political feasibility when setting policy for

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[57] In Adams (2006).

passenger vehicles, and explores the origins of these tensions as well as the implications for policy.

This concluding chapter aims to bring these themes together, first by recapping the main findings of each part of the work and the implications for research and policy. The second part of this chapter combines insights from the individual parts of this work to develop recommendations for policy.

8.1 Micro-level Studies of Household Response

Households could employ a wide range of strategies to reduce the impact of rising energy prices on their own economic welfare. To accurately forecast the impact of policies on households, it is important to understand the relative importance of different response strategies, the conditions under which they are employed, interactions among them, and ultimately the contribution to energy use and environmental outcomes. Previous studies have focused on the estimation and comparison of aggregate short- and long-run elasticities of demand for fuel and vehicle-miles traveled with respect to fuel price. Strategies employed by households may differ in the short and long runs and also depend on characteristics of the household as well as the vehicles it owns.

The study performed in this dissertation focuses on short-run estimates. The first contribution of this thesis was to measure elasticities of household demand for vehicle-miles traveled (VMT) and fuel with respect to fuel price, and to show that households reduce gasoline use proportionally more than VMT in response to fuel price increases. I then measured the effect of price-per-mile savings faced by a household facing a fixed fleet of vehicles (short-run effect) on vehicle switching, both in terms of total distance and by trip. I found that the vehicle switching response was modest, and that switching propensity decreased with household income.

8.1.1 Implications for Research

The econometric study in this work contributes to an ongoing inquiry into household response strategies that underpin the observed elasticities of demand for gasoline and VMT. Quantifying the contribution of vehicle switching to short-run gasoline demand reduction is one step toward better understanding household decision-making, not just with respect to individual vehicle use decisions, but how these vehicles are used by the household as a fleet. The fact that modest vehicle switching occurs suggests that there is some slack in the way households are able to allocate their vehicles to trips.

One important limitation of this study is its focus on a single, short thirteen-month period. Beyond studying short-run household vehicle usage decisions, a more comprehensive study would investigate long run effects, expanding the study to consider how households decide which vehicles to purchase in addition to how they will use them as part of the household-owned fleet. Moreover, given that gasoline prices increased in the U.S. over much of the period between 2002 and 2008, it would be of interest to measure whether households had already shifted more miles of travel to their higher fuel efficiency vehicle to take advantage of available savings prior to the price fluctuations in 2008 and 2009. Evidence from the National Household Transportation Survey in the U.S. suggests that the more vehicles a household owns, the lower the average daily miles of travel by any particular vehicle (FHWA, 2009a). The relationship between vehicle efficiency (as well as other vehicle attributes) and the allocation of vehicles to particular trips is not well understood. More detailed econometric studies using this survey and other data sources would be able to shed light on these questions.

Studies of micro-level household vehicle purchase and use behavior could become increasingly important if alternative fuel vehicles that enable large reductions in gasoline use are adopted into household fleets. Purchasing or using such a vehicle would offer unprecedented potential to reduce fuel use without reducing VMT, far beyond the opportunities facing households in the present study. Understanding to what extent this source of flexibility could influence vehicle purchase decisions as well as switching behavior in practice merits further study. Its salience is even greater for vehicles that would introduce additional trade-offs to obtain fuel savings, such as reductions in range, interior volume, or horsepower, or limitations on refueling, such as long recharge times and a lack of readily available refueling infrastructure.

Finally, an interesting direction for future research involves testing for non-linear effects of gasoline prices on gasoline demand and vehicle switching using alternative model specifications. For example, individuals may have altered their travel behavior and vehicle utilization more dramatically when gasoline prices rose above $4 per gallon in the summer of 2008, suggesting a threshold effect.

8.1.2 Implications for Policy

The transport-focused energy policies analyzed in other parts of this thesis are in essence "blunt instruments," in other words, they apply equally to consumers regardless of socioeconomic and vehicle use characteristics. However, heterogeneity in vehicle purchase and use behavior will mean that the costs of policies will be distributed unequally across households. An important task for policymakers involves characterizing heterogeneity as a first step to determining the necessity for, and appropriateness of, proposed redistributive schemes. For example, a fuel economy standard (FES) policy that acts at the point of vehicle purchase does not discriminate on the basis of vehicle usage. An FES policy would also fail to account for vehicle switching behavior, differences in the aggressiveness of driving styles, and other factors that could be employed by households to reduce fuel use beyond the purchase of a more efficient vehicle.

Studies such as the one undertaken here and others could help to inform policymakers of the consequences of these blunt instruments—in other words, the dependence of policy costs and fuel savings achieved on factors outside a policy's realm of influence, but that could alter the effectiveness of the policy in practice. For instance, a policy that results in more efficient vehicles in garages would be more effective in reducing fuel use if combined with a policy that incentivizes increased use of more efficient vehicles on the road. This study provides initial evidence that fuel price modestly affects fuel use through the vehicle switching response, although more work is needed to understand the interactions of vehicle switching with multi-year policies such as a fuel tax or an FES policy that would also have long-run effects on the composition of the vehicle fleet.

8.2 Technology-rich Macroeconomic Models of Passenger Vehicle Transport

A number of modeling approaches have been used to assess climate and energy policies for passenger vehicle transport in terms of their effect on technology adoption, cost, petroleum use, and GHG emissions. Despite an abundance of models representing a wide range of disciplinary foundations, models used in policy analysis have not previously captured both extensive passenger vehicle system detail and economic feedbacks in an integrated fashion. One contribution of this thesis was to develop a technology-rich representation of the passenger vehicle transport sector in a computable general equilibrium (CGE) model, advancing the state of empirical modeling in this area.

8.2.1 Implications for Research

The model developed for this work provides a basis for a wide range of future studies in several respects. First, the methodology developed to represent passenger vehicles in the model could be applied to other energy-intensive consumer durable goods by adapting the model developments described in **Chapter 4**. Using a similar approach, the characteristics (including the costs of incremental efficiency improvements) of household appliances such as refrigerators, washing machines, or air conditioners (or even a composite good representing multiple appliances) could be used to capture how targeted policies could affect household purchase and use decisions. The method could even be extended to investment goods such as housing or commercial buildings with appropriate data on the opportunities for, and costs of, reducing energy consumption through new construction or retrofits.

In terms of modeling the environmental and energy impact of passenger vehicles, the new model structure enables a number of useful extensions. A first step would be to consider the combined effects of policy choices in a broader set of countries and regions and their impacts on global fuel prices, fuel demand, import-export balances, and GHG emissions. A large number of countries have announced fuel economy standards, which could be simulated in the model. With the required data, researchers could expand the scope of this work to air pollutant emissions from passenger vehicles. By representing explicitly the opportunities for investment in vehicle efficiency and its trade-off with the fuel requirement, the new structure can be used to assess how policies that focus primarily on vehicle efficiency could affect other important characteristics of the vehicle that scale with fuel use or VMT, such as local air pollutant emissions and their associated health and environmental effects as well as non-CO_2 GHG emissions, congestion, safety, and other concerns.

One of the limitations of this method is the representation of the new and used passenger vehicle fleets in terms of a single representative (or average) vehicle, whereas in reality considerable diversity in vehicle size, driving distance, and usage patterns may constrain the adoption of technology. For specific policy questions, representing this additional detail may be vitally important. Depending on the interests of the analyst, the vehicle fleet could be disaggregated according to size, weight class, distance, or usage characteristics. A useful extension of the current model would be to represent more explicitly the modest fraction of light-duty vehicles owned by businesses and government (as opposed to households) and the (potentially different) incentives for technology adoption in these fleets. For example, these vehicles typically have a higher annual mileage, and so fuel-related operating costs would tend to account for a larger fraction of total cost of ownership (Davis et al., 2009).

A second limitation of this model is the exogenous representation of constraints on adoption of alternative fuel vehicles (AFVs). Methods for representing factors beyond technology cost (including spatial factors such as exposure to advertising, word-of-mouth, or spatially heterogeneous infrastructure constraints) that could affect the early adoption of alternative fuel vehicles could be developed based on ongoing research that has focused on characterizing the contribution of these factors to consumers' adoption decisions.

8.2.2 Implications for Policy

Models currently used within the transport energy and environmental policy community to evaluate the impacts of policies typically do not take consumer preferences into account when forecasting policy compliance scenarios. These models often include considerable detail in their representation of the vehicle fleet, options for technological improvement, and the process of fleet turnover. They are applied to forecast the gasoline use and GHG emissions impacts of the introduction of new vehicle technologies, based on a view informed by both government and industry of what could be reasonably achieved. The EPA and NHTSA models, which were used to assess compliance strategies and the cost-effectiveness of harmonized fuel economy and per-mile GHG emissions standards for 2012 to 2016, belong to this category of models (EPA, 2010b). One limitation of these models is that they do not capture the effect policies will have on vehicle and fuel prices, which will have implications for other sectors. They also do not capture the effects of interactions among policies that target different parts of the passenger vehicle system, as in the case when the FES and RFS policies are combined.

The model developed for this analysis captures these important relationships and price feedbacks. It further allows the calculation of policy cost by a method that considers adjustments across the entire economy, and can be applied to consider interactions with policies imposed on the same or related sectors. Policymakers could usefully compare the aggregate policy cost estimates from fleet accounting approaches with those that emerge from economy-wide computable general equilibrium models that include a detailed representation of the passenger vehicle fleet to identify the sources of discrepancies as a step to improving on existing methods.

8.3 Energy and Environmental Policy Design for Passenger Vehicles

The modeling analysis performed in this work investigated two transport-specific energy policies, alone and in combination with an economy-wide constraint on GHG emissions. The objective of this analysis was to evaluate the costs of different policies and the impacts on technology, passenger vehicle gasoline use, and GHG emissions. Three important lessons emerge. First, in terms of the cost of achieving cumulative reductions in passenger vehicle gasoline use, the RFS and FES policies are at least six to fourteen times more expensive as a gasoline tax (on a discounted basis, depending on whether advanced biofuels are available). The FES-sharp policy and both RFS policy paths are the least costly of the regulatory instruments, while the FES-gradual path was by far the most costly because of the high cost associated with introducing very high levels of vehicle efficiency in the later periods. The analysis also showed that these policies produced very modest GHG emissions reductions. Second, the analysis showed that combining FES and RFS policies results in less reduction in passenger vehicle gasoline use than the sum of reductions under each policy implemented in isolation, while the cost of combining policies is roughly additive. Third, when an FES or RFS policy was combined with a CAT policy, the analysis showed that at best the regulatory instruments achieved an identical outcome (with no additional cost). Moreover, if policies achieved additional reductions in passenger vehicle gasoline use, the cost of meeting the GHG emissions constraint also increased. The question for policymakers then becomes, what level of gasoline reduction from passenger vehicles is desirable, given the technological options available and range of costs and reductions associated with each instrument? Sensitivity analysis to the consumer payback period demonstrated that under high discounting conditions, an FES Policy had the effect of increasing investment in vehicle efficiency (including adoption of PHEVs) relative to the No FES Policy (high discounting) baseline. This effect was more pronounced in the CAT policy case because the effect of the FES policy scales with the price of fuel, and fuel prices increase more under a CAT policy.

