Trends and Drivers of the Performance – Fuel Economy Tradeoff in New Automobiles

by

Donald Warren MacKenzie

Bachelor of Applied Science in Chemical Engineering
The University of British Columbia, 2001

Submitted to the Engineering Systems Division
in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Technology and Policy

at the

Massachusetts Institute of Technology

June 2009

Signature of Author………
Technology and Policy Program, Engineering Systems Division
May 14, 2009

Certified by……..
John B. Heywood
Sun Jae Professor of Mechanical Engineering
Thesis Supervisor

Accepted by……
Dava J. Newman
Professor of Aeronautics and Astronautics and Engineering Systems
Director, Technology and Policy Program

Trends and Drivers of the
Performance – Fuel Economy Tradeoff in New Automobiles
by
Donald Warren MacKenzie

Submitted to the Engineering Systems Division on May 14, 2009 in
Partial Fulfillment of the Requirements for
the Degree of Master of Science in Technology and Policy

Abstract

Cars sold in the United States have steadily become more fuel-efficient since the 1970s, and assessments of emerging technologies demonstrate a significant potential for continued evolutionary improvements. However, historic efficiency improvements have not always translated into reduced rates of fuel consumption. Instead, most of the technological progress of the past 20 years has been dedicated to offsetting increased acceleration performance, while fuel consumption has languished. This work addresses the questions of (1) why new technology is dedicated to performance rather than fuel consumption, and (2) what policy structures and stringencies can most effectively encourage new technology to be dedicated to reducing fuel consumption.

A technology allocation model was developed which couples projections of fuel consumption and performance tradeoffs to consumers' willingness to pay for these attributes, in order to maximize the combined value of these attributes to consumers. The model was calibrated using stated willingness to pay, car price data, and historic trends in performance and fuel consumption.

The model was used to investigate the effects of various policies on the balance between performance and fuel consumption. Particular attention was paid to the Emphasis on Reducing Fuel Consumption (ERFC), which quantifies the amount of technology dedicated to improving fuel consumption rather than other attributes. Under baseline conditions of constant gasoline price and no policy intervention, the majority of new technology continues to flow to increasing performance. The performance-fuel consumption balance is sensitive to policy signals. Fuel taxes, incentives (e.g. feebates), and fuel economy standards are all shown to be effective for increasing ERFC, although they have different implications for consumers' costs and automakers' profitability. Policies that merely increase the rate of technology deployment are found to be less effective for increasing emphasis on reducing fuel consumption.

Thesis Supervisor: John B. Heywood
                      Sun Jae Professor of Mechanical Engineering

Acknowledgments

This work would not have been possible without the support of many people within MIT and beyond.

I would like to thank my wonderful wife, Kate, for her support and encouragement over the past two years.

Thank you to Professor John Heywood for his guidance and mentorship in conducting and reporting this research.

Thank you to all of my fellow group members, past and present, whose work I have relied on for my own research, and who have helped me along by asking the right questions and giving honest feedback. Thanks to Lynette Cheah, Irene Berry, and Valerie Karplus, for editing sections of this thesis; and especially to Jeff McAulay for providing such useful feedback on the whole thing.

Table of Contents

8

1 Introduction

The challenges posed by petroleum dependence and greenhouse gas emissions are tightly interlinked with the transportation sector, and especially with cars and light-duty trucks, in the United States. The U.S. transportation sector relied on petroleum for 95% of its energy requirements in 2007, while accounting for nearly 70% of U.S. petroleum demand. The majority of this demand is for gasoline to fuel light-duty vehicles (cars and light trucks). Gasoline, consumed almost entirely by light-duty automobiles, accounted for approximately two-thirds of transportation energy demand, or 45% of total U.S. petroleum demand. (Energy Information Administration, ; Federal Highway Administration, 2008) Furthermore, the combustion of petroleum by cars and light trucks accounted for nearly 20% of U.S. greenhouse gas emissions in 2007. (U.S. Environmental Protection Agency, 2009)

1.1 Technology, Fuel Consumption, and Other Attributes

The development and adoption of efficiency-enhancing technologies holds the promise of significantly reducing petroleum demand and greenhouse gas emissions from automobiles in the future. Fuel consumption (typically expressed in liters per 100km), along with distance traveled and fuel type, is a primary determinant of petroleum demand and emissions from vehicles. (Bandivadekar et al., 2008) Technologies are expected to be deployed over the next 25 years that could reduce the fuel consumption of new automobiles, while maintaining current levels of size, performance, and safety. New technologies include both incremental, evolutionary refinements of vehicles with naturally-aspirated, spark-ignition engines, and more radical technologies such as turbocharging and hybridization that can deliver more of a step-change improvement in efficiency. (Bandivadekar et al., 2008; National Research Council (U.S.). Committee on the Effectiveness and Impact of Corporate Average Fuel Economy Standards, National Research Council (U.S.). Board on Energy and Environmental Systems, & National Research Council (U.S.). Transportation Research Board, 2002)

The introduction of efficiency-enhancing technologies does not ensure that vehicle fuel consumption will be reduced, because of the inherent tradeoff between fuel consumption and other vehicle attributes. The inclusion of more advanced technologies in new vehicle designs can either be applied to reducing fuel consumption, or to offsetting the effects of other design changes that would tend to increase fuel consumption. (Cheah, Bandivadekar, Bodek, Kasseris, & Heywood, 2008) The latter include increases in size or power, the addition of power accessories, or of features that add weight, such as soundproofing or safety equipment. (An & DeCicco, 2007) More generally, any given vehicle can be redesigned to have lower fuel consumption by trading off other attributes, such as size and performance, even if no new efficiency technologies are added. Similarly, performance and size can be improved without adding new technology, though doing so will come at the expense of fuel consumption (or some other attribute).

The tradeoff between competing vehicle attributes is illustrated conceptually in Figure 1-1 for the case of vehicle acceleration and fuel consumption. For a certain baseline level of technological capability, there exists a feasible range of acceleration and fuel consumption characteristics, represented by Region I. Although any combination of acceleration times and fuel consumption values within Region I is feasible, only those combinations that fall on the curve between Region I and Region II are said to be *technically efficient*. Thus, the optimal allocation of technology will always fall along this curve. (Wetzstein, 2005) The tradeoff between performance and fuel consumption can therefore be thought of as moving back and forth along this "frontier" of design possibilities.
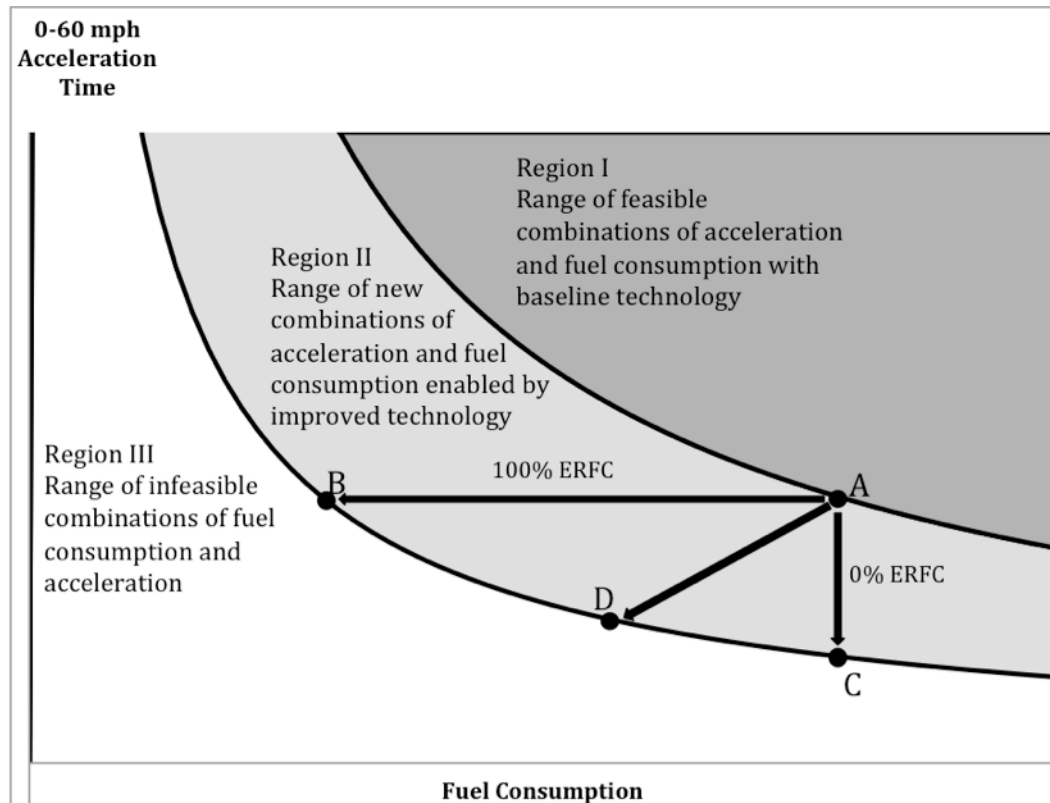
Figure 1-1: Range of feasible combinations of acceleration and fuel consumption expands with improved technology. Based on Cheah et al. (2008).

As technology improves over time, the range of possibilities expands, enabling manufacturers to improve acceleration or fuel consumption performance without sacrificing other attributes. The range of possibilities enabled by the new technology is represented in Figure 1-1 by Region II. New efficiency technologies added to vehicles will generally reduce the vehicle's fuel consumption or enhance its performance, and some may do both. For example, substituting a lighter-weight material into a vehicle while keeping everything else the same will both reduce the vehicle's fuel consumption and increase its power/weight ratio (reducing its 0-60 mph time). An engineering team making such a technology improvement might then downsize the engine to restore power/weight to its original level, while realizing a further improvement in fuel consumption. Or, they might elect to increase engine power, delivering an additional boost to performance, while returning fuel consumption to its initial level. (Cheah et al., 2008) Thus, even with "win-win" technologies that improve both performance and fuel consumption, design changes

can be used to effectively convert improved performance into better fuel consumption, or vice versa.

Cheah et al. (2008) introduced a parameter called *emphasis on reducing fuel consumption* (ERFC) to quantify the degree to which improvements in vehicle efficiency are realized as reductions in fuel consumption. ERFC is defined as the ratio of the reduction in fuel consumption realized over some time interval, to the reduction that would have been possible if all other vehicle attributes were held constant. This is illustrated in Figure 1-1, for the simplified case in which only performance is traded off against fuel consumption. Starting from initial fuel consumption and acceleration values defined by point 'A', moving horizontally left to point 'B' is defined as an ERFC of 100%, since acceleration is held constant and all of the new technology introduced is dedicated to reducing fuel consumption. Moving vertically down to point 'C', on the other hand, corresponds to 0% ERFC. For a general point 'D', the ERFC is given by the following equation:

Equation 1-1

$$ERFC = \frac{FC_A - FC_D}{FC_A - FC_B}$$

Although ERFC values between 0-100% are of the greatest interest in this work, ERFC is not limited to this range. Negative values of ERFC are possible, if fuel consumption actually increases over time. Similarly, values of ERFC greater than 100% are possible if some other attribute is given up to decrease fuel consumption. For example, if acceleration times increase above their initial level, then ERFC may exceed 100%.

1.2   Trends in Vehicle Technology and Attributes

The technical efficiency of new vehicles, and the corresponding range of design possibilities, has increased steadily over time since at least the 1970s. (An & DeCicco, 2007; U.S. EPA, 2008) An and DeCicco (2007) developed a performance-size-fuel economy index (PSFI) to "capture important aspects of the energy-related

12

services that automobiles provide," and to help quantify the overall rate of improvement in technical efficiency. They defined PSFI for cars as the product of the power/weight ratio, size (interior volume), and fuel economy:

Equation 1-2

$$PSFI = \frac{P}{W_I} \cdot S \cdot FE$$

An and DeCicco found that PSFI increased linearly from 1977 through 2005, reflecting steady improvements in the technical efficiency of new vehicles, as shown for cars in Figure 1-2. (An & DeCicco, 2007)
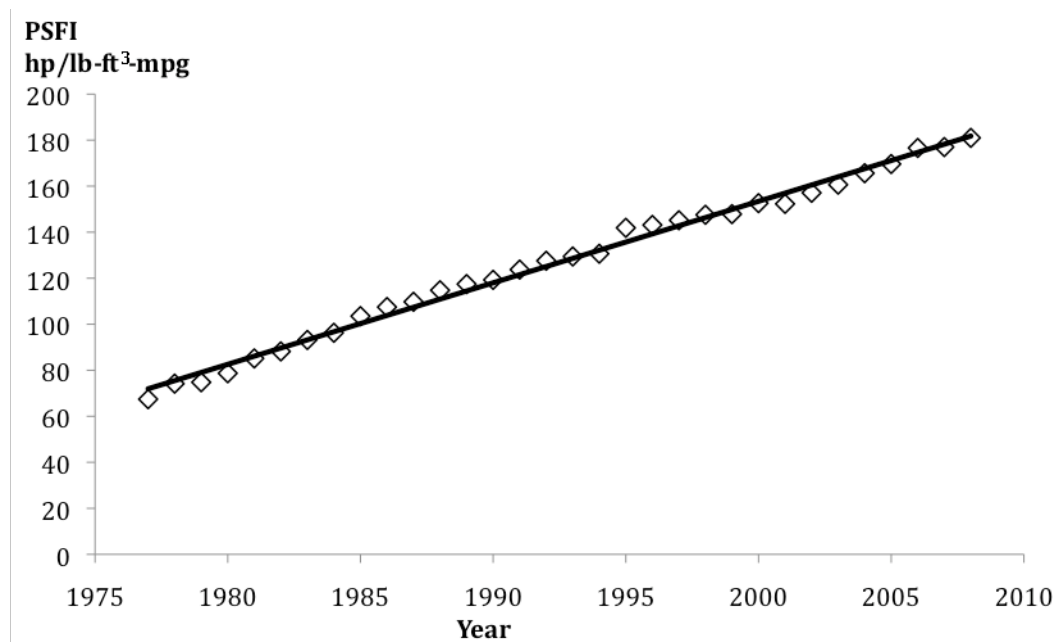
Figure 1-2: Average Performance-Size-Fuel Economy Index (PSFI) of new U.S. cars, 1977-2008. (An & DeCicco, 2007; U.S. EPA, 2008)

Historically, the steady growth in technical efficiency of U.S. cars has not translated into steady reductions in fuel consumption. Instead, cars in the U.S. have seen substantial increases in performance and little improvement in fuel consumption. Figure 1-3 shows how the constituent factors of PSFI have changed since 1977. Fuel economy increased rapidly through the mid-1980s, when fuel prices were high and Corporate Average Fuel Economy (CAFE) standards were being ramped up, but has remained relatively flat since then. (Energy Information Administration, 2009;

National Highway Traffic Safety Administration, 2004) The average power/weight ratio declined slightly, then began an upward trend that has continued through 2008. The size of the average car, as measured by interior volume, has remained relatively constant. These trends indicate that offsetting continually increasing performance has been the primary application of more advanced technologies introduced into new U.S. cars over the past 25 years. For this reason, the work reported here focuses primarily on the tradeoff between performance and fuel consumption in future vehicles.
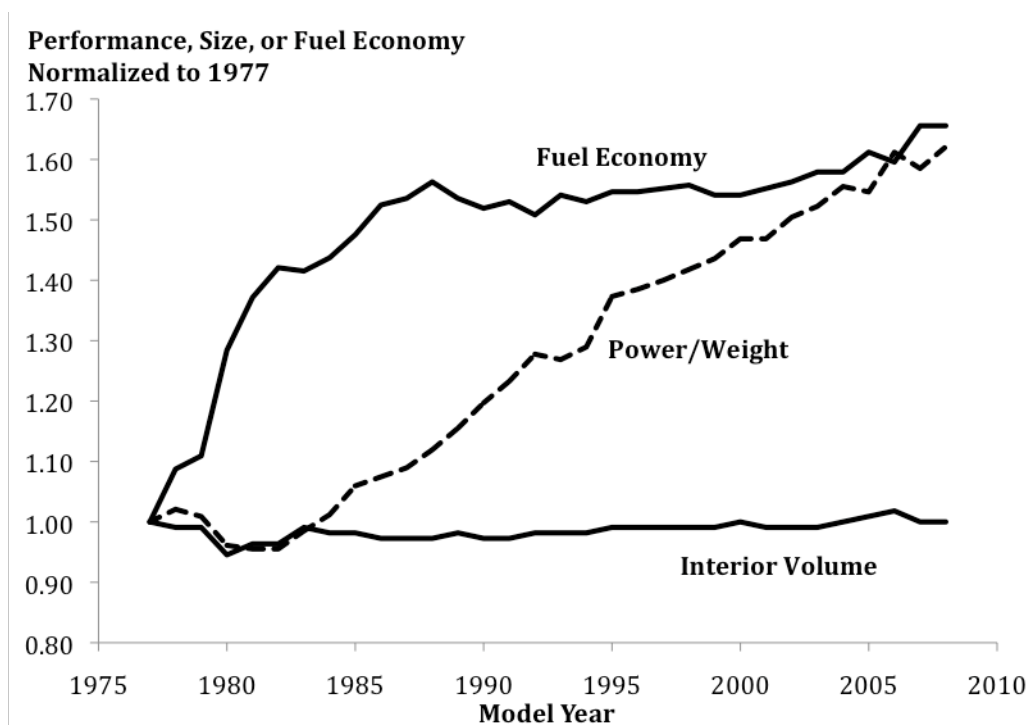
Figure 1-3: Average performance, size, and fuel economy of new U.S. cars, 1977-2008. Values are indexed to 1977 averages. (U.S. EPA, 2008)

The emphasis on reducing fuel consumption (ERFC) for new U.S. cars has been low for most of the past 20 years. Cheah et al. (2008) calculated an ERFC of 8% for the average new car between 1995 and 2006. However, the precise value of ERFC is sensitive to year to year fluctuations in fuel consumption and other attributes, so it is instructive to calculate ERFC values for many different time intervals. Figure 1-4 shows the ERFC values calculated for each year since 1982, applying the methodology of Cheah et al. (2008). In each year, the ERFC is calculated based on

14

the change in attributes over the preceding 5 years.[1] In the early 1980s, ERFC exceeded 100%, reflecting the decline in performance (and size) since the late 1970s, as shown in Figure 1-3. ERFC waned through the 1980s as gasoline prices fell and Corporate Average Fuel Economy standards stabilized (Figure 1-5, Figure 1-6), bottoming out at -13% in 1992. ERFC varied between approximately 0 and 20% through 2003, then jumped as gasoline prices again rose.
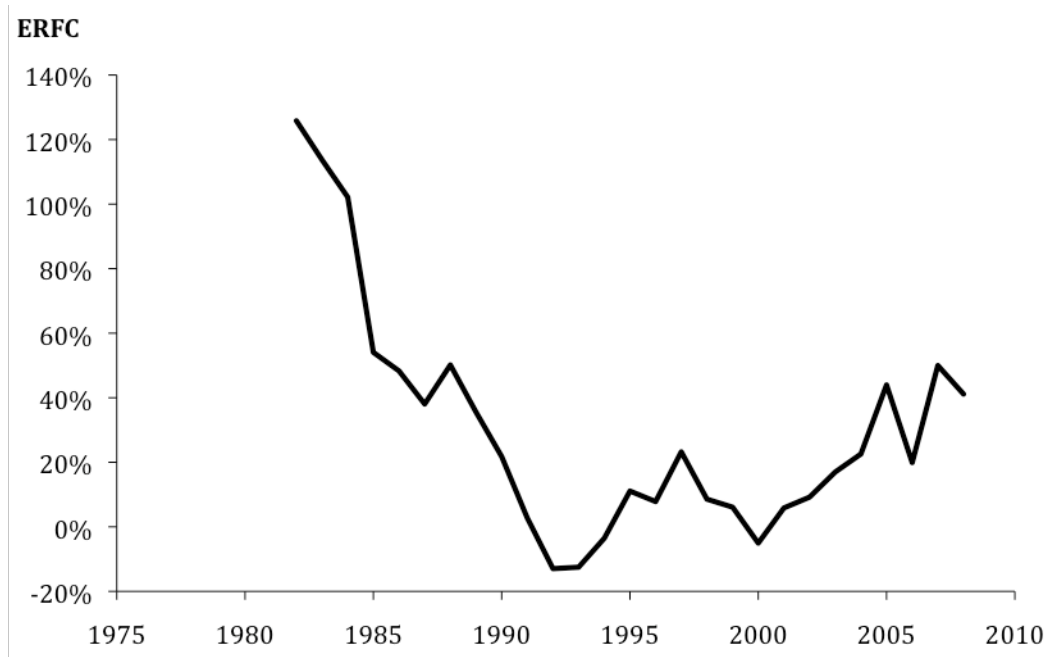
Figure 1-4: Historic emphasis on reducing fuel consumption (ERFC) for average new U.S. car. For each year, ERFC was calculated based on the change in fuel consumption and performance-size-fuel economy index (PSFI) over the preceding 5 years. (Cheah et al., 2008; U.S. EPA, 2008)

In the present work, the period from 1991 to 2003 is of particular interest. Both gasoline prices and CAFE standards in the U.S. were relatively stable during this period, and for the 5 years prior. (Figure 1-5, Figure 1-6) Therefore, it is useful to examine trends during this period to elucidate consumers' valuation of performance and fuel consumption, undistorted by regulations or volatile fuel prices.