8.3.1 Implications for Research

One important implication of this work for ongoing research on transport-focused energy and environment policies is that it highlights the importance of using economy-wide (or at least multi-sector) models for policy evaluation. Transportation accounts for a large share of household expenditures and also a large share of total energy use, making general equilibrium effects important when it comes to the evaluation of policies. A partial equilibrium analysis considering only an FES or an RFS policy and limited to the passenger vehicle transport sector would fail to identify interactions among policies that arise from redundancy in household responses that the policies elicit (for instance, both incentivize investment in vehicle fuel efficiency above baseline levels) as well as offsetting effects on GHG emissions by increasing fuel demand in other sectors.

The model used here could also be easily adapted to perform the same analysis for other regions, to investigate additional policy questions, or to investigate the effects of policies on particular technologies, sectors, or household types with further disaggregation. A second area for future research involves a deeper investigation of the role of consumer discounting behavior with respect to energy-intensive consumption, and more accurately representing this behavior in models for policy analysis. For instance, if consumers are truly undervaluing fuel savings (an empirical question subject to debate), one could investigate whether or not an FES policy is the most cost-effective way to return consumers to pattern of consumption consistent with lifetime payback periods applied to new vehicle purchases. Moreover, it would then be important to investigate the effects of policy in the face of systematic undervaluation of *all* temporally-removed costs (and savings) across the entire household consumption bundle. A policy that narrowly targets undervaluation of fuel cost (savings) with respect to passenger vehicles might have the perverse effect of exaggerating similar undervaluation related to goods not targeted by the regulation.

8.3.2 Implications for Policy

In the United States today, a fuel economy standard and renewable fuel standard are implemented in combination, but the regulatory analysis for each policy is generally undertaken separately. The fact that interactions among policies matter to the total overall impact (as well as the costs) suggests that this approach may be misguided. If government agencies insist on regulating vehicles and fuels separately, this thesis supports the argument that the impacts of policies should be evaluated together in an integrated framework. This type of analysis would require closer coordination across agencies within the government that focus on disparate parts of the vehicle transport system.

The analysis undertaken in this work complements a large body of literature that has attempted to evaluate the cost and impact of different policies focused on reducing petroleum use and GHG emissions from passenger vehicles. The policies considered here are representative policies, motivated by recent interest and policy decisions in the United States. However, a wide range of policies not modeled in this analysis could be analyzed with minimal extension of the present effort. These include, but are not limited to, low carbon fuel standards, a per-mile emissions constraint, and a renewable electricity standard. Moreover, the effect of a suite of policies that bear on a single sector, such as the recent coordinated attempts to fund battery research and development, PHEV and EV production facilities, consumer tax rebates for PHEV and EV purchases, and infrastructure investments, could likewise be examined using this modeling framework.

8.4 Political Analysis

The final inquiry in this thesis described the tensions between economic efficiency and political feasibility for each of the transport-focused energy policies considered in the earlier chapters. Tensions were described at the level of policy justification, choice of policy type, and in terms of the design decisions within individual policies. Identifying these tensions provides a starting point for evaluating alternative courses of action, which will be taken up in **Section 8.5** of this chapter.

8.4.1 Implications for Research

The analysis in **Chapter 7** focused specifically on the political feasibility of the transport-focused energy policies—the federal excise tax on gasoline, the Corporate Average Fuel Economy program, and the Renewable Fuel Standard. A more comprehensive analysis could extend the scope of this work to include additional examples of passenger vehicle policies, past and present. In particular it would be very interesting to study a larger sample of failed and successful efforts to implement policies designed to correct vehicle transport-related externalities (for instance, this list could include mitigating congestion and local air pollution as well as addressing energy and climate goals). This study could be usefully expanded to look at state-level initiatives as well. An important goal of such studies would be to understand whether or not alignment between economic efficiency and political feasibility were correlated with successful policy outcomes, and if not, to explore the reasons why.

The existence of tensions between economic efficiency and political feasibility is not unique to policy for passenger vehicles. However, the salience and consequences of these tensions for political feasibility may be linked to features of the passenger vehicle case, leading to the question of whether variation exists across sectors in terms of the importance of the tensions in explaining observed outcomes. It would also be interesting to investigate whether tensions at a particular level (policy justification, policy type, or policy design choices) are more or less likely to affect the political feasibility of a particular policy.

8.4.2 Implications for Policy

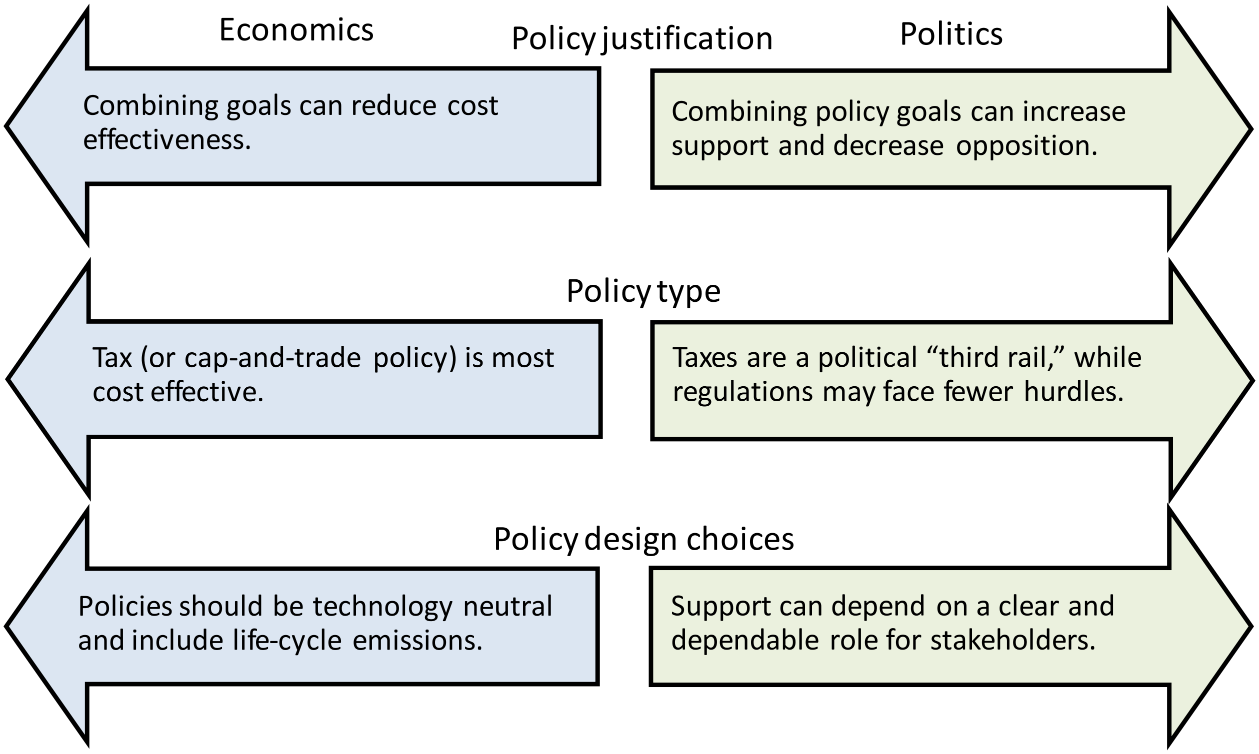
If raising awareness of tensions between economic and political motivations helps to prompt more frank discussion of the trade-offs inherent in policy choices, this thesis was perhaps already a worthwhile exercise. Unfortunately, to the extent that even recognition of these tensions proves inconvenient for individual bargaining positions, the prospects for political traction will be limited. Nevertheless, recognizing the roots and pervasiveness of the tensions outlined in **Chapter 7** as applied to climate and energy policy for passenger vehicles could help to move the debate toward a greater focus on compromise positions and reduce polarization. For instance, it could prompt frank discussion on additional criteria for selecting policies that could be used together with economic rationales to map productive alternative policy trajectories. In the final section, I suggest an approach that could prove useful in this regard.

8.5 Synthesis

With the findings of each of the four individual parts of this thesis in hand, I return to the task of integrating them in order to answer the main question of this thesis: What concrete recommendations emerge for policy going forward? Answering this question requires thinking first about the state of U.S. policy today, second about long term policy goals, and third, about what policy tool(s), acting as stepping stones, would help to enable the desired transition.

Figure 8.1 captures the main message of **Chapter 7**, which is that in many ways the policy option(s) that would most efficiently internalize the externality are not available at present due to political considerations. First, a narrowly targeted policy may be less difficult to justify if its advocates claim it will accomplish a wide range of goals (which would attract the support of varied stakeholders). Second, the burden of the most cost-effective policy instrument may be very visible to consumers and affect fuel use across many sectors, whereas command-and-control regulations are more surgical, with the burden falling on a smaller number of potential objectors. Moreover, excluded parties might also face incentives to support a narrowly targeted policy, if it substitutes for a broader alternative policy that would require them to make costly adjustments. Finally, within particular policies, policy design variables can be used to offer direct benefits to affected parties, for example, by limiting emissions coverage, defining the stringency and trajectory of policy targets, and perhaps even directing damaging effects toward politically diffuse or weak interests.

Fig. 8.1 Tensions between economic efficiency and political feasibility when it comes to climate and energy policy for passenger vehicles.



8.5.1 What Question(s) Should Policymakers be Asking?

With an appreciation for the diversity of household responses (**Chapter 3**), an awareness of the cost-effectiveness ordering of policies for particular goals (**Chapter 6**), and an understanding of the tensions between the economics and politics (**Chapter 7**), it is possible to tackle perhaps the most difficult and most important question in this thesis. This question asks: how could one use the four-part analysis in this dissertation to identify feasible courses of action that will move the U.S. in the right direction?

By many measures, today’s reality and current policy trajectory remain far from the GHG emissions trajectory scientists claim is required to reduce likelihood of the worst climate change outcomes, while nearly all passenger vehicles still depend on petroleum, much of it imported. Advocates of change claim the costs of inaction will be high, and will expose society to acute risks of climate warming and petroleum supply disruptions. The economic approach would suggest structuring the problem in terms of the costs and benefits. The policy that maximizes discounted net benefits would then be selected. Viewed this way, the problem is simply a matter of careful and precise accounting. This type of cost-benefit (as well as cost-effectiveness) analysis is one way of valuing the outcomes of policies, although as discussed it is far from the only consideration that enters into the policy process.

This work has underscored the importance of an interdisciplinary approach to policy evaluation. Policies that seem attractive in economic terms may prove intractable when viewed through a kaleidoscopic political lens. Each policy may look more or less attractive to particular stakeholders, depending on the criteria each uses to value policy outcomes. In many cases, influential stakeholders will have every incentive to judge a policy’s merit based on the benefits that it provides to them, for instance, financial gain, reduced risk, competitive advantage, or influence in future rounds of policy decisions. As shown in **Chapter 7** for the case of passenger vehicles, making a policy politically workable may require policymakers to abandon the same policy design principles that make them economically optimal. To proponents of cost-effective solutions, this situation could seem hopeless. Regardless, there must be something useful a candid, integrated look at the situation from multiple disciplinary angles can contribute.

8.5.2 A Way Forward?

In synthesizing the lessons of this work to provide recommendations for policy here, I first seek to be clear about the criteria I am using to value outcomes. The first criterion is economic cost. Resources saved by pursuing the most cost-effective strategy increase the resources available for pursuing other public policy priorities, while net benefits can be redistributed to compensate affected parties. However, I also recognize that the economically preferred policy will not always be available, for a combination of reasons cited above and in **Chapter 7**. I therefore suggest stronger emphasis on an additional criterion to value policy outcomes alongside cost-effectiveness: specifically, I suggest considering the effect a policy's implementation could have on progress toward the stated goal(s) (focusing on measures of effectiveness and setting aside cost for a moment) and, at the same time, create conditions that would incentivize stakeholders to increase policy cost effectiveness in the future. In presenting the recommendations that emerge from integrating the earlier findings of this work, I suggest several ways of considering policies on the basis of these criteria.

The first conclusion is that, using cost-effectiveness criteria alone, a gasoline tax emerges as the superior policy choice—by a lot. The next least costly regulatory policies are six to fourteen times the cost of the gasoline tax on a discounted basis. A gasoline tax would provide the greatest aggregate benefits to consumers. Appropriate mechanisms for redistributing the gasoline tax revenues could help to address asymmetries in the incidence of the tax across the driving population. One main problem is that the policy that achieves the optimal result happens to be a tax, which is ideologically unpalatable and has widespread impacts on vehicles, fuels, and consumers, leaving few advocates to support it. Even if it is off-limits for the foreseeable future, it is useful to keep the gasoline tax in mind, both as a benchmark against which to compare policy designs as well as a possible future option if ideology or interests change.

The second conclusion describes conditions under which the regulatory policies examined here could do better in terms of cost-effectiveness, as well as which choices should be ruled out. If policymakers want to accomplish a cumulative reduction in fuel use with a fuel economy standard, targets should start early and ramp down at a rate that takes full advantage of the gasoline use reductions that will result from displacing miles-driven by a less efficient vehicle with a more efficient one. To understand this point, perhaps it helps to imagine the total miles that will be traveled by all vehicles between 2010 and 2050. The more of these miles are driven in more (relative to less) efficient vehicles, the greater the total gasoline reduction will be. However, if the standard is staged such that a large fraction of the reductions must come in the later years, the required fuel consumption of new vehicles will need to reach a much tighter eventual target. Banking, credit trading, or other flexibility mechanisms could help to reduce the cost of the policy. In order to be effective as a GHG emissions reduction policy, any fuel economy standard should include, in an average sense, the upstream emissions associated with fuel use. Building explicit provisions into fuel economy regulations that require revisiting these provisions periodically over the compliance horizon could help to increase the cost effectiveness of the policy. Changes in political conditions or stakeholder incentives could increase the likelihood of adopting these provisions at a later point.

Of the regulatory policies, I argue here that a renewable fuel standard is superior for several (both economic and non-economic reasons), provided that certain conditions are met. A renewable fuel standard is more attractive relative to a fuel economy standard because it allows reductions to come from both the new and used vehicle fleets. It is also attractive because it operates through a price signal, incentivizing some investment in vehicle fuel economy and eliciting a demand response in much the same way as a tax prices the externality into gasoline purchases. On the political side, the price signal created by an RFS has the advantage that it is less “visible” to consumers and perhaps less subject to ideological objections. It could even be viewed as a stepping stone to an outright gasoline tax, if biofuels costs could be reduced to the point that a modest tax alone would guarantee their adoption (indeed, in the tax scenarios, biofuels were adopted based purely on market signals in the later periods). However, there are several important—indeed, essential—caveats to which this conclusion is sensitive: first, the cost of adding biofuels must actually be reflected in the fuel price to consumers. If biofuels are subsidized, consumers will not perceive this price signal. Second, the policy should be applied without making exceptions for particular fuel suppliers or refiners. However, failing to make exceptions may have the unintended effects of changing the competitive landscape, as companies with aging assets incapable of being easily adapted to biofuels production and blending may be suddenly at a disadvantage. Third, if sold as a GHG emissions reduction policy, biofuels from various sources must be evaluated on the basis of full life-cycle GHG emissions accounting, including any emissions resulting from land use change. As an alternative to a renewable fuel standard, a low carbon fuel standard may be more economically attractive based on the fact that it allows a wider range of alternative fuels to displace gasoline. Evaluating the economic and political feasibility of this policy is a topic for another study.

The third conclusion of this thesis relates to the role of combining regulatory policies. This thesis illustrated earlier the importance of evaluating regulatory policies in combination because of the potential for interaction effects that could result in a reduction in cost effectiveness. Agencies should be required to conduct joint assessments of the effects of policies because of the potential for offsetting effects among them. Furthermore, if two regulatory policies prove more politically feasible than a single, market-based instrument (such as a gasoline tax or a transport GHG emissions cap), I argue here that the former arrangement could be viewed as a stepping stone toward eventual reconsideration or acceptance of a more comprehensive market-based instrument. The underlying logic is as follows: by creating institutional structures for performing policy impact assessments with a broader scope (extending in this case to multiple policies) then these institutions will have incentives (and arguably greater capabilities) to move to market-based policies that would achieve the same level of fuel use and GHG emissions reductions at reduced cost. To ensure that this option is revisited, explicit provisions for a comparison between the performance of a patchwork regulatory approach and a comparable economy-wide market-based policy could be written into authorizing legislation.

The fourth and final conclusion of this thesis relates to combining regulatory policies focused on gasoline use reduction with a cap-and-trade system. Since it is not clear how much of a reduction in gasoline use the CAT policy will achieve, policymakers wanting to ensure significant cuts in passenger vehicle gasoline use might consider adding a policy instrument specifically for this purpose. However, they need to be aware that adding the policy will produce no *additional* GHG reduction benefits, and that the additional reductions in gasoline use will come at a cost. It is up to policymakers to decide whether or not they are willing to accept the additional cost. If a CAT policy proves unacceptable politically without explicitly including a fuel economy standard or renewable fuel standard or both, then adding either or both of these policies could either have no effect on cost or gasoline use (if not binding), or a non-negligible effect on both cost as well as gasoline use. Choosing a relatively modest target might be a politically acceptable way to ensure some minimum level of gasoline reduction occurs.

8.5.3 How Do We Get Started?

Together, these recommendations are intended to help policymakers grapple with the trade-offs inherent in policy choices, and to motivate policy action that, although perhaps not initially the most economically efficient, creates incentives for revisiting and increasing policy cost effectiveness over time. This long-term vision raises the question: how should we get started today?

This thesis has offered several explanations for the current policy situation in the United States, which involves reliance on regulatory policies and persistent aversion to a tax on gasoline, despite economic arguments in its favor. Moving away from the status quo will have to be done gradually, and in concluding this thesis, I offer two possible strategies. Researchers and policymakers could investigate the potential for using dual policy approaches aimed at phasing out one policy in favor of a more cost-effective one. For example, an initially low but gradually rising gasoline tax could be combined with a minimum fuel economy standard. Automakers would benefit from certain and clear fuel economy requirements, while consumers would face incentives to value fuel economy for its ability to offset the impact of gasoline price increases. Specifying a clear timeline for revisiting the impact of this dual policy approach, for identifying the role of the gasoline tax in demand for vehicle fuel economy, and identifying appropriate minimum target fuel economy levels that are not binding could form important steps toward implementing this policy. Any gasoline tax policy would need to be combined with appropriate redistributive provisions to address equity concerns. On the other hand, policymakers should generally avoid expecting a single regulatory policy instrument that targets only one part of the system to accomplish significant reduction in fuel use without high costs. Another flavor of the dual policy approach involves introducing provisions that increase the cost effectiveness of a particular policy type. For example, adding credit trading provisions to an FES policy, moving to a percentage versus volumetric blending target for an RFS policy, or removing subsidies on the production of advanced biofuels to allow fuel cost to increase, thereby encouraging a reduction in demand, are all strategies that could be considered starting from the policies on the books today.

Gradual but meaningful changes that start with today’s policies and incorporate the most politically feasible principles of cost-effective design are perhaps the best way to ensure that aggressive targets for petroleum use and GHG emissions reductions can be achieved over the longer term. This discipline, it is hoped, will keep U.S. policy on roads that encounter fewer political obstacles to achieving energy security and climate goals, while encouraging a shift to more direct routes over time.

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Appendix A: Parameterization of the Passenger Vehicle Transport Sector in the EPPA Model: Methods and Data

Here I describe the model used for this analysis, the MIT Emissions Prediction and Policy Analysis model, and provide additional detail on the methods and data sources used to parameterize the new passenger vehicle transport sector. This appendix accompanies the description of the modeling method found in **Chapter 4**. It closely parallels the structure of Chapter 4, providing general background on the model before focusing on each of the three model developments in detail.

A.1 Detailed Description of the MIT Emissions Prediction and Policy Analysis (EPPA) Model

The Emissions Prediction and Policy Analysis (EPPA) model is a recursive-dynamic general equilibrium model of the world economy developed by the Joint Program on the Science and Policy of Global Change at the Massachusetts Institute of Technology (Paltsev et al., 2005). The EPPA model is built using the Global Trade Analysis Project (GTAP) dataset (Hertel, 1997; Dimaranan & McDougall, 2002). For use in the EPPA model, the GTAP dataset is aggregated into 16 regions and 24 sectors. The model also includes several advanced technology sectors that are not explicitly represented in the GTAP data (**Table A1**). Additional data for emissions of greenhouse gases (carbon dioxide, CO_2; methane, CH_4; nitrous oxide, N_2O; hydrofluorocarbons, HFCs; perfluorocarbons, PFCs; and sulphur hexafluoride, SF_6) and air pollutants (sulphur dioxide, SO_2; nitrogen oxides, NO_x; black carbon, BC; organic carbon, OC; ammonia, NH_3; carbon monoxide, CO; and non-methane volatile organic compounds, VOC) are based on United States Environmental Protection Agency inventory data and projects (Paltsev et al., 2005).

Much of the sectoral and technology detail included in the EPPA model is focused on providing a more accurate representation of energy production and use as it may change over time or as a result of policies that constrain greenhouse gas (GHG) emissions. The base year of the EPPA model is 2004, and the model is solved recursively in five-year intervals starting with the year 2005. The EPPA model represents production and consumption sectors as nested Constant Elasticity of Substitution (CES) functions (or the Cobb-Douglas and Leontief special cases of the CES). The model is formulated as a system of equations in the GAMS software system and solved using MPSGE modeling language (Rutherford, 1995). The EPPA model has been used in a wide variety of policy applications (e.g., Clarke et al., 2007).

Table A1 Sectors and regions in the EPPA model.

Sectors	***Regions***
Non-Energy	***Developed***
Agriculture	USA
Forestry	Canada
Energy-Intensive Products	Japan
Other Industries Products	Europe
Industrial Transportation	Australia & Oceania
Household Transportation	Russia
Food	Eastern Europe
Services	***Developing***
Energy	India
Coal	China
Crude Oil	Indonesia
Refined Oil	Rest of East Asia
Natural Gas	Mexico
Electricity Generation Technologies	Central & South America
Fossil	Middle East
Hydro	Africa
Nuclear	Rest of Europe and Central Asia
Solar and Wind	Dynamic Asia
Biomass	
Natural Gas Combined Cycle (NGCC)	
NGCC with CO_2 Capture and Storage (CCS)	
Advanced Coal with CCS	
Synthetic Gas from Coal	
Hydrogen from Coal	
Hydrogen from Gas	
Oil from Shale	
Liquid Fuel from Biomass	

Note: Detail on aggregation of sectors from the GTAP sectors and the addition of advanced technologies are provided in Paltsev et al. (2010).