---

[1] For example, the ERFC reported for 2008 is based on the change in attributes between 2003 and 2008.
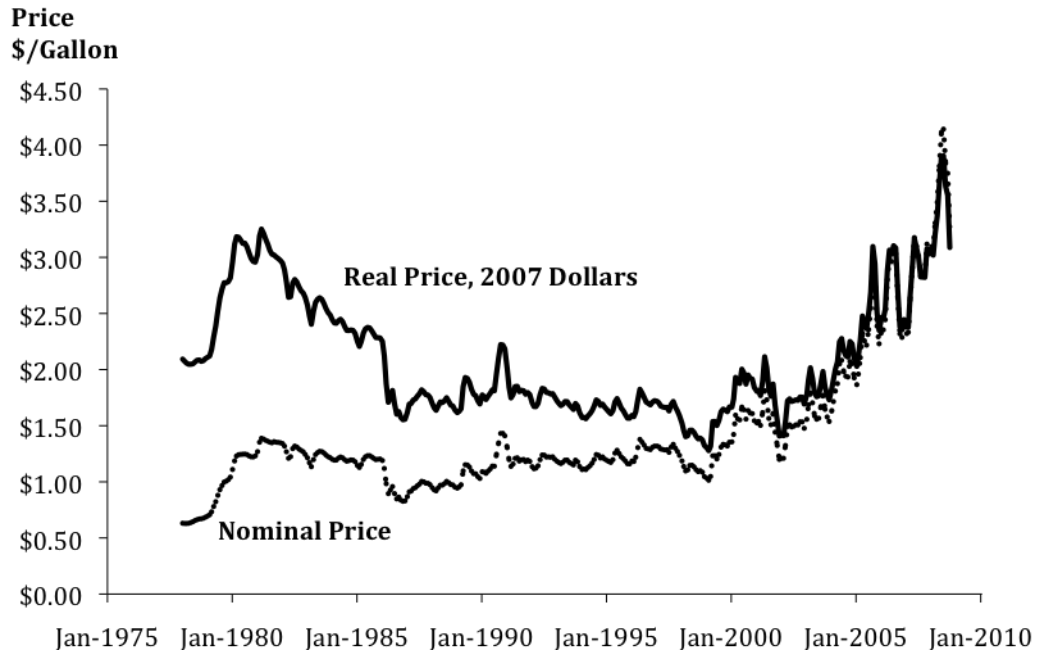
Figure 1-5: Gasoline price, U.S. city average retail price (including taxes), all grades and formulations. (Bureau of Labor Statistics, 2008; Energy Information Administration, 2009)
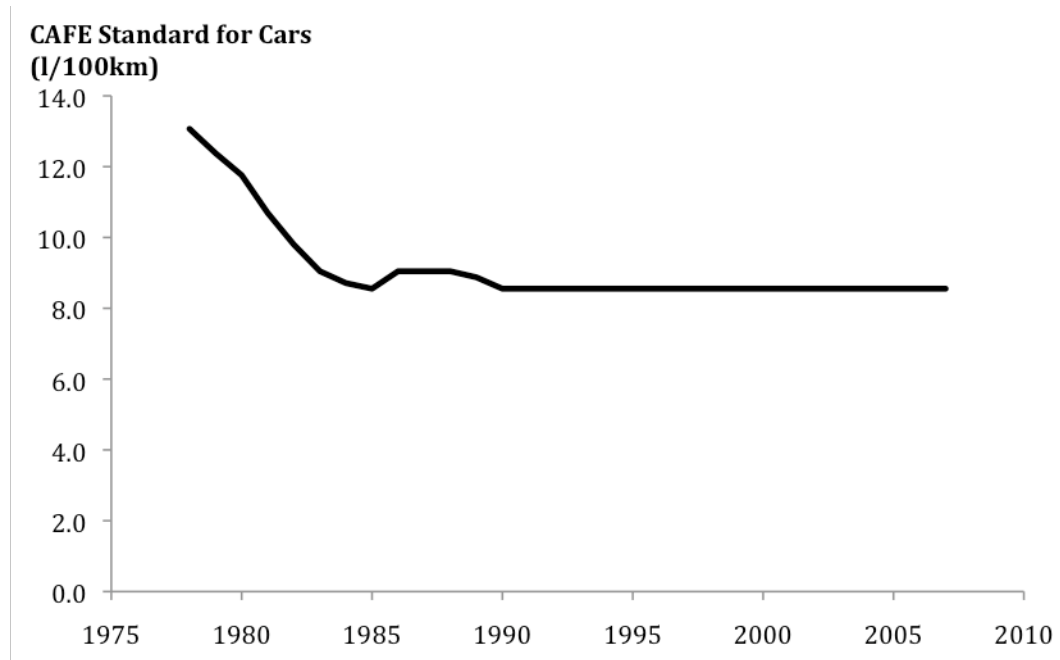
Figure 1-6: Corporate Average Fuel Economy (CAFE) standards for new U.S. cars, 1978-2007. (National Highway Traffic Safety Administration, 2004)

16

1.3 A Technology Allocation Framework

In order for more advanced technologies to contribute to reductions in automotive petroleum demand and greenhouse gas emissions, the efficiency enhancements they deliver must be converted into actual reductions in fuel consumption. Previous work at MIT has shown that directing evolutionary technology improvements to lowering fuel consumption can reduce fuel demand and emissions by amounts comparable to those offered by more radical advanced technology vehicles, a least through 2035.[2] The likelihood of these evolutionary technologies entering the market over the next 25 years is high, so they represent a safe bet for improving vehicle efficiency. (Bandivadekar et al., 2008) However, as shown in the preceding section, new efficiency-enhancing technologies have not been directed to reducing the fuel consumption of U.S. cars recently. In other words, emphasis on reducing fuel consumption (ERFC) will need to increase above historic levels in order for these expected improvements to be realized as reductions in fuel consumption. Therefore, an understanding of how the auto industry allocates more advanced technologies among fuel consumption and competing attributes would be invaluable for policymakers interested in reducing fuel consumption.

Many analyses of future fuel consumption potential and related policies overlook the inherent tradeoff between performance and fuel consumption, and the issue of allocating technologies among competing attributes. They instead adopt what can be called a *technology adoption* framework. Under a technology adoption framework, a certain set of individual technologies is assumed to be available over a particular timeframe, and vehicle performance and other attributes are fixed at a pre-determined level. Manufacturers are assumed to adopt only those technologies that are cost-effective under the given policy environment, while leaving others "on the shelf." (Greene, Patterson, Singh, & Li, 2005; National Highway Traffic Safety

---

[2] Advanced technology vehicles here include hybrids, plug-in hybrids, clean diesels, and turbocharged spark-ignition vehicles.

Administration, 2008; National Research Council (U.S.). Committee on the Effectiveness and Impact of Corporate Average Fuel Economy Standards et al., 2002) The rate of technological evolution predicted by these technology adoption models varies widely, depending on the assumed price of fuel and relevant government policies.

The technology adoption framework employed in many analyses may be unrepresentative of the automotive system for several reasons. First, the wide variability that they suggest for technology adoption rates is inconsistent with the finding of An and DeCicco that overall technical efficiency has improved quite steadily over the past 30 years, even as design priorities have swung back and forth between performance and fuel consumption. (An & DeCicco, 2007) Second, in the near to medium term, manufacturers are subject to practical limits on their ability to incorporate more advanced technologies into vehicle designs. (Klier & Linn, 2008) Finally, automotive product planners work in an environment of limited capital, and generally make tradeoffs in which they forego improvements in one attribute in order to fund improvements in another attribute, while maintaining "budget discipline." (Hill, Edwards, & Szakaly, 2007)

In this work, a *technology allocation* framework is used to explore the relationship between automotive performance and fuel consumption. The historically stable rate of technological improvement, limitations on readily available technology, and tradeoff-based design process suggest that this framework may be better suited to modeling technology decisions related to automotive fuel consumption. In contrast to the standard technology adoption framework, the technology allocation framework used here assumes that the degree of adoption of more advanced technologies is fixed over a given time interval, and seeks to understand how those technologies will be allocated to the competing attributes of performance and fuel consumption. Rather than asking "how much technology will be adopted?" the technology allocation framework asks "how will particular attributes change as technology is introduced?"

18

Other authors have implied the value of using a technology allocation framework to evaluate future technology decisions. Evans (2008) noted that technology adoption models "may, to some extent, overlook the complex trade-offs manufacturers must make against vehicle attributes within a constrained budget," and that "manufacturers may still prefer to direct technologies to improve the power and size of vehicles," if those attributes are more valuable than reductions in fuel consumption. An and DeCicco (2007) point out that "Given a certain state of technological capability, exactly what technologies are used and how they are used are defined within a constrained product development budget." Like Evans, they acknowledge that "numerous economic trade-offs occur in the context of product planning," and recommend future work investigating "what conditions are needed for technical efficiency gains to be allocated for meeting policy objectives."