A.1.1 The Household Transport Sector in EPPA

Previous work augmented the GTAP data set to create a transportation sector in Version 4 of the EPPA model that supplied the transportation needs of households (Paltsev et al., 2005). In this version of the model, the household chooses between purchased transport and the services of household-owned vehicles. The sector structure and method used to calculate input shares for the previous version of the household vehicle transport sector for Version 4 of the EPPA model is described in Paltsev et al. (2004). Briefly, the fraction of household consumption expenditures devoted to household passenger vehicle transport is calculated for each region in the base year. Household expenditures on refined oil for transportation (defined as a percentage of total household refined oil consumption, in most countries around 90%) and annual expenditures on new vehicles for the base year are then used to specify the fuel and vehicle inputs, respectively. Expenditures on services (including vehicle insurance and maintenance) in each region are calculated as a residual by subtracting the other two inputs, fuel and vehicle expenditures, from total expenditures on household transport services. This method was designed to permit input share calculations for household vehicle transport despite a paucity of data for many world regions. The method for calculating expenditure shares for the new and used vehicle fleets is similar, but requires some extensions of this approach, and is discussed later in **Section A3**.

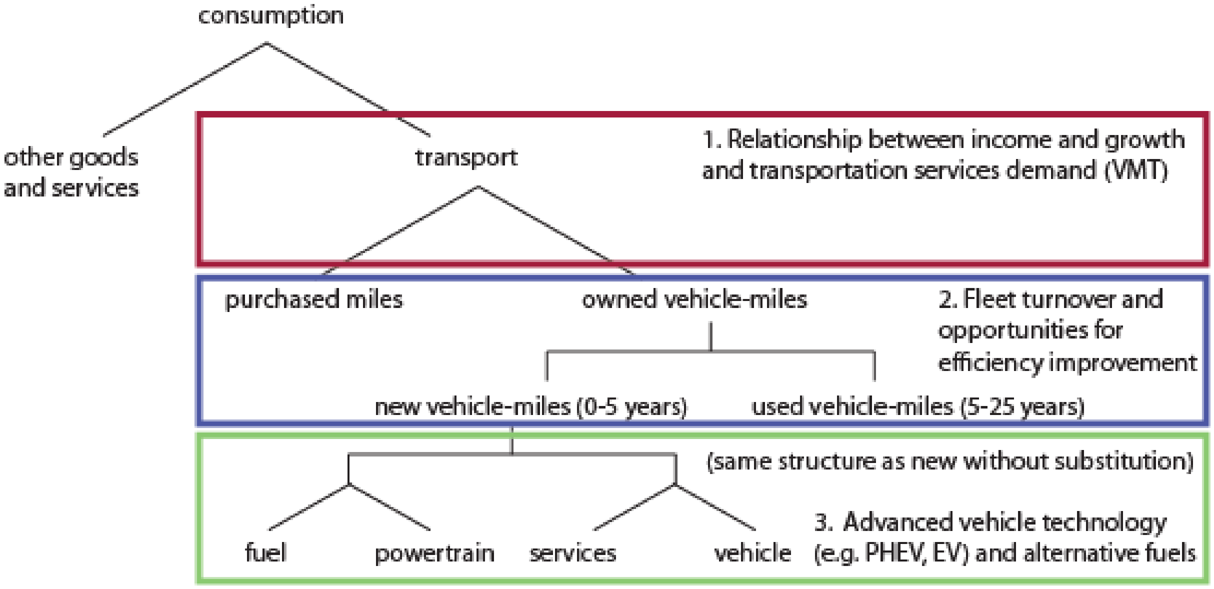
Elasticities of substitution among fuel, vehicle efficiency investment, and other vehicle-related expenditures reflect a combination of technical and behavioral properties of the household response to changes in relative prices. The most crucial elasticities given our interests in the effect of energy and climate policies are those that determine substitution toward or away from petroleum-based or GHG-intensive fuels within the own-supplied transport sector and reliance on passenger vehicles versus other modes of transport. The main evidence for these substitution elasticities comes from econometric studies (see Paltsev et al., 2004 for a more detailed description).

A.1.2 Summary of Modifications to the EPPA Model

The remainder of **Appendix A** parallels **Chapter 4**, providing additional detail on the data and methods used to parameterize the new household vehicle transport sector in Version 5 of the MIT EPPA model. A summary of the new structure, with each of the developments highlighted on the right-hand side next to each box can be found in **Figure A1** below.

To implement the detailed physical and economic accounting in the passenger vehicle transport sector (the output of which is indicated as owned vehicle-miles in the figure), global data on the physical characteristics of the fleet (number of vehicles, vehicle-miles traveled, and fuel use) as well as economic characteristics (the levelized cost of vehicle ownership, comprised of capital, fuel, and services components) were used to parameterize the passenger vehicle transport sector in the benchmark year. Econometric estimates were used to set the income elasticities used to parameterize the Stone-Geary utility function and the substitution elasticities that determine substitution between fuel and fuel abatement-related vehicle capital.

Figure A1 (also **Figure 4.1**) Schematic overview of the new developments in the passenger vehicle transport sector incorporated into the representative consumer's utility function in the MIT EPPA model.[58] New developments are numbered on the right-hand side of the utility function structure.



A.2 Development 1: Demand for Transport Services: Methods and Data

This section elaborates on the empirical data and methods used to relate changes in per capita income and demand for vehicle transportation services over time. Briefly, the strategy applied here is to represent how the share of expenditures devoted to passenger vehicle transport will change with per capita income.

In the benchmark year 2004 spending on vehicle transport services and number of miles traveled defines a fixed relationship in terms of dollars per mile in USD 2004. This relationship is assumed to change over time either as a result of income effects (which are captured in a changing income elasticity of demand, implemented using Stone-Geary Preferences) or price effects (which is determined by relative prices and substitution elasticities). Estimates of the passenger vehicle transport expenditure share are roughly consistent across sources, although differ markedly in several isolated cases, as shown in **Table A2**. The differences are likely due to differences in the definition of vehicle transport expenditures. The estimates in the top row labeled "EPPA5" were used in this analysis.

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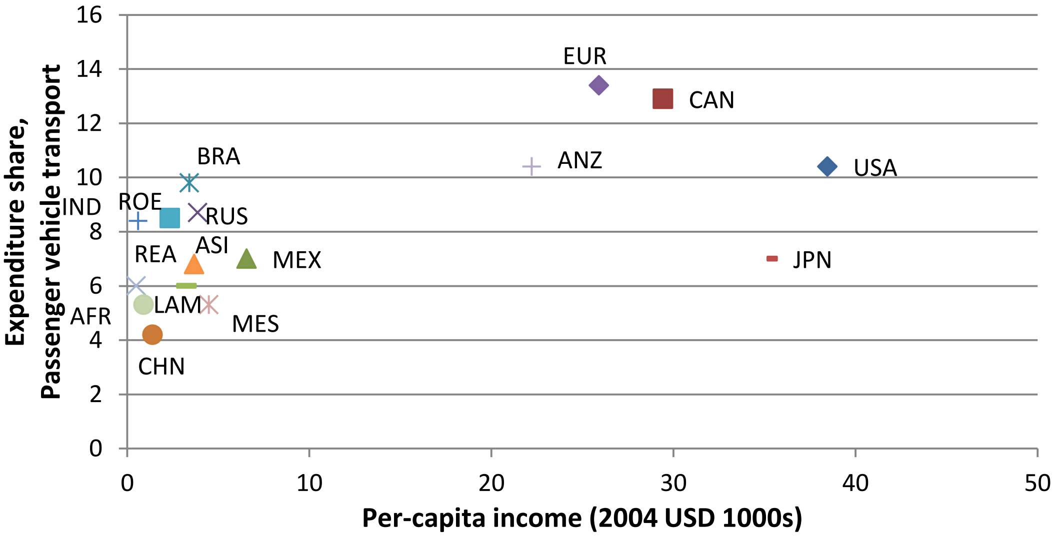
[58] Other CGE models typically use a similar structure for the consumer or household utility function.

Table A2 Top-down estimates of vehicle transport expenditure share in % by EPPA region.[59]

Region	USA	CAN	MEX	JPN	ANZ	EUR	ROE	RUS	ASI	CHN	IND	AFR	MES	BRA	LAM	REA
EPPA5	10.4	12.9	7	7	10.4	13.4	8.5	8.7	6.8	4.2	8.4	9.8	5.3	9	6	6
Meyer et al. (2007)	12	12	7	10	10	11	10	10	9	7	7	7	7	7	7	9
GMID (2010)[60]	10.3	10.8	8.5	7.5	9.8	9.3	6.7	8.0	7.8	5.0	6.3	4.1	6.1	6.1	4.6	4.9

Figure A2 plots a cross section of expenditure share estimates against per capita income, which demonstrates that in general, developed countries/regions have a larger transport expenditure share than developing countries/regions, although there is variation in share size at both high and low per capita income levels.

Figure A2 The relationship between per capita income and budget share spent on passenger vehicle transport (purchase and operating costs) in each of the 16 world regions in 2004 (GTAP).



Since this analysis focuses primarily on the United States, and rich historical data is available, I focus on the relationship between per capita income and passenger vehicle transport expenditure share in the U.S. The historical share of spending on passenger vehicle transport and per capita income is shown in **Figure A3**. The large reduction in transport expenditure share coincides with the Second World War. Expenditure shares rebounded in the 1950s and remained steady until 1980, when they show signs of an overall decline despite some sharp fluctuations. It

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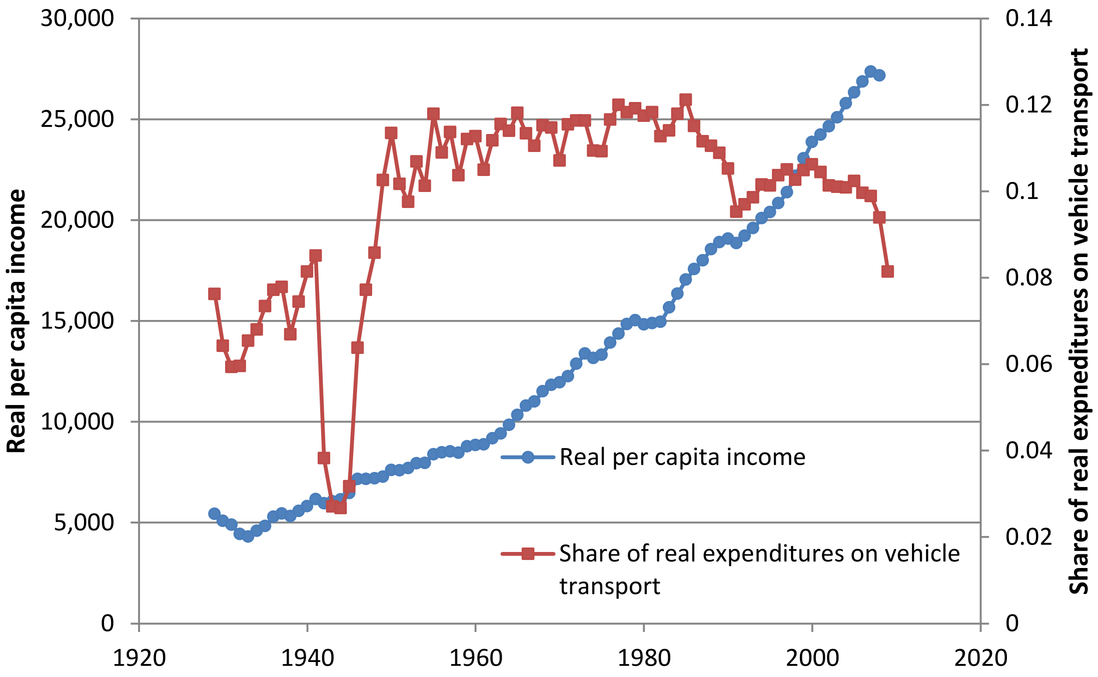
[59] For EPPA countries or regions not resolved in the Meyer et al. (2007) or GMID (2010) databases, shares are approximated based on the population-weighted average of a subset of countries (GMID, 2010) or based on the closest regional grouping (Meyer et al., 2007).