1.4   Thesis Overview

The work reported in this thesis seeks to improve upon the understanding of the performance - fuel consumption tradeoff by introducing a technology allocation perspective to the modeling of manufacturers' technology decisions. Such understanding can provide guidance to policymakers interested in increasing the emphasis on reducing fuel consumption as more advanced technologies are introduced into the fleet. It was hypothesized that,

> *In the absence of policy intervention, emphasis on reducing fuel consumption will remain near zero in the United States, and technology improvements will be directed overwhelmingly toward increasing performance.*

The work also aims to provide an assessment of the structures and stringencies of policies that can most effectively stimulate an increase in ERFC, while maintaining a robust automotive manufacturing industry. Chapter 2 examines the stringency of some key government policies in Europe and the U.S. that directly influence the tradeoff between performance and fuel consumption, and compares them on a common basis. Chapter 3 documents the development of a technology allocation modeling framework, including the approach used, rationale, key equations, and

assumptions. Chapter 4 establishes a baseline scenario for future technology allocation to performance and fuel consumption, calibrated against historic trends in performance and fuel consumption. In Chapter 5, the technology allocation response to changes in fuel price and a variety of government policies is explored using the model, and the implications for consumers' value of more advanced technologies are evaluated. Chapter 6 presents some conclusions drawn from the work and discusses opportunities to expand and improve upon this work in the future.

1.4.1 Scope of Work

This work focuses on the potential for evolutionary technology improvements in new U.S. cars, and how they might be allocated to performance or fuel consumption improvements. As discussed in Section 1.1, incremental, evolutionary technologies offer significant potential for efficiency improvements, and have a high likelihood of deployment, over the next 25 years. More radical technologies, such as hybridization, are characterized by greater uncertainty in many respects, and are not considered in this work.[3]

Although light trucks make up approximately half of the U.S. light-duty vehicle market (U.S. EPA, 2008), the work reported here examined only cars (and cars were considered only in a fleet-average fashion, rather than by segments). The purpose of the work was not to calculate precise results for every class of vehicle, but rather to explore the use of a technology allocation framework for investigating the tradeoff between fuel consumption and competing attributes and to initiate further discussions.

In the interest of keeping the work tractable for this initial exploration, the analysis focuses specifically on the tradeoff between performance and fuel consumption, and

---

[3] Importantly, the technical tradeoffs between performance and fuel consumption attributes are not as well quantified for advanced technology vehicles as they are for conventional, naturally aspirated spark-ignition vehicles.

excludes consideration of other attributes that are certainly related to fuel consumption, such as vehicle size. As shown in Section 1.2, performance has been the major beneficiary of recent improvements in the technical efficiency of cars. Stemming the growth in vehicle performance may offer the greatest opportunity for increasing emphasis on reducing fuel consumption, so performance was chosen as the attribute to be traded off against fuel consumption in this work.

1.4.2 Some Notes on Conventions

Throughout this thesis, unless otherwise noted, all dollar figures are quoted in constant 2007 dollars, and were adjusted from their nominal values using the consumer price index for all urban consumer consumers. (Bureau of Labor Statistics, 2008)

Except as noted, fuel economy and fuel consumption values represent unadjusted, laboratory test values, as measured by a 55/45 weighted average of the city (FTP) and highway fuel economy tests. These figures are the same ones used for determining compliance with Corporate Average Fuel Economy standards. (49 U.S.C. 32904(c))

Power and weight feature prominently in discussions of vehicle performance throughout this work. Unless noted otherwise, power refers to the engine peak horsepower, and weight refers to the vehicle's inertia weight (equal to its curb weight plus 300 pounds). These conventions are consistent with those used by An and DeCicco (2007) and Cheah et al. (2008).

2   Incentives Linking Performance and Fuel Consumption

There is a broad variety of policies that can influence the tradeoff between vehicle performance and fuel consumption. These policies can come in form of standards, taxes, or rebates; they can be applied at the time of purchase or may recur over the life of the vehicle; and they may target fuel consumption, greenhouse gas emissions, engine power, or any of a variety of other attributes. (Evans, 2008) Evans provides a useful introduction to these policies, discusses their relative strengths and weaknesses, and compares the stringencies of several systems of standards and fuel taxes employed in various countries. He stops short, however, of calculating the incentive rates, i.e. the marginal cost or benefit that incentive-based systems impose directly on fuel consumption or related attributes. Because the present work focuses on the relationship between consumers' value of vehicle attributes and the optimal allocation of technologies, incentive systems that place a price directly on specific attributes are of particular interest. Therefore, this chapter examines the stringency of some of the major incentive-type policies that are employed in the U.S. and in selected European countries, and estimates the equivalent stringency of certain European policies if they were applied to the U.S. car market. These values will provide a useful context for the modeling of incentive effects, presented in Chapter 5. First, however, a brief overview is provided of the structure of incentive systems and related nomenclature.

2.1   Incentive Structures

Incentive systems can be penalty-based, reward-based, or a mix of the two. A penalty-based system would be one that imposes some penalty, such as a tax or fee, on vehicles depending on some attribute of interest. A reward-based system takes the opposite approach, providing a subsidy or other benefit to vehicles that are deemed to have desirable attributes. Also possible is a mixed system of rewards and penalties, commonly known as a feebate system. Regardless of whether they are

reward-based, penalty-based, or mixed, incentives systems can be defined by three key characteristics. (Evans, 2008)

The first defining characteristic of an incentive system is the attribute on which it is based. The present work is concerned with the performance-fuel consumption tradeoff, and so considers incentive systems based on fuel consumption and on attributes related to acceleration.

The second key feature of an incentive system is its rate, which defines the amount of penalty charged or reward offered for a given unit change in an attribute. Put another way, the rate is the derivative of the incentive amount with respect to the attribute of interest. In the case of a fuel consumption incentive program, the rate would be expressed in dollars per unit change in fuel consumption. The simplest rate structure for an incentive system is to have a constant rate, whereby the incentive amount is linearly proportional to the change in the attribute of interest. (Greene et al., 2005) Importantly, a constant rate is also a condition for achieving the largest fuel consumption response at the least cost. According to the equimarginal principle, total costs are minimized and economic efficiency is achieved when marginal costs are equal across all vehicles and manufacturers. (Field, 1994) Therefore, a uniform rate should be a central principle of any incentive system if economic efficiency is desired.

The third key feature of an incentive program is its pivot point, which is the attribute level at which the incentive amount is zero. This is most relevant for mixed (feebate) type incentive systems, wherein the pivot point is the level of fuel consumption above which a fee is charged and below which a rebate is offered. (Evans, 2008) However, a penalty-based system can be thought of as a system in which the pivot point is below the lowest fuel consumption level on the market, and a reward-based system can be thought of as a system in which the pivot point is higher than the highest fuel consumption rate on the market. The selection of the pivot point determines whether the incentive system will be a net collector of

revenue for the government, will incur net costs, or will be made revenue-neutral (i.e. the total fees collected equal the total rebates paid out).

2.2 Incentives Targeting Fuel Consumption

The first type of incentives considered here is the type that places a price on fuel consumption (or fuel economy). In the United States, federal policies do this directly. In many European countries, there are policies that do this indirectly, by creating incentives based on greenhouse gas emissions. (Evans, 2008)

2.2.1 Direct Incentives on Fuel Consumption

Two major federal policies define incentive rates for fuel consumption of new vehicles in the United States: Corporate Average Fuel Economy (CAFE) standards and the gas guzzler tax. (Evans, 2008) Although CAFE is a standards-based program, it imposes civil penalties on auto manufacturers whose average fuel economy falls short of the required standard. These penalties increase with the fuel economy shortfall, and therefore impose a marginal cost on higher fuel consumption. The amount of the penalty for new car fleets in 2009 is shown in Figure 2-1. The marginal cost of higher fuel consumption (i.e. the slope of the curve) for car fleets that just miss the standard (8.6 l/100km or 27.5 mpg) is approximately $180 per car for each 1l/100km by which they miss the standard.[4] However, the penalty only applies to vehicle fleets that fail to meet the applicable standard, so there is no policy incentive for manufacturers to continue to decrease fuel consumption below the level mandated by the CAFE standard.

---

[4] Because the penalty is based on fuel economy rather than fuel consumption, the marginal penalty rate decreases as fuel consumption rises. This is reflected by the concave shape of the curve in Figure 2-1. The marginal penalty would decrease to less than $100 per (1l/100km) for a fleet averaging more than 11.4 l/100km (less than 20.6 mpg).
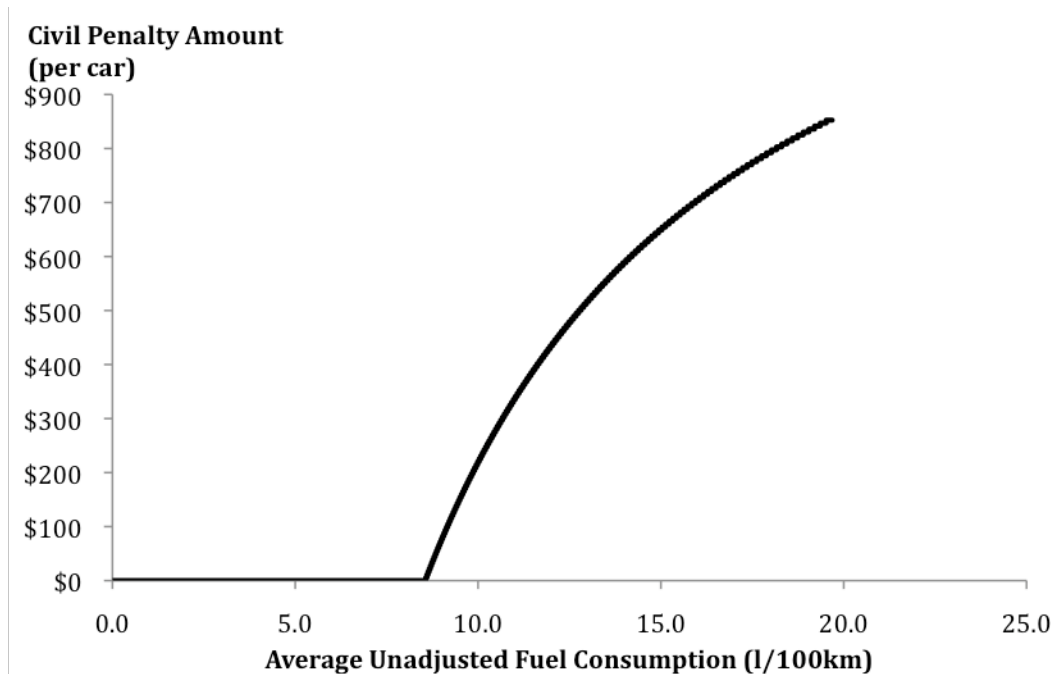
Figure 2-1: Civil penalties assessed for failure to meet U.S. Corporate Average Fuel Economy (CAFE) standards. Civil penalties are assessed on the average fuel economy of a manufacturer's fleet. (49 CFR § 578.6(h))