[60] GMID is the Global Market Information Database (2010), which provides data on total expenditures, vehicle operating expenditures, and new and used vehicle purchases. For some regions, data was only available for a subset of countries.

is also clear that the size of the transport expenditure share is vulnerable to income shocks—for instance, the large dip in 2008 to 2009 reflects the effects of the global recession.

Figure A3 Time trend for the United States in real per capita income (blue) and share of real expenditures on vehicle transport (red).



Source: BEA, 2010.

Since the objective is to identify income elasticities of demand for VMT, and how these elasticities will change over time, I rely on a 2002 meta-study of literature estimates of VMT elasticities. Hanly et al. (2002) provide evidence that the long-run average income elasticity of demand for VMT is 0.73, but there is significant variation across estimates. The average, standard deviation, and range for estimates of long-run income elasticity of demand for VMT are shown in **Table A3**. These long-run elasticities are based on countries and U.S. regions chosen for their similarity to the United Kingdom in terms of vehicle ownership and demographic characteristics. The study notes a declining trend in income elasticity of demand as per capita income increases.

Table A3 Income elasticity of demand for VMT based on Hanly et al. (2002).

Average elasticity	0.73
Standard deviation	0.48
Range (upper, lower)	0.12, 1.47
Number of estimates	7

Data shown in **Figure 4.2** for the United States supports a long-run income elasticity of 0.7 since 1970, but this is not a tight estimate of income elasticity of demand because price effects and other possible confounding variables (such as fuel economy regulations) are not separated out. In the present analysis I acknowledge the difficulty of obtaining precise empirical estimates (the estimates presented in Table A3 have a large range), and the difficultly of using these income elasticity of demand estimates to project forward. I therefore use these estimates as a guide, choosing 0.7 as a reference case value for developed countries and 1 for developing countries, but explore the sensitivity to alternative specifications. The results of the sensitivity analysis are shown in **Section C** below.

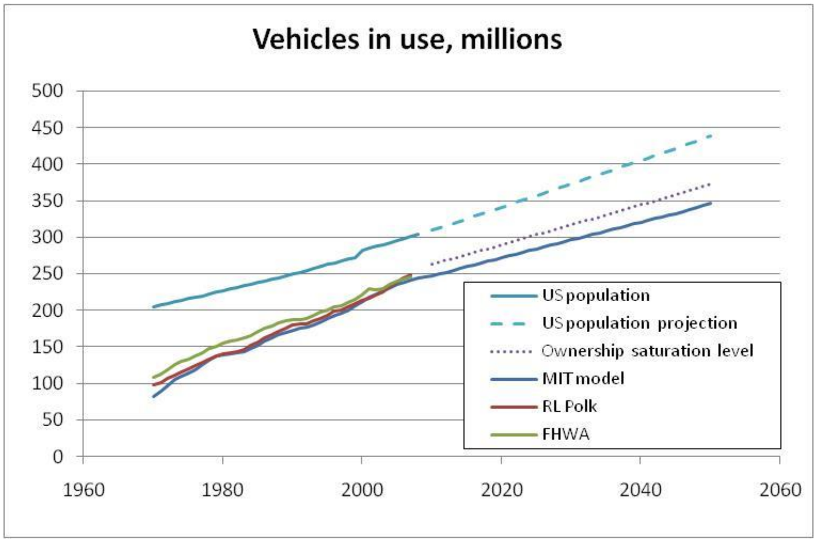
A.2.1 Estimated Trends in Income Elasticity of VMT Demand in Each of the 16 World Regions and Sample Outputs

The income elasticity of demand for a particular model region is defined across ranges of per capita income. This section illustrates the effect of changing underlying assumptions about the relationship between per capita income and the income elasticity of demand for VMT. This part focuses on the United States because of data limitations for other regions.

Table A4 Vehicle ownership projections from the MIT EPPA model, Version 5.

Year	**U.S. Population (millions, projected)**	**Annual Growth (%)**	**Vehicles (millions, projected)**
2010	310,233		235
2015	325,540	0.97%	247
2020	341,387	0.96%	259
2025	357,452	0.92%	271
2030	373,504	0.88%	283
2035	389,531	0.84%	295
2040	405,655	0.81%	307
2045	422,059	0.80%	320
2050	439,010	0.79%	333

Figure A4 Vehicle stock growth projections from the Sloan Automotive Lab fleet model.



Source: Cheah, 2010.

It should be noted that average per capita income is an imperfect predictor demand for transportation services, in particular because it ignores disparities in household vehicle purchasing behavior across the income distribution. Since the decision to purchase a vehicle exhibits a "threshold" effect, or occurs at the point when income is sufficiently high and stable to enable a household to afford ownership, a method that defines growth in VMT on the basis of the average income in the population could be misleading. To ensure that the forecasted expenditure shares by region do not follow unrealistic trends, I check the model projections against those made by modeling approaches that do account for income disparities in the population.

To simplify the task of estimating income elasticities of demand in all world regions, four scenarios embodying different assumptions were used to produce forecast for vehicle ownership through 2050:

1. Income elasticity of demand for VMT-\$ equal to 1 in all regions (EPPA Version 4).
2. Income elasticity of demand for VMT-\$ equal to 0.70 in developed countries and equal to 1 in developing countries.
3. Income elasticity of demand for VMT-\$ equal to 0.70 in developed countries and equal to 1.5 in developing regions until average per capita income reaches \$7,500 USD 2004, at which point income elasticity drops to 0.70.
4. Income elasticity of demand for VMT-\$ equal to 0.70 in developed countries until 2030, then dropping to 0.60 in the United States after 2030 (all else constant).

A comparison of fleet growth projections under the different elasticity assumptions is shown in **Table A5**. Demand for VMT in Scenario 1 experiences a 3.2-fold increase in 2050 relative to

2010, Scenario 2 a 3-fold increase, Scenario 3 a 3.3-fold increase, and Scenario 4 a 2.3-fold increase (largely due to much slower growth in the United States starting in 2035).

In this analysis, I use Scenario 4 as the reference case scenario because it produces fleet growth estimates for the United States that are consistent with a constant level of vehicle ownership (**Table A4**) (which occurs at the point when per capita vehicle sales equals the per capita number of vehicles scrapped) and a reputable U.S. fleet model, the Sloan Automotive Lab Fleet Model (**Figure A4**) (Bandivadekar et al., 2008; Cheah, 2010).

A.2.2 Review of Real Vehicle Price Trends

It is important to note here that vehicles have changed significantly over time in terms of their aesthetic and functional attributes, contributing to an increase in the real vehicle price. Historical trends in vehicle attributes and real vehicle prices over time are described in Abeles (2004).

The new modeling approach has the ability to represent trends in this type of change in vehicle attributes over time, if desired, and the impacts of quality changes on energy-related attributes. Quality changes could be energy-intensive, energy-saving, or energy-neutral, depending on the type of modification that is made. Modifications that involve adding weight, horsepower, or additional features will also increase the energy requirement of the vehicle (Cheah, 2010). Modifications that increase the demand for energy would increase the non-powertrain expenditure share which, due to the Leontief structure of the substitution between the powertrain-fuel nest and the services-vehicle nest, would result in corresponding increased requirement for fuel (or spending on fuel efficiency).

Table A5 A comparison of vehicle stock projections and compound annual growth rates under four different assumptions about the income elasticity of demand in each of the world regions.

Region	USA	CAN	MEX	JPN	ANZ	EUR	ROE	RUS	ASI	CHN	IND	BRA	AFR	MES	LAM	REA	Total
A) All regions have same income elasticity of demand (old EPPA, equal to unity)																	
2010	236	20	18	83	16	225	31	30	29	48	26	28	10	11	14	18	**843**
2050	599	55	44	153	44	480	85	73	72	267	127	75	26	30	39	65	**2234**
Avg. CAGR	2.4%	2.5%	2.2%	1.5%	2.5%	1.9%	2.5%	2.3%	2.3%	4.4%	4.0%	2.5%	2.6%	2.6%	2.6%	3.2%	**2.5%**
B) Developed regions - low elasticity (<1), developing regions - high elasticity (>1)																	
2010	234	19	19	80	16	221	32	25	26	56	29	31	8	12	15	20	**844**
2050	431	38	44	119	31	360	85	50	51	272	130	76	18	30	39	66	**1840**
Avg. CAGR	1.5%	1.7%	2.2%	1.0%	1.7%	1.2%	2.5%	1.7%	1.7%	4.0%	3.8%	2.3%	2.0%	2.3%	2.4%	3.0%	**2.0%**
C) Developed regions - low elasticity (<1), developing regions except Africa initially high elasticity then low elasticity above per capita income $7,500 USD 2004 (>1)																	
2010	234	19	18	80	16	221	31	25	26	48	26	28	8	11	14	18	**825**
2050	433	38	31	120	31	361	85	49	51	169	133	52	18	19	27	66	**1683**
Avg. CAGR	1.5%	1.7%	1.4%	1.0%	1.7%	1.2%	2.6%	1.7%	1.7%	3.2%	4.1%	1.5%	2.0%	1.5%	1.6%	3.2%	**1.8%**
D) Developed regions - low elasticity (<1), developing regions – high elasticity (>1), U.S. elasticity reduced to 0.6 after 2030.																	
2010	234	19	18	80	16	221	31	25	26	48	26	28	8	11	14	18	**825**
2050	328	38	44	119	31	360	85	50	51	273	131	76	18	30	39	66	**1739**
Avg. CAGR	0.8%	1.7%	2.3%	1.0%	1.7%	1.2%	2.6%	1.7%	1.7%	4.4%	4.1%	2.5%	2.0%	2.5%	2.6%	3.3%	**1.9%**

A.3 Development 2: Representing Engineering Detail and Abatement Opportunities in the Existing Vehicle Fleet – Methods and Data

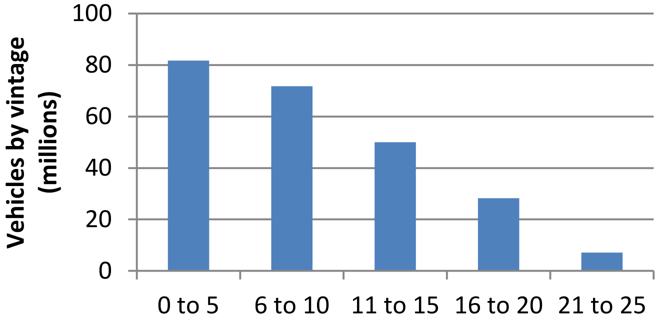
This section describes the parameterization of the new and used vehicle fleets and opportunities for incremental improvement in new vehicle efficiency. First, the data underlying the simplified fleet turnover algorithm is described. Second, the calculation of expenditure shares is described. Third, the parameterization of the elasticity of substitution that determines how increases in fuel price induce investments in fuel efficiency is discussed.