The U.S. gas guzzler tax differs from the CAFE penalty in that it applies to individual vehicles rather than to fleet averages, applies only to cars and not to light trucks, and imposes a much higher (and more constant) price on fuel consumption. The gas guzzler tax schedule is shown in Figure 2-2. The dashed line in Figure 2-2 is fitted to the midpoint fuel consumption value of each tax bracket, and its slope reflects an average tax rate of approximately $730 for each 1l/100km by which a car's fuel consumption exceeds the no-tax maximum (10.5 l/100km or 22.5 mpg). However, like the CAFE penalties, the gas guzzler tax provides no incentive to decrease fuel consumption below the no-tax maximum.
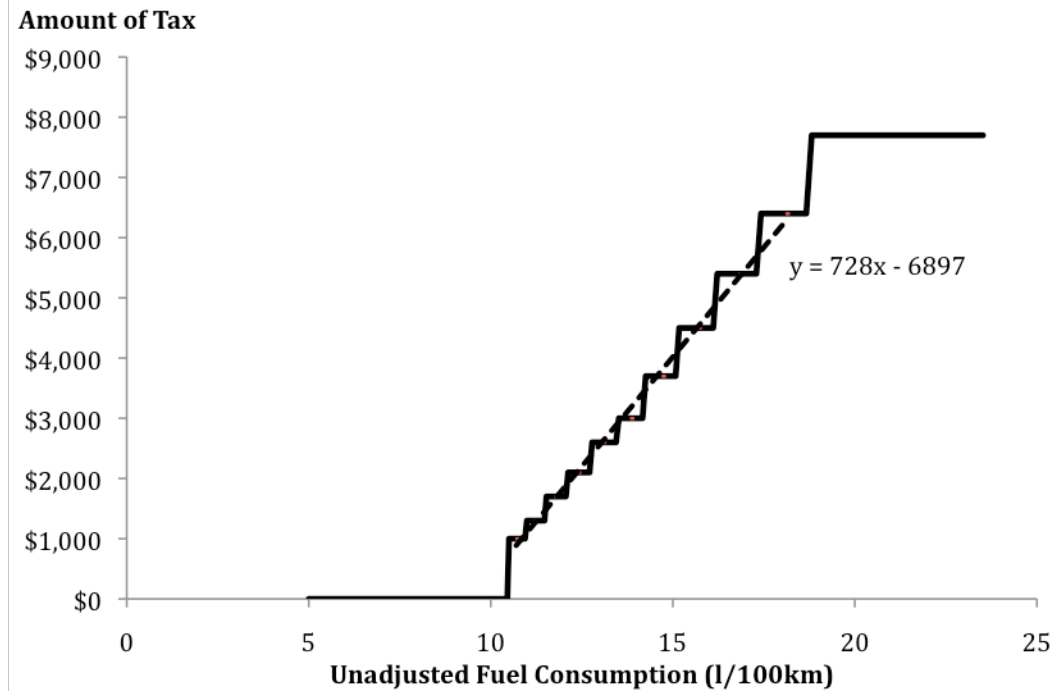
Figure 2-2: U.S. gas guzzler tax schedule. Gas guzzler tax is assessed on individual vehicles, irrespective of manufacturer's average fleet fuel consumption. (U.S. EPA, 2006)

2.2.2 Greenhouse Gas Incentives

Several European countries have created incentive programs for fuel consumption, in effect, by basing vehicle tax rates on CO_2 emissions. Policies targeting greenhouse gas emissions are closely related to those targeting fuel consumption, because CO_2 is the primary greenhouse gas emitted during automobile operation, and is proportional to the amount of fuel used. (An & Sauer, 2004) In 2008, France introduced a "bonus-malus" feebate system that is based on tailpipe CO_2 emissions, as shown in Figure 2-3. (ACEA, 2008) Other than the very large bonus for vehicles emitting less than 60 g/km, the system offers an average incentive rate of €18 per 1g/km reduction in tailpipe CO_2 emissions, as illustrated by the dashed line. However, because the bonus-malus system classifies vehicles into large bins, it will deliver large benefits for some reductions and no benefits for other reductions, depending on the initial emissions level and the amount of reduction. Thus, the average incentive rate is offered as a broad measure of stringency rather than a precise estimate of the benefit of reducing emissions in a particular vehicle. France

also charges an annual ownership tax on cars owned by businesses, which varies from €2 to €19 per (g CO_2/km). The tax is progressive, with higher-emitting vehicles being subject to the higher per-gram rates. (ACEA, 2008)

Amount of Bonus (+) or Tax (-)
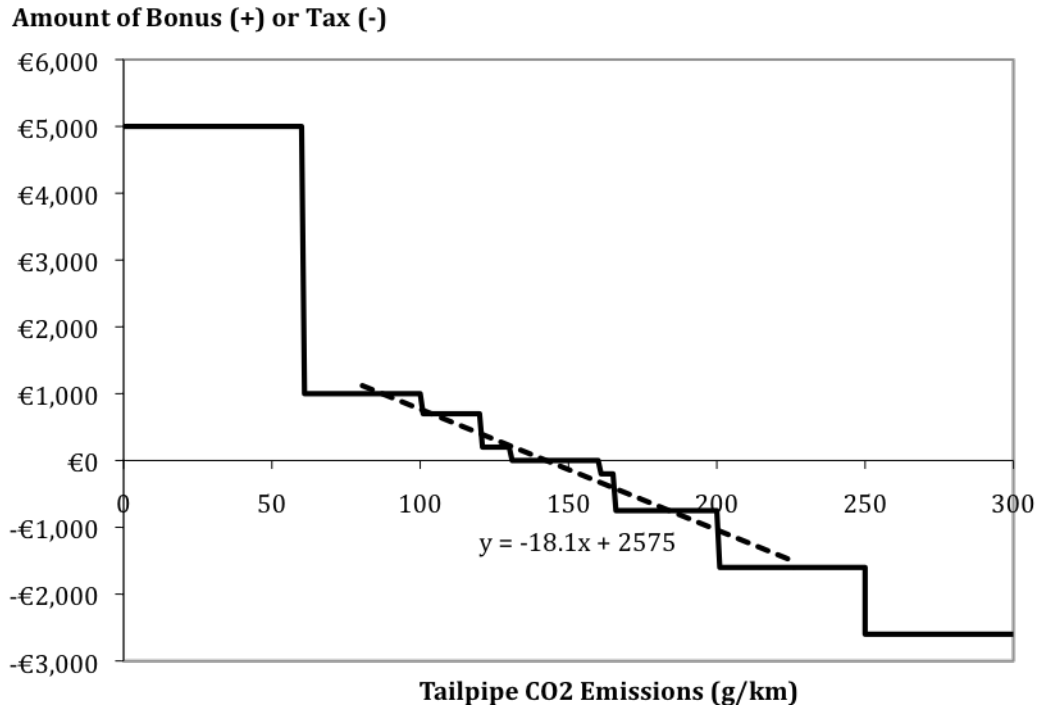
Figure 2-3: Taxes and bonuses offered on first registration of new vehicles in France in 2009, based on tailpipe CO_2 emissions as measured on the New European Drive Cycle (NEDC). (ACEA, 2008)

Other European countries, too, have created incentives for lower fuel consumption through CO_2-based vehicle taxes on vehicles. (ACEA, 2008) Several of these are summarized in Table 2-1, for both vehicle acquisition and ownership. Like the French bonus-malus system, many of these systems make use of emissions bins, so the incremental incentive amount for changing emissions in a particular vehicle may not accurately reflect the overall stringency estimates shown in Table 2-1. Although Portugal has some extremely high rates, it employs a progressive, marginal tax system, in which the tax rate increases as the emissions level increases. As a result, the higher rates are charged only on the emissions in the highest brackets (much like income taxes in the U.S.).

Table 2-1: CO_2-based acquisition and ownership tax rates for gasoline-fueled cars in selected European countries. Also shown is the equivalent stringency of the European CO_2 policies if applied to U.S. cars. European policies are expressed in terms of the New European Drive Cycle, and U.S. equivalents are based on the unadjusted CAFE cycle. Assumes 8,800 g CO_2 per U.S. gallon of gasoline. Currency conversions based on average exchange rates through the first 4 months of 2009. (*Germany joins EU in tying car fees to emissions.*2009; ACEA, 2008; An & Sauer, 2004; Bank of Canada, 2009; Ward's, 2007; Ward's, 2008; Ward's, 2009)

	European Policy per (g CO_2/km)		*Equivalent for Average U.S. Car per (l/100km)*	
	Acquisition Tax	*Annual Ownership Tax*	*Acquisition Tax*	*Annual Ownership Tax*
France	€ 18	€ 2-19 [5]	$ 620	$ 520 [5]
Germany	N/A	€ 2.00	N/A	$ 70
United Kingdom	N/A	~£ 1.30-3.50	N/A	~$ 50
Portugal	€ 5-115	~€ 1.00-3.00	$ 2,900	~$ 30

The European policies vary widely in their stringency and would impose vastly different marginal tax rates if applied to the average new model year 2008 U.S. car. The policies were converted from the European basis to the U.S. basis using the assumptions of An and Sauer (2004) to correct for the different test cycles and the use of fuel consumption rather than a CO_2 metric. Considering both the acquisition tax and the first 3 years' ownership taxes, Germany and the UK would impose an incentive rate on the order of $200 for each 1l/100km of fuel consumption if applied to the average new model year 2008 U.S. car. In contrast, the marginal tax rates imposed by the French system would be several times larger, and that imposed by the Portuguese system would be an order of magnitude larger.

---

[5] France has a CO_2-based annual tax for business vehicles but not for personal vehicles.

2.3 Incentives Targeting Performance

A number of European countries employ incentives targeting attributes closely related to performance. Here, two types of incentives are considered: those targeting engine displacement, and those targeting engine power.

2.3.1 Engine Displacement Incentives

Both Portugal and Belgium base their vehicle acquisition and ownership taxes in part on engine displacement. Portugal charges an acquisition tax of €0.90 for each cubic centimeter (cc) of displacement up to 1,250 cc, and €4.25 for each cc in excess of 1,250. Its annual ownership tax increases with displacement, with a net effect on the order of € 0.05-0.25 per cc. Belgium charges a progressive tax on displacement, with the marginal rates increasing at higher displacements. (ACEA, 2008) The ranges of marginal tax rates in Portugal and Belgium are summarized in Table 2-2.

Table 2-2: Engine displacement-based acquisition and ownership taxes for gasoline-fueled cars in selected European countries. Also shown is the equivalent stringency of the European policies if applied to the average new U.S. car in 2008. Currency conversions based on average exchange rates through the first 4 months of 2009. (ACEA, 2008; Bank of Canada, 2009; Ward's, 2007; Ward's, 2008; Ward's, 2009)

	European Policy per cubic centimeter		Equivalent for Average U.S. Car per second of 0-60 mph time	
	Acquisition Tax	*Annual Ownership Tax*	*Acquisition Tax*	*Annual Ownership Tax*
Portugal	€ 0.90-4.25	~€ 0.05-0.25	$ 3,600	~$ 200
Belgium	~ € 0.10-5.00	~€ 0.20-0.90	~$ 2,000	~$ 600

The average car sold in the U.S. would pay a steep price for its performance in Belgium or Portugal. Engine displacement is a major determinant of engine power, which in turn is a major driver of vehicle performance. By applying the correlations between these attributes (see Section 3.3.1 and Appendix A for these correlations),

30

it is possible to estimate the marginal tax rate per unit performance that would result if the European policies were applied to the average new model year 2008 U.S. car. In this way, the equivalent tax rates on performance (expressed per 1-second reduction in 0-60 mph time) shown in Table 2-2 were calculated. Including both the acquisition tax and the first 3 years of ownership tax, the average new model year 2008 U.S. car would face a marginal tax rate on its performance on the order of $4,000 per 1-second reduction under both the Belgian and the Portuguese systems.

2.3.2   Engine Power Incentives

Several European countries, including Belgium and Italy, base vehicle taxes in whole or in part on engine power. As discussed in the preceding section, Belgium has a progressive registration tax schedule based on engine displacement. However, it also employs a parallel tax schedule based on engine power, and registrants must pay the higher of the two rates calculated for a particular vehicle. Italy bases both acquisition and ownership taxes on engine power. (ACEA, 2008) The marginal rates for these two countries are summarized in Table 2-3. Using the correlation between power/weight ratio and acceleration developed in Section 3.3.1, the equivalent tax rates that would be imposed by these policies on the average new model year 2008 U.S. car were calculated. These are shown in Table 2-3 as well. If applied to the average new 2008 U.S. car, the Italian taxes would impose a total marginal rate on the order of $500 for each second of 0-60 mph time, including both the acquisition tax and 3 years of ownership taxes. The marginal rate imposed by the Belgian system is comparable to that imposed by Belgium's parallel displacement-based system, indicating that the two are reasonably well coordinated.

Table 2-3: Engine power-based acquisition and ownership taxes for gasoline-fueled cars in selected European countries. Also shown is the equivalent stringency of the European policies if applied to the average new U.S. car in 2008. Currency conversions based on average exchange rates through the first 4 months of 2009. (ACEA, 2008; Bank of Canada, 2009; Ward's, 2007; Ward's, 2008; Ward's, 2009)

	European policy *per kilowatt*		*Equivalent for Average U.S. Car* *per second of 0-60 mph time*	
	Acquisition Tax	*Annual Ownership Tax*	*Acquisition Tax*	*Annual Ownership Tax*
Italy	€ 3.51	€ 2.58-4.26	~ $120	~$ 140
Belgium	~€ 4-70	N/A	~ $ 2,000	N/A[6]

2.4 Conclusions

The U.S. and various European countries already employ policies that place prices on fuel consumption or performance. In the U.S., the stringency of these policies ranges from less than $100 (the civil penalties imposed by the CAFE program) to more than $700 (the gas guzzler tax) for each 1l/100km of fuel consumption. However, these policies do not apply to all vehicles. In Europe, tax policies based on CO_2 emissions effectively put a price on fuel consumption as well, imposing widely variable tax rates. Among major European automotive markets, the tax policies would impose rates ranging from roughly $200 - $600 for each 1l/100km of fuel consumption. These values are generally consistent with the stringency of U.S. policies, but unlike the U.S., they apply to all cars. Several European countries have policies targeting attributes related to vehicle performance. The stringency of these policies varies widely, and if applied to the average new U.S. car, they would generally impose marginal rates on the order of $500 - $4,000 for each second of 0-60 mph time.

---

[6] Although there is no power-based ownership tax on cars in Belgium, the displacement-based ownership tax discussed in Section 2.3.1 still applies to these vehicles.

3 Development of a Technology Allocation Model

In this chapter, the development of the technology allocation model is explained. First, the purpose of the model and the associated principles are introduced. Next, the general framework for the model is developed. Finally, a discussion of the specific assumptions and values used in the model is undertaken.

3.1 Modeling Purpose and Principles

The purpose of the technology allocation model is to identify the optimal allocation of efficiency-enhancing technologies among competing vehicle attributes, from the perspective of the auto industry as a whole. Specifically, the model trades off performance and fuel consumption based on consumers' willingness to pay for these attributes. The fundamental principle underlying the model is that of maximizing the value delivered to consumers by new, efficiency-enhancing technologies. In its current form, the model is not intended to replicate the decisions of individual auto manufacturers for specific vehicle models; rather, it is meant to shed light on the trends and drivers affecting the industry as a whole. In addition, it must be emphasized that the model is focused on medium- and long-term trends, which may be markedly different than short-term responses.

The purpose of the model is to calculate the optimal allocation of technology to the competing attributes of performance and fuel consumption over the medium to long term. In this context, the term "optimal" does not refer to the ideal balancing of performance and fuel consumption according to any normative standard of social welfare. Rather, "optimal" refers simply to the balance of performance and fuel consumption that will maximize the value to consumers, as measured by their aggregated willingness to pay. The implied perspective is that of automobile manufacturers seeking to provide the best possible value proposition to their customers, in order to maximize their own profitability. Understanding the perspective of the manufacturers is key, because they are the ones who ultimately decide on what tradeoffs will be made in a vehicle design and on the allocation of

more advanced technologies to performance and fuel consumption. (Hill et al., 2007)

Two assumptions are implicit in the definition of optimality employed in this work. First, it is assumed that the revenues that automobile manufacturers can realize from the sale of a vehicle fleet will be maximized when consumers' value is maximized. Second, it is assumed that the cost of implementing a given suite of technologies is constant regardless of how the technologies are applied to performance and fuel consumption. If applying technology toward performance were more or less costly than applying the same technology toward fuel consumption reductions, then maximizing consumer value (or revenues) alone would not be sufficient to identify the optimal allocation of technology.

The model's results are relevant over the medium to long term. Klier and Linn (2008) have identified three stages of response to fuel economy regulations. In the short term, which they define as 1-2 years, a firm's only practical response to an increase in fuel economy standards is to shift prices in order to influence the mix of vehicles they sell. Over the long term, which they identify as 10 years or more, firms can make decisions to employ additional advanced technology. Klier and Linn define the medium term as falling between these two, and specifically identify 5 years as the scale of a medium-term response, relating this value to the design lifecycle of a typical vehicle model. During the medium term, they argue, manufacturers can make decisions about design priorities in new vehicles, such as balancing performance and fuel consumption. (Klier & Linn, 2008) New vehicle designs are typically begun 2-3 years before a vehicle is launched, and a given design may be in production for 4-5 years (typically) or even as long as 10 years. Manufacturers typically have a "cycle plan" in place that governs their portfolio planning process for the next 10-15 years. (Hill et al., 2007) The purpose of the technology allocation model is to explore the tradeoff between performance and fuel consumption that occurs over the medium to long term. For these purposes, this is assumed to mean 10 years or more. The rationale for this definition is that 10 years is ample time for manufacturers to

perceive a shift in consumer preferences (or public policy signals), to re-prioritize design attributes in the product planning process, and to get the re-optimized models into production.

Consumers' value of vehicles is calculated using a technique based on the Direct Value method. (McConville & Cook, 1996; Monroe & Cook, 1997) The value to consumers is calculated by multiplying consumers' willingness to pay for an improvement in an attribute by the degree to which that attribute is improved. Consumers have heterogeneous preferences, and it is expected that there is a distribution of willingness to pay values among different vehicle purchasers. Therefore, the median willingness to pay is used as the basis of calculating value throughout this work. (Monroe & Cook, 1997) Additionally, it is assumed that the value of performance is independent of the value of fuel consumption, meaning that the total value can be determined by adding the two independent values associated with performance improvements and fuel consumption improvements. (McConville & Cook, 1996)

In this work, it will be helpful to distinguish between the terms willingness to pay (WTP) and value. The term *value* is used here to describe the total increase in the amount of money that a consumer would spend on a vehicle due to an improvement in an attribute. The term *willingness to pay* is used to describe the marginal amount that a consumer would be willing to pay per unit improvement in a particular attribute – that is, the partial derivative of value with respect to that attribute. For example, consumers' *willingness to pay* for horsepower might be $10 per horsepower. If horsepower were increased by 10 hp, then consumers' *value* of the horsepower increase would be $100.

3.2 Model Structure

The technology allocation model is based on the principle of optimizing the application of new, efficiency-enhancing technologies to competing vehicle attributes. As currently implemented, the model trades off two key vehicle

attributes: performance (as measured by the 0-60 mile per hour acceleration time) and fuel consumption (the inverse of fuel economy, measured in liters of fuel consumed per 100 km driven). The model is designed to answer the question,

> *What is the optimal balance of performance and fuel consumption that will maximize the value of these attributes to consumers, subject to the constraint of technological feasibility?*

The optimal balance of performance and fuel consumption is determined by maximizing the combined value of reductions in acceleration time and reductions in fuel consumption, as discussed in Section 3.1. The technological constraint is based on extrapolations of past trends, confirmed by engineering assessments of likely technological improvements, as discussed in Section 3.3.2.