A.3.1 Fleet Turnover

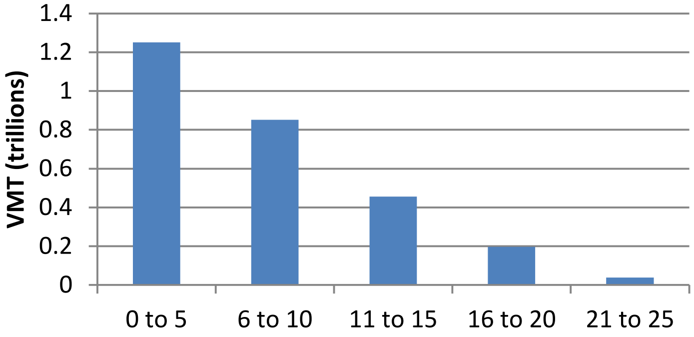
The process of fleet turnover was modeled by considering the contribution of vehicles to vehicle-miles traveled (VMT) by age. The rationale for focusing vehicle-miles traveled is that 1) they represent the services provided by the vehicle capital stock, and are thus an appropriate measure of the quantity of sector output, 2) using vehicles instead of VMT would not capture the contribution of vehicles by age to VMT (for instance, because the share of VMT driven on the oldest vehicles is significantly smaller than the share of oldest vehicle son the road), and 3) both fuel use and GHG emissions scale with VMT, given a fleet of vehicles with certain efficiency characteristics. The second point is illustrated below by comparing the distribution of vehicles and VMT by vintage (**Figure A5**).

Figure A5 Bottom-up calculation of the contribution of different vintages of vehicles by age in the United States to a) total on-road vehicles and b) vehicle-miles traveled.

a)

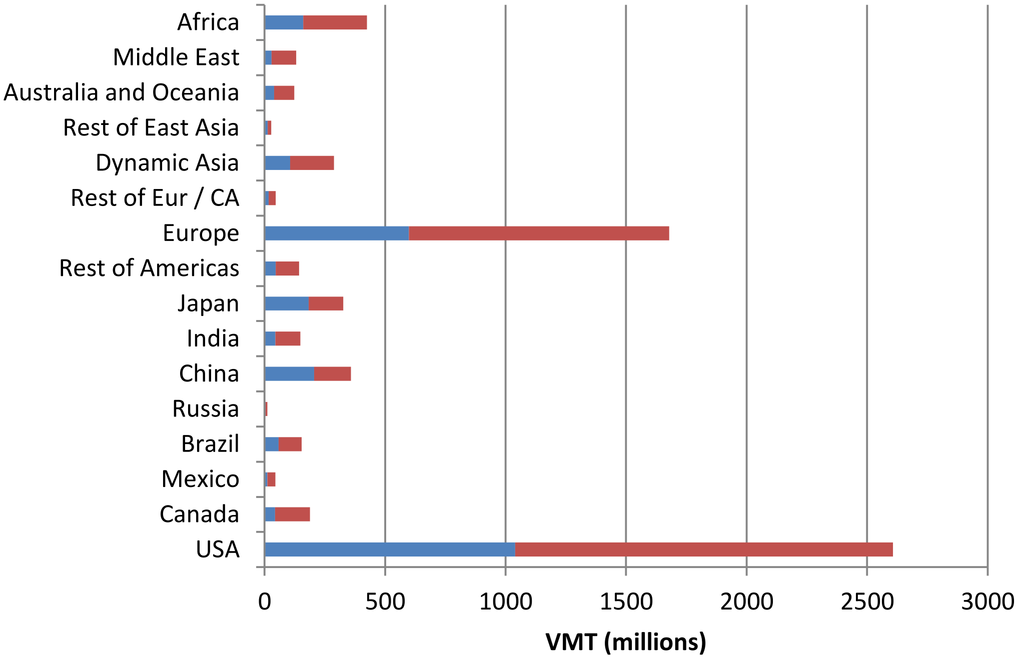


b)



Source: Sloan Automotive Laboratory Fleet Model (Cheah, 2010).

Figure A6 The contribution of new and used vehicles to total VMT by EPPA region (Blue – new VMT; Red – used VMT).



Sources: Global Market Information Database, 2010; IRF, 2009.

In the EPPA model only two vehicle vintages are explicitly represented, but the VMT contribution and the characteristic average efficiency of the four underlying five-year used vehicle vintages is tracked over time. In order to calibrate new and used fleets in the EPPA model in the benchmark year 2004, I first calculate the fraction of miles driven in new (zero to five-year-old) versus used (over five-year-old) vehicles in each of the 16 EPPA regions. This calculation is done using data on VMT and, where known, the fraction of miles-traveled in vehicles zero to five years old. Where not known, a fixed percentage (40%) of total vehicle-miles is assumed to be driven in new vehicles, while the remaining 60% are driven in used vehicles. **Figure A6** shows the reported total VMT and the split between new and used vehicles in each region. The number of new and used vehicles, as well as total VMT, is shown in **Table A6**.

Table A6 Number of vehicles in new and used fleets in 2004 and total VMT assumed in each of the EPPA model regions.

Country / Region	**New Vehicles (1,000 units)**	**Used Vehicles (1,000 units)**	**Total VMT (billions)**
USA	65,000	165,000	2,608
Canada	4,097	13,823	188
Mexico	3,709	10,579	44
Brazil	6,479	10,578	154
Russia	7,267	16,942	12
China	9,997	7,362	358
India	2,586	6,033	148
Japan	23,841	18,936	327
Rest of Americas	3,677	13,171	143
Europe	79,023	148,737	1,679
Rest of Europe and Central Asia	3,225	15,002	46
Dynamic Asia	11,078	18,750	287
Rest of East Asia	766	1,552	28
Australia and Oceania	4,190	9,016	122
Middle East	2,444	16,733	131
Africa	3,867	8,897	425
Total	**231,242**	**481,111**	**6,699**

Sources: Global Market Information Database, 2010; IRF, 2009.

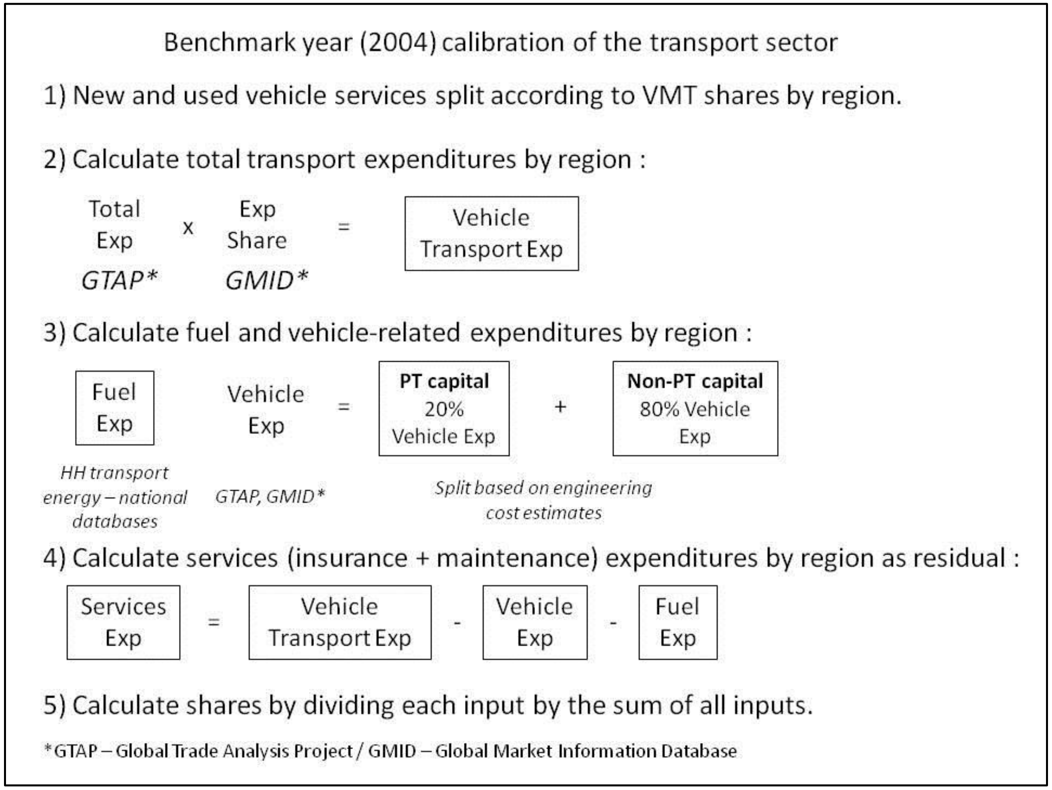
A.3.2 Cost Shares for Existing Vehicle Technology by Vintage

Tracking the technical efficiency of vehicles by age as they move through the fleet is important to obtaining accurate forecasts of fuel requirements and associated emissions. In this section I provide a detailed description of the data used to parameterize the vehicle fleet in the United States, and describe the data, simplifications, and assumptions that were used to obtain shares for the vehicle fleets in other regions.

The procedure used to determine the expenditure shares for passenger vehicle transport is shown in **Figure A7**. The procedure is similar to the calculation of expenditure shares in previous versions of the EPPA model. First, the VMT driven in new and used vehicles is determined by region in the benchmark year, 2004. Second, total passenger vehicle transport expenditures are obtained by applying the expenditure share calculated above (in future periods, this share is controlled by the income elasticity of demand). Third, fuel and vehicle requirements are calculated. The fuel requirement in both energy units (exajoules) and value terms (USD) for 2004 are calculated by region. Expenditures on vehicles are obtained from the GTAP database, while number of vehicles is obtained from the World Road Statistics (IRF, 2009) and Global Market Information Database (GMID, 2010). Fourth, spending on services is calculated as a residual. Fifth, shares are calculated and shown in Figure A7b. In the benchmark year, new and used vehicles represent the fleet average fuel efficiency, but the efficiency of new and used vehicles diverges over time in the presence of incentives to increase new vehicle efficiency.

Figure A7 Detailed description of the calculation of and values of expenditure shares for both new and used vehicles in the passenger vehicle transport sector in the 16 EPPA regions.

a)



Benchmark year (2004) calibration of the transport sector

1) New and used vehicle services split according to VMT shares by region.

2) Calculate total transport expenditures by region :

3) Calculate fuel and vehicle-related expenditures by region :

4) Calculate services (insurance + maintenance) expenditures by region as residual :

5) Calculate shares by dividing each input by the sum of all inputs.

*GTAP – Global Trade Analysis Project / GMID – Global Market Information Database

b)

Input	USA	CAN	MEX	JPN	ANZ	EUR	ROE	RUS	ASI	CHN	IND	BRA	AFR	MES	LAM	REA
Refined oil	0.096	0.099	0.280	0.083	0.105	0.062	0.247	0.303	0.382	0.465	0.656	0.304	0.472	0.453	0.372	0.307
PT capital	0.055	0.092	0.018	0.061	0.066	0.091	0.101	0.080	0.113	0.022	0.006	0.125	0.093	0.095	0.066	0.051
Non-PT capital	0.221	0.370	0.072	0.244	0.262	0.366	0.401	0.320	0.455	0.088	0.026	0.499	0.371	0.384	0.263	0.202
Insurance / Maintenance	0.628	0.438	0.631	0.612	0.567	0.481	0.251	0.297	0.050	0.425	0.311	0.072	0.065	0.067	0.299	0.440

A.3.2 Derivation of Formula for Elasticity of Substitution using Cost-effectiveness Data

To capture how increases in the fuel cost per mile could induce consumers to substitute investment in fuel efficiency to offset these fuel costs, I use detailed engineering estimates to construct a supply curve for gasoline fuel abatement for the internal combustion engine vehicle, which in turn can be used to estimate an elasticity of substitution that captures propensity to invest in new passenger vehicle fuel efficiency. This section describes the theory, based on the method outlined in Hyman et al. (2002) for handling non-CO_2 GHG emissions, which leads to the construction of the abatement supply curves and the estimation of the elasticity of substitution. Here I use U.S. based data to estimate this curve, and assume as a first approximation that other regions the shape of this relationship will not be radically different, given the global nature of the automotive industry and its suppliers, although the starting level of fuel economy does often differ across regions.