3.2.1 Value of New Technologies

The total value to consumers of improved technology (ΔV_{tech}) is calculated as the sum of the increase in value due to better fuel consumption (ΔV_{FC}) and the value due to faster acceleration (ΔV_A), as shown in Equation 3-1.

Equation 3-1

$$\Delta V_{tech} = \Delta V_{FC} + \Delta V_A$$

The values of lower fuel consumption and faster acceleration are calculated as shown in Equation 3-2 and Equation 3-3, respectively.

Equation 3-2

$$V_{FC} = v_{FC} \cdot (FC_0 - FC_y) + V_{FC,0}$$

Equation 3-3

$$V_A = v_A \cdot (A_0 - A_y) + V_{A,0}$$

In Equation 3-2, FC_0 is the baseline fuel consumption, FC_y is the final fuel consumption in year y, v_{FC} represents consumers' willingness to pay per unit reduction in fuel consumption. Similarly, in Equation 3-3, A_0 is the baseline 0-60 mph time, A_y is the 0-60 mph acceleration time in year y, and v_A is the willingness of

consumers to pay for each unit reduction in 0-60 mph acceleration time. In the present work, the willingness to pay values reflect the preferences of the median consumer, although a similar approach could be applied using disaggregated consumer preference data.

3.2.2 Constraints on Technological Feasibility

The range of feasible combinations of fuel consumption and acceleration performance is limited by the technological capabilities of the auto industry at any given time. For positive values of willingness to pay in the framework given above, total willingness to pay would be maximized by reducing both acceleration time and fuel consumption to zero, which is obviously a technical impossibility. In general, the technological constraint can be represented mathematically by the inequality shown in Equation 3-4, in which p>0 and q<0. This relationship is discussed in greater detail in Section 3.3.2.

Equation 3-4

$$A \geq p \cdot FC^q$$

The technological constraint states that for a given level of technological capability, the minimum 0-60 mph time varies with the fuel consumption. As discussed in Section 1.1, the efficient use of technological capabilities demands that A will always be set equal to the minimum level feasible according to the constraint given by Equation 3-4.

3.2.3 Optimizing Technology Allocation

Because the current model trades off only two parameters, it is straightforward to maximize willingness to pay by substituting Equation 3-2, Equation 3-3, and Equation 3-4 into Equation 3-1 and differentiating with respect to fuel consumption, which yields the following:

Equation 3-5

$$\frac{dV_{tech}}{dFC} = -v_{FC} - v_A \cdot p \cdot q \cdot FC^{q-1}$$

To locate the critical level of fuel consumption for which V_{tech} is maximized, the expression in Equation 3-5 is set equal to zero and rearranged:

Equation 3-6

$$FC_{Optimal} = \left(-\frac{v_{FC}}{v_A \cdot p \cdot q} \right)^{\frac{1}{q-1}}$$

Equation 3-6 provides the optimal level of fuel consumption when given values of willingness-to-pay for fuel consumption and acceleration, and when the technical tradeoff between performance and fuel consumption is well characterized. The result is then used to calculate the optimal acceleration time and the corresponding increases in consumers' value. In addition, the optimal fuel consumption is used to calculate the optimal ERFC that corresponds to the specified conditions. Under these optimal conditions, the marginal increase in value due to for lower fuel consumption is exactly offset by the marginal decrease in value that comes from the necessarily slower acceleration.

3.3 Model Inputs & Assumptions

3.3.1 Relationship between Acceleration and Power/Weight Ratio

In order to evaluate historic trends and to correctly predict characteristics of conventional (naturally aspirated, spark-ignition) vehicles, it is helpful to understand the relationship between cars' power, weight, and acceleration. The U.S. EPA estimates 0-60 mph acceleration times using a pair of long-established correlations of the form:

Equation 3-7

$$A = c \cdot \left(\frac{P}{W_I} \right)^{d}$$

In Equation 3-7, P is the vehicle's rated peak horsepower, W_I is the vehicle's inertia weight (curb weight plus 300 pounds), and c and d are constants. EPA employs one set of values of c and d for vehicles with manual transmissions and another for vehicles with automatic transmissions, (U.S. EPA, 2008) as noted in Table 3-1. The two correlations produce estimates that differ by 3% or less over the range of P/W_I values applicable to most vehicles. These correlations, however, are based on vehicles from 1974-1975, (Malliaris, Hsia, & Gould, 1976) making their applicability to today's cars questionable.

Table 3-1: Constants used by EPA (U.S. EPA, 2008) and Berry(Berry, 2010) to estimate 0-60 mph times, and constants derived in this work from Consumer Reports data.(Consumer Reports, 2009)

	c	d
EPA: Automatic	0.892	-0.805
EPA: Manual	0.967	-0.775
Berry	0.845	-0.757
This Work	**0.668**	**-0.865**

The correlations used by EPA to estimate 0-60 mph times over-predict the acceleration times for modern vehicles. In a forthcoming thesis, Berry compiled a list of reported 0-60 mph times for modern (model year 2007 and later) vehicles and found that the EPA correlations generally over-predict the 0-60 mph time for most contemporary vehicles by 1-2 seconds. (Berry, 2010) Modern vehicles likely realize 0-60 times superior to those of 1970s-era vehicles with the same P/W_I values because of improvements in transmission technology, flatter torque curves, and reductions in rolling resistance and aerodynamic drag. Berry fit a curve of the same form as Equation 3-7 to her data, and the parameters for her correlation are

listed in Table 3-1. Berry's data and correlation are compared with the EPA curves in Figure 3-1. Although Berry's correlation provides a better fit than the EPA curves, especially for P/W_I values in the range of 0.06-0.12 hp/lb, her curve appears to under-predict 0-60 mph times in the 0.03-0.05 hp/lb range. The latter range includes many of the most popular models, accounting for more than half of all car volume in the U.S. in 2008. (Ward's, 2007; Ward's, 2008; Ward's, 2009)
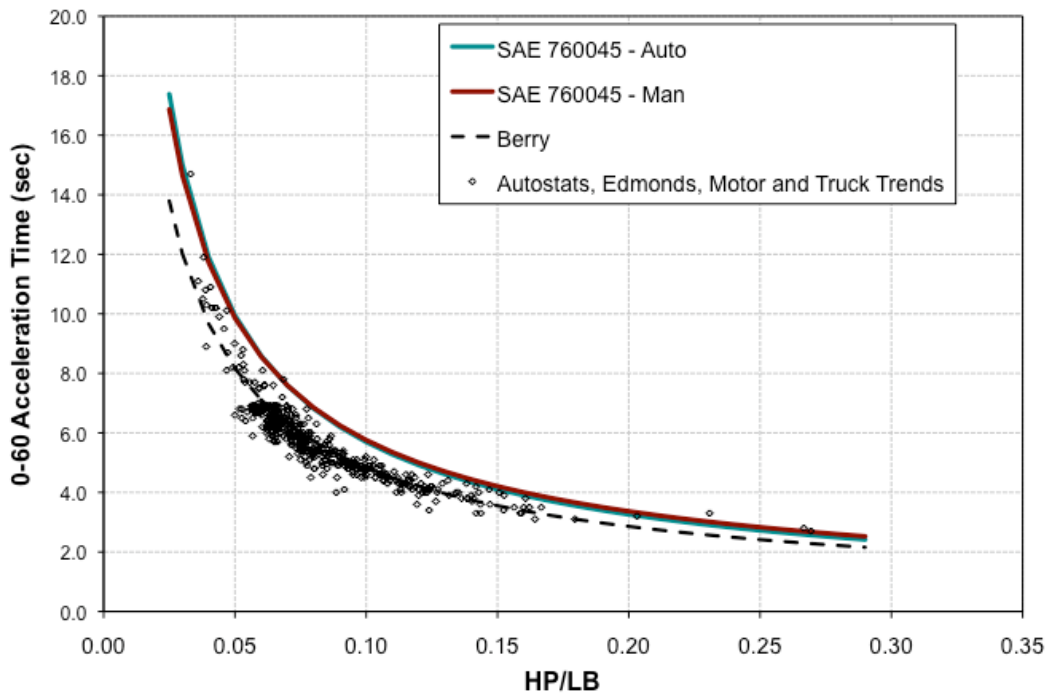
Figure 3-1: Acceleration and Power/Weight relationships reported by EPA and Berry (includes both cars and light trucks).(Berry, 2010)

A second set of data, from Consumer Reports (2009), provides the basis for a correlation that better estimates the 0-60 mph times in the region of interest. The Consumer Reports data include many of the most popular vehicles sold in the United States between 2003 and 2009. (Ward's, 2008; Ward's, 2009) Figure 3-2 and Figure 3-3 show the relationships between power/weight ratio and acceleration times as reported by Consumer Reports for cars with automatic and manual transmissions, respectively, along with fitted curves of the form given in Equation 3-7.