The structure of the passenger vehicle transport sector includes a branch that corresponds to vehicle powertrain capital and fuel inputs, with the balance between them over time defined by the propensity to invest in vehicle fuel efficiency in response to rising per-mile fuel costs. The elasticity of substitution defines the change in input shares in response to a change in relative input prices, holding output constant. In other words, it is the percent change in the intensity of one input compared to the percent change in the rate of technical substitution.

To illustrate how the elasticity of substitution can be derived using the MAC curve approach, let us begin by defining several variables:

$\sigma_{F,K_{PT}}$	Elasticity of substitution between fuel and vehicle capital
Y_F	Quantity of fuel, expressed as a unit cost
Y_{PT}	Quantity of powertrain capital, expressed as a unit cost
X_{FPT}	Fuel-powertrain bundle, total value, expressed as a unit cost
X_{KS}	Capital-services bundle, total value, expressed as a unit cost
A	Efficiency parameter
C	Total cost
θ	Cost share for input Y_F

The powertrain "sector" of the new passenger vehicle transport services corresponds to output produced according to the CES production function:

$$X_{FPT} = A\left[\theta X_{PT}^{\frac{\sigma}{(\sigma-1)}} + (1-\theta)X_{F}^{\frac{\sigma}{(\sigma-1)}}\right]^{\frac{\sigma}{(\sigma-1)}} \tag{A.1}$$

The utility function is optimized subject to the constraint that:

$$C = X_F P_F + X_{PT} P_{PT} \tag{A.2}$$

Solving for X_F and X_{PT} in terms of C and prices, we obtain:

$$X_F = C\left[P_F + \left(\left(\frac{1-\theta}{\theta}\right)(P_F/P_{PT})\right)^{\sigma} P_{PT}\right]^{-1} \tag{A.3}$$

$$X_{PT} = C\left[P_{PT} + \left(\left(\frac{1-\theta}{\theta}\right)(P_{PT}/P_F)\right)^{-\sigma} P_F\right]^{-1} \tag{A.4}$$

When these expressions are plugged into the original objective function and simplified, the expression for total production cost is obtained as follows:

$$C = \frac{X_{FPT}}{A}\left[\theta P_F^{(1-\sigma)} + (1-\theta)^{\sigma} P_{PT}^{(1-\sigma)}\right]^{\frac{1}{1-\sigma}} \tag{A.5}$$

By taking the first derivative of **Equation A.5** with respect to price, by Shephard’s Lemma we are able to recover demand functions for X_F and X_{PT}:

$$X_F = \frac{X_{FPT}}{A}\left[\left(\frac{A}{X_{FPT}}\right)\left(\theta\frac{C}{P_F}\right)\right]^{\sigma} \tag{A.6}$$

$$X_{PT} = \frac{X_{FPT}}{A}\left[\left(\frac{A}{X_{FPT}}\right)(1-\theta)\left(\frac{C}{P_{PT}}\right)\right]^{\sigma} \tag{A.7}$$

The price elasticity of demand for fuel is then found by differentiating the demand function for fuel with respect to the price of fuel, and multiplying by P_F/X_F:

$$\epsilon_{D_F} = \frac{dX_F}{dP_F}\frac{P_F}{X_F} = \left(-\frac{\sigma}{P_F}X_F + \frac{\sigma}{C}X_F^2\right)\frac{P_F}{X_F} \tag{A.8}$$

This expression can be simplified, yielding:

$$\epsilon_{D_F} = -\sigma + \frac{\sigma X_F P_F}{C} \tag{A.9}$$

Solving this expression for σ yields an expression for the elasticity of substitution in terms of the price elasticity of demand, the quantity X_F, and the price P_F:

$$\sigma = \frac{-\epsilon_{D_F}}{1-\left(\frac{X_F P_F}{C}\right)} \tag{A.10}$$

Simplifying the denominator by substituting the constraint expression (**Equation A.2**) for C results in an expression for the elasticity of substitution in terms of the price elasticity of demand and the fuel expenditure share:

$$\sigma_{F,K_{PT}} = \frac{-\epsilon_{D_F}}{1-\theta} \tag{A.11}$$

This expression follows the same logic as the expression derived in Hyman et al. (2002) and elaborates on related discussion in **Chapter 4**.

It is important to understand the consequences of the overall EPPA nested structure for the way that this substitution elasticity will operate. The demand for vehicle services will determine how many vehicles (and related services) are required, as well as the required balance of fuel and abatement capital. Thus the nested structure simulates how vehicle owners are able to trade-off between fuel and efficiency expenditures in order to achieve a desired level of vehicle services. Given that X_{FPT}, the output of the powertrain half of the sector structure, and X_{KS} are required in fixed proportions (Leontief or zero substitution), the total X_{FPT} requirement will always be equal to X_F plus X_{PT}. The resulting relationship between gasoline reduction potential and cost per gallon reduced represents the supply of abatement opportunities that will be undertaken at a particular price of fuel. The price elasticity of demand can be estimated from the engineering-cost curve described by the following relationships:

$$P_E = \alpha X_F^{\beta} \tag{A.12}$$

Rearranging for X_F gives:

$$X_F = \left(\frac{P_E}{\alpha}\right)^{\frac{1}{\beta}} \tag{A.13}$$

$$\epsilon_D = \frac{d\log(X_F)}{d\log(P_F)} = \frac{1}{\beta} \tag{A.14}$$

To obtain the value of β, and thus ϵ_D, I fit a linear regression as follows:

$$\log P_F = \log\alpha + \beta\log(X_{FPT} - X_{PT}) \tag{A.15}$$

I express abatement ω_{PT}as a percentage of total fuel use (or abatement) expenses:

$$\log P_F = \log \alpha + \beta \log(1 - \omega_{PT}) \tag{A.16}$$

Fitting a curve to data from the U.S. EPA on the cost of abatement for cars and light duty trucks yields the estimates for the price elasticity of demand and elasticity of substitution as shown in **Figure 4.6**.

A.4 Development 3: Alternative Fuel Vehicles

In order to represent the range of propulsion systems that can use fuels other than gasoline, I create separate production technologies that compete with the existing gasoline-powered ICE propulsion system. These technologies are grouped into three categories based on the underlying fuels required: partial or full battery electric vehicles, hydrogen fuel cell electric vehicles, compressed natural gas vehicles, and flex-fuel vehicles. This section describes each technology and briefly reviews the literature on production costs and expected consumer retail prices for the different powertrain technologies.

A.4.1 Alternative Propulsion Systems in the MIT EPPA Model

The following paragraphs describe several classes of alternative propulsion technologies that are more expensive to produce than existing internal combustion engine (ICE-only) vehicles, but offer higher fuel efficiencies of travel and additional potential to lower greenhouse gas (GHG) emissions. Each of these technologies is implemented in the MIT EPPA model as a perfect substitute for the ICE-only vehicle that is not active in the base year, but could become active if the levelized cost of travel using one of these propulsion system types drops below the levelized cost of the ICE-only vehicle.

The four classes of alternative propulsion systems that can be represented in the MIT EPPA model include the flex-fuel vehicle (FFV), electric-drive vehicles (such as the battery or plug-in hybrid electric vehicle, full EV or PHEV), the hydrogen fuel cell electric vehicle (FCEV), and the compressed natural gas (CNG) vehicle. The analysis focuses only on the electric-drive options, given that current expected costs favor PHEVs or EVs over CNGVs or FCEVs (Sandoval et al., 2009; Paltsev et al., 2010). Nevertheless, the flexible model framework allows exploration of sensitivity to these assumptions.

A.4.2 Battery and Plug-in (Hybrid) Electric Vehicles

Propulsion systems that wholly or partially rely on battery-stored electricity supplied by the electric power grid are battery electric vehicles (BEVs) or plug-in hybrid electric vehicles (PHEVs). BEVs include a larger battery that is optimized for storing the energy required to drive longer distances and providing power to drive the wheels over a full range of driving conditions. These vehicles are limited by the range the battery can supply, which may vary depending on driving conditions and driving style. PHEVs include a battery that together with a (possibly downsized) ICE drives the wheels. On a PHEV the ICE can act as a range-extender (taking over when battery energy reserved for electric-only mileage is exhausted) or can be used to supplement the ICE engine in a so-called “blended” configuration, in which the battery-motor and gasoline ICE are used over the range of speeds and power requirements where each operates most efficiently.

The overall technical efficiency of each propulsion system is captured in the MIT EPPA model by representing the electricity and gasoline fuel requirements in a manner similar to the input shares described above for the ICE. Although the battery-motor system has higher efficiency than gasoline combustion in the ICE, upstream efficiency losses due to the generation and transmission of electricity bring the overall life-cycle efficiency closer to the ICE. Given its multi-sector coverage, the EPPA model captures well-to-wheels emissions for all powertrain types.

A.4.3 PHEV and BEV Cost Estimates

For both the PHEV and BEV, the cost and performance of the battery system is an important contributor to the total vehicle cost and its attractiveness to consumers. Achieving the performance metrics of energy and power density (energy or power delivered per unit volume) at a reasonable cost, while delivering reliability, durability, and rapid, convenient refueling, is a major challenge for technology developers. This section reviews the literature on current and projected cost estimates for electric vehicles and supporting infrastructure.

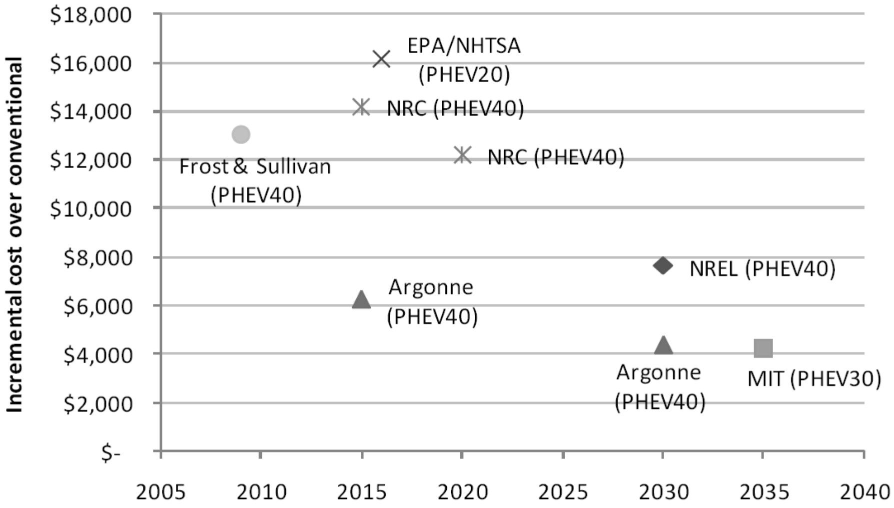
PHEVs and BEVs are expensive at present, in large part due to the high cost of the battery system, but this cost is expected to decline over time and with production on larger scales. The magnitude of potential cost reductions available is matter of debate. Some studies suggest that large reductions in cost per vehicle will be possible as production is scaled up, while other studies argue that cost reductions in battery systems have been largely realized through other applications (e.g. consumer electronics) and the cost of the battery system will not fall significantly with scale. **Figure A8** shows estimates by a number of studies of the incremental cost of a PHEV with 20, 30 or 40 mile all-electric range at various time points in the future.

In the EPPA model, the current cost of the PHEV is specified relative to the ICE-only vehicle as a markup, or percentage difference in cost relative to the base technology. It is important that the cost estimate be based on the true cost of converting the "average" U.S. vehicle to hybrid technology. In reality, consumers in different market niches may have more or less to gain by adopting a PHEV or BEV, and a more realistic projection of adoption could be obtained by considering the underlying market heterogeneity. This analysis relies on the careful use of averages. However, the interpretation of the results attempts to be mindful of segment-specific opportunities and challenges to the adoption of a particular new propulsion system.

In order to determine the markup for PHEVs and EVs, I assume a conventional vehicle base cost of USD $20,000. Based on the cost trajectories shown in Figure A8, the markup of the PHEV40 falls from around 60% in 2010 to 20% in 2030 (Cheah & Heywood, 2010). In the sensitivity analysis (described in Chapter 5) I consider a range of markups for the conventional technology in order to capture both the upper and lower bound of the technology's forecasted potential.

The specific implementation of the markup is part of the "eppaback.gms" file in the EPPA model code. The typically parameterization of a backstop technology in EPPA involves calculating the cost of inputs required to produce one unit of output, and then applying a markup to all cost shares proportionately to indicate that it is more expensive relative to the existing technology it is competing against. In the case of the PHEV and BEV, I first identify the components of the powertrain that will contribute to an increased PHEV and BEV cost. I then represent the increased cost by adding it to the vehicle powertrain capital component. The result is that vehicles adopting this powertrain type will be more expensive by an amount due to the additional cost of the advanced propulsion system.

Figure A8 Incremental cost of alternative fuel vehicle over conventional vehicle.



Source: Cheah & Heywood, 2010.

A.5 Modeling Constraints on Market Adoption

Once an AFV becomes economically competitive with existing technology, its share of new vehicle sales could still be limited by several factors. First, the vehicle market includes a diverse range of segments—the categories of passenger cars and light trucks can be broken down further into sub-compact, compact, mid-size, and full size for cars and various size and weight classes for trucks as well. A particular alternative propulsion system may be better suited for certain vehicle segments than others, based on attributes such as performance, interior space, and haulage requirements. A small city car may be a good candidate for a battery-motor propulsion system, while a fuel cell system may offer its greatest economic and environmental benefits on vehicles that travel long distances with significant haulage requirements. Such constraints represent limitations on demand for a particular AFV system.

Supply side considerations need to be considered as well. Even if the entire market demanded electric vehicles tomorrow, purchasing or retooling assembly equipment, sourcing parts, training personnel, and marketing vehicles to consumers would require time and expense.

To simulate these supply and demand-side constraints, a resource requirement for the production and deployment of an AFV is added to the model. This resource constraint relaxes as the sector grows. The amount of resource available for growth in any period is determined by the cost-competitiveness of the new relative to the existing technology. The fixed factor equation is described in Karplus et al. (2010).

Appendix B: EPPA and SAL Fleet Model Projections

B.1 Comparison of EPPA U.S. Fleet Projections with the Sloan Automotive Laboratory (SAL) Fleet Model

A fleet model was developed by members of the Sloan Automotive Laboratory (SAL) to investigate the prospects for reducing petroleum use and GHG emissions initially through 2035 (Bandivadekar et al., 2008) and later through 2050 (Cheah, 2010) by exploring the impact of exogenous assumptions on the adoption rates for new technologies. The model was used extensively to represent U.S. fleet efficiency characteristics by vintage and the process of fleet turnover in the MIT EPPA model. One major difference between the SAL fleet model and the EPPA model is that the EPPA model represents a large subset of light-duty vehicles, household-owned passenger vehicles, while the SAL fleet model represents all light-duty vehicles. The EPPA model passenger vehicle fleet does not include vehicles owned by businesses and government, which remain aggregated in the TRAN sector of EPPA (which includes commercial vehicles, medium- and heavy-duty trucks, freight, aviation, and marine).

Table B1 Forecasted vehicles, VMT, energy use, fuel economy, and GHG emissions using the Sloan Automotive Laboratory Fleet Model. Assumes vehicle efficiency improvement of 0.5% per year.

Year	Vehicle Stock (millions)	VMT (billion km)	Gasoline (billions L)	VMT (billions miles)	Fuel use (billion gallons gasoline eq.)	Average Fuel Efficiency (mpg)	GHG emissions (Mt CO_2-eq.)
2008	255	4559	590	2831	156	18.2	1267
2009	257	4547	582	2824	154	18.4	1251
2010	259	4549	576	2826	152	18.6	1238
2011	261	4578	573	2843	151	18.8	1230
2012	263	4628	571	2874	151	19.1	1226
2013	266	4695	571	2916	151	19.4	1226
2014	268	4767	572	2961	151	19.6	1227
2015	272	4841	573	3007	151	19.9	1230
2016	274	4911	573	3050	151	20.2	1231
2017	277	4981	574	3094	151	20.4	1233
2018	280	5047	575	3135	152	20.7	1234
2019	281	5106	574	3171	152	20.9	1233
2020	284	5170	575	3211	152	21.2	1234
2021	286	5229	575	3248	152	21.4	1234
2022	288	5287	575	3284	152	21.6	1235
2023	291	5346	576	3321	152	21.9	1236
2024	294	5402	576	3355	152	22.1	1237
2025	296	5456	577	3389	152	22.3	1238
2026	297	5502	576	3417	152	22.5	1237
2027	300	5553	577	3449	152	22.7	1239
2028	302	5599	577	3478	152	22.9	1239
2029	303	5644	577	3505	152	23.0	1238
2030	305	5686	576	3532	152	23.2	1238
2031	307	5735	577	3562	152	23.4	1239
2032	307	5773	576	3586	152	23.6	1236
2033	309	5819	576	3614	152	23.8	1236
2034	311	5865	576	3643	152	24.0	1237
2035	312	5910	576	3671	152	24.2	1236
2036	314	5960	576	3702	152	24.4	1237
2037	316	6006	576	3730	152	24.6	1236
2038	318	6056	576	3762	152	24.7	1237
2039	320	6107	576	3793	152	24.9	1238
2040	322	6155	577	3823	152	25.1	1238
2041	324	6203	577	3853	152	25.3	1238
2042	326	6251	576	3883	152	25.5	1238
2043	328	6301	577	3913	152	25.7	1239
2044	331	6357	578	3949	153	25.9	1242
2045	335	6415	580	3984	153	26.0	1246
2046	339	6474	582	4021	154	26.2	1250
2047	342	6535	584	4059	154	26.3	1254
2048	346	6597	586	4098	155	26.5	1259
2049	350	6662	589	4138	155	26.6	1264
2050	354	6730	592	4180	156	26.8	1270

Table B2 Projected passenger vehicle ownership, travel demand, and energy trends for the U.S. in the reference scenario. Fuel efficiency improvement is driven by the price of gasoline.

Year	Vehicles (millions)	VMT (trillion)	Fuel use (billion gallons gasoline eq.)
2004	200	2.40	117
2005	203	2.44	118
2010	201	2.42	116
2015	217	2.65	125
2020	230	2.83	131
2025	242	3.01	137
2030	257	3.22	143
2035	272	3.43	149
2040	288	3.63	152
2045	304	3.84	154
2050	319	4.03	155

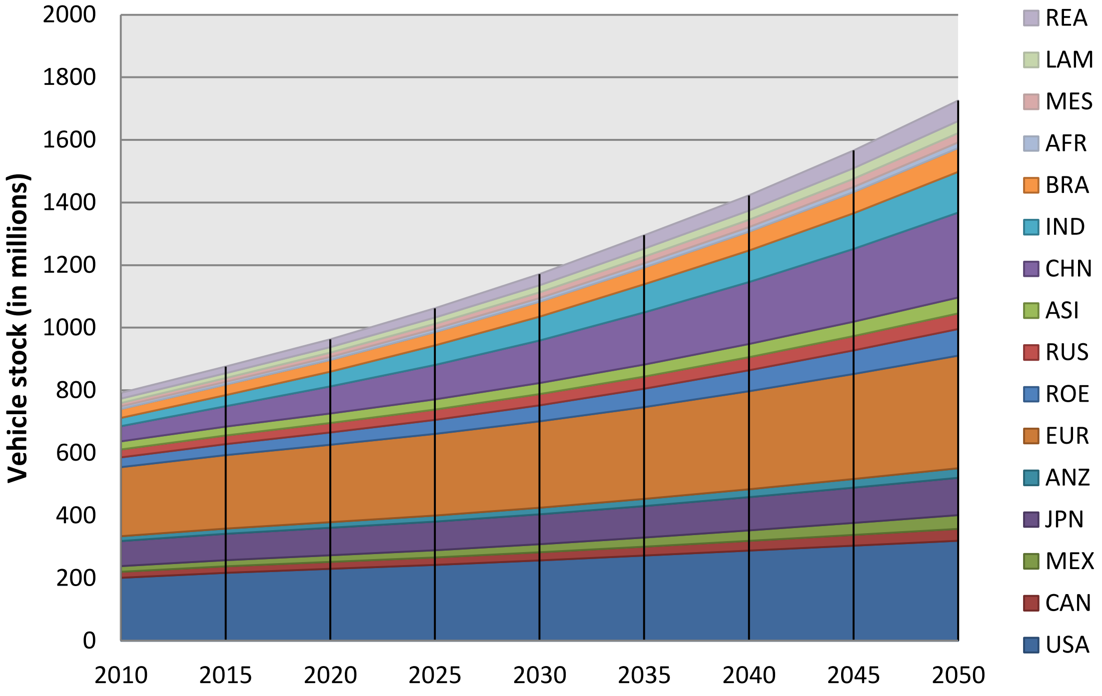
B.2 EPPA model global fleet projections

Table B3 EPPA passenger vehicle fleets for the 16 EPPA regions through 2050 (in millions), both in a) tabular and b) graphical form. A list of the abbreviations for the different EPPA regions is shown in c).

a)

	USA	CAN	MEX	JPN	ANZ	EUR	ROE	RUS	ASI	CHN	IND	BRA	AFR	MES	LAM	REA
2010	201	19	18	80	16	221	31	25	26	48	26	28	8	11	14	18
2030	257	26	26	95	21	276	51	36	35	136	76	48	12	18	23	36
2050	319	38	44	119	31	360	85	50	51	271	130	76	18	30	39	65

b)



c)

Single country regions:		Composite regions:	
USA	USA	**LAM**	Rest of Americas
CAN	Canada	**EUR**	Europe
MEX	Mexico	**ROE**	Rest of Europe and Central Asia
BRA	Brazil	**ASI**	Dynamic Asia
RUS	Russia	**REA**	Rest of East Asia
CHN	China	**ANZ**	Australia and Oceania
IND	India	**MES**	Middle East
JPN	Japan	**AFR**	Africa