0-60 mph Acceleration Time (seconds)

$$y = 0.668x^{-0.865}$$
$$R^2 = 0.883$$

Power / Weight (hp/lb)

Figure 3-2: Acceleration and Power/Weight data for model year 2003-09 cars with automatic transmissions. (Consumer Reports, 2009)

0-60 mph Acceleration Time (seconds)

$$y = 0.811x^{-0.771}$$
$$R^2 = 0.895$$
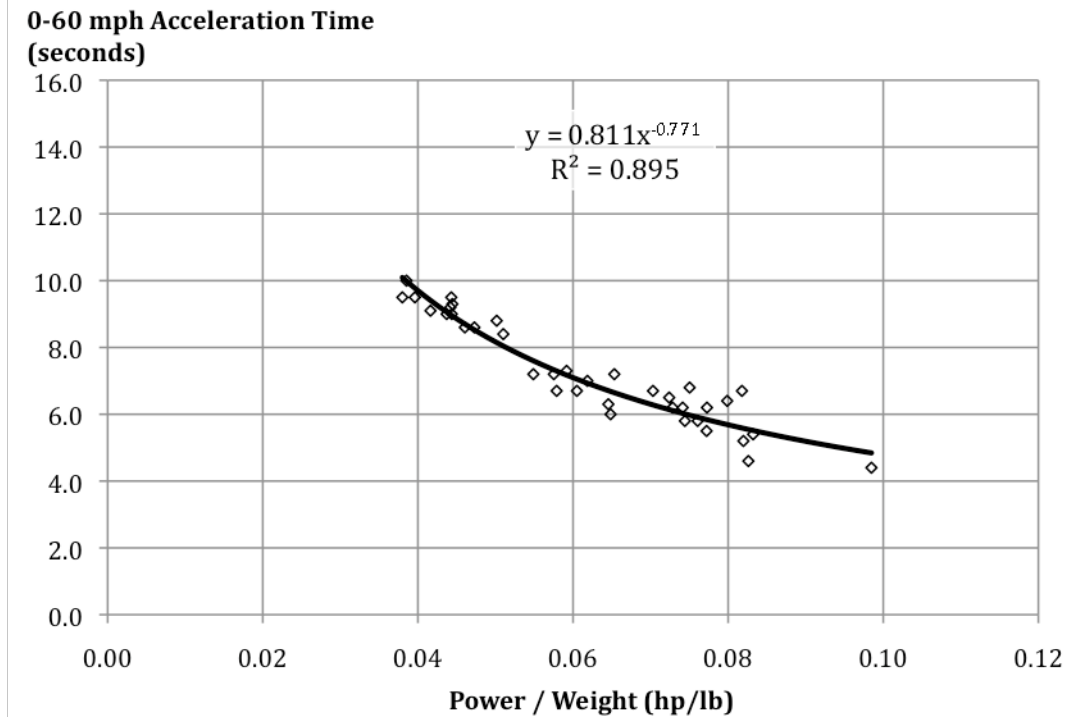
Power / Weight (hp/lb)

Figure 3-3: Acceleration and Power/Weight data for model year 2003-09 cars with manual transmissions. (Consumer Reports, 2009)

The analysis of the Consumer Reports data confirms that while EPA's correlations over-predict 0-60 mph times for modern cars, Berry's correlation under-predicts them. The correlation developed here for cars with automatic transmissions, based on Consumer Reports data, is compared with the curves 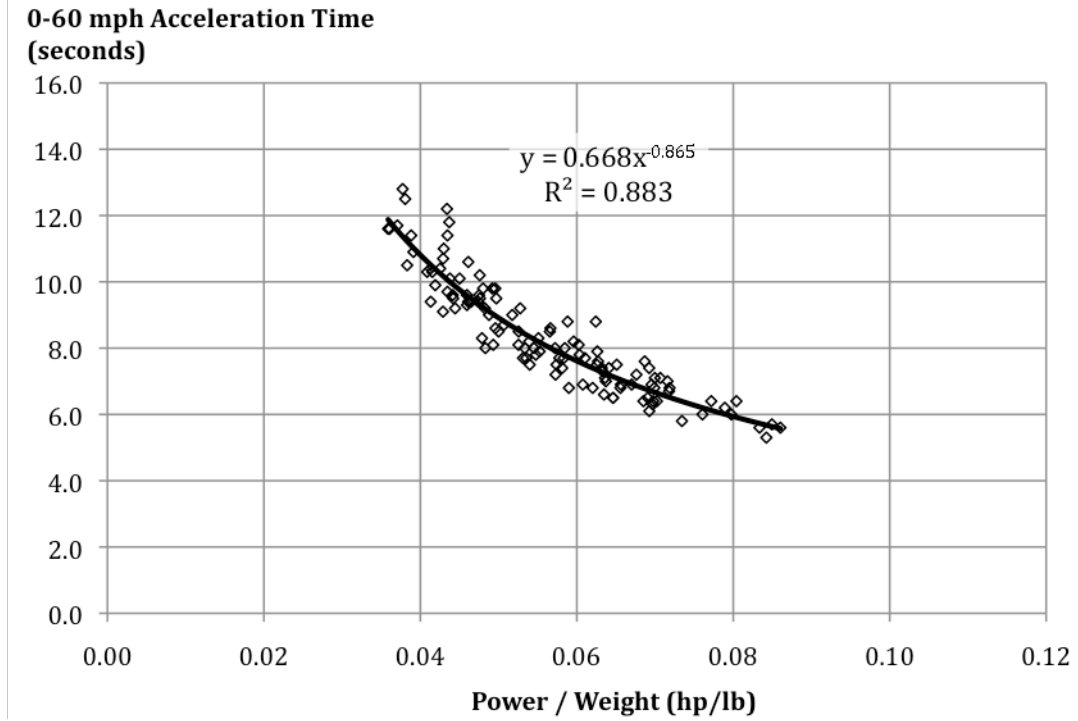reported by Berry and EPA in Figure 3-4. Also shown are the data points employed by Berry and those obtained from Consumer Reports.
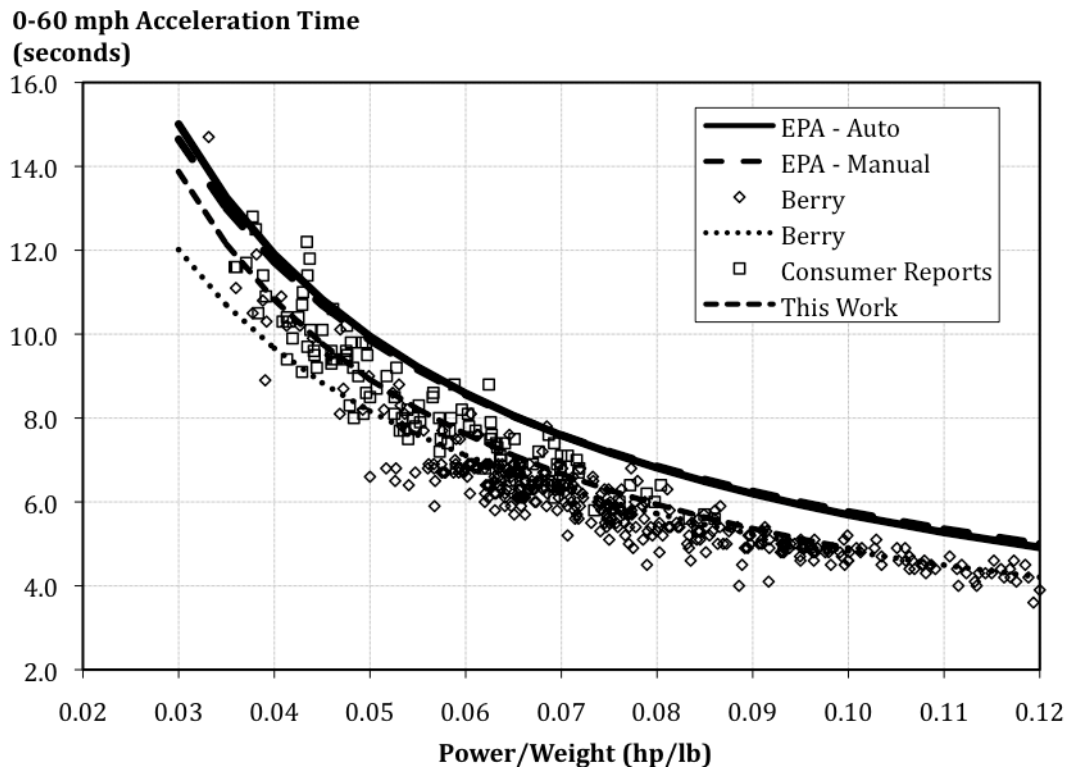
Figure 3-4: Comparison of Acceleration – Power/Weight relationships. The correlation developed here from Consumer Reports data provides a better fit at the lower end of the power/weight range, where most of today's popular vehicles fall. (Berry, 2010; Consumer Reports, 2009; U.S. EPA, 2008)

Analyses throughout the rest of this work are based on the correlation derived from Consumer Reports' data for cars with automatic transmissions, which is the most relevant correlation for the purposes of this research. Approximately 80 percent of cars sold in the United States in 2008 had automatic transmissions. (U.S. EPA, 2008) Furthermore, this work is principally concerned with the behavior of the average new car, rather than with the high-performance outliers that bias Berry's data. The Consumer Reports data cover the entire range of power/weight values that would

be expected for the average new car between now and 2035, for ERFC values between 0 and 150 percent and rates of technological improvement consistent with historic trends. (see Section 3.3.2)

3.3.2 The Acceleration - Fuel Consumption Tradeoff

In this work, the growth in technological capabilities over time is modeled using the performance-size-fuel economy index (PSFI). An and DeCicco (2007) developed PSFI as a metric for overall technical efficiency of cars, based on three primary measures of vehicle utility: size, power/weight, and fuel economy. PSFI is defined in Equation 3-8, in which P and W_I have the same meaning as in Equation 3-7, S is its interior volume (size) in ft^3, and FE is its fuel economy in mpg. (An & DeCicco, 2007) The suitability of PSFI for modeling the performance-fuel consumption tradeoff is evaluated later in this section.

Equation 3-8

$$PSFI = \left(\frac{P}{W_I} \right) \cdot S \cdot FE$$

PSFI has grown in a remarkably consistent, linear fashion since the 1970s, as discussed in Chapter 1 (and shown in Figure 1-2). This linear growth has persisted through times of high and low oil prices, times both constrained and unconstrained by CAFE standards, and times of differing emphasis on performance and fuel consumption. (An & DeCicco, 2007)

Future technological capabilities are estimated by extrapolating the linear growth trend in PSFI. Using this approach, the tradeoff between acceleration and fuel consumption is modeled by rearranging Equation 3-8 to obtain an expression for P/W_I, and substituting this expression into Equation 3-7. In this way, the curves shown in Figure 3-5 were generated. These curves are of the form given by Equation 3-4, for which q is equal to -0.865 (identical to d from Table 3-1), and p is given by Equation 3-9.

Equation 3-9

$$p = c \cdot \left(\frac{PSFI}{k \cdot S} \right)^{d}$$

In the above expression, c has a value of 0.668 (as in Table 3-1), S (the interior volume) is assumed to equal its 2005 value of 111 ft³, and k =235.2 mpg-(l/100km) is a conversion factor used to convert between fuel economy in units of mpg and fuel consumption in units of liters/100km.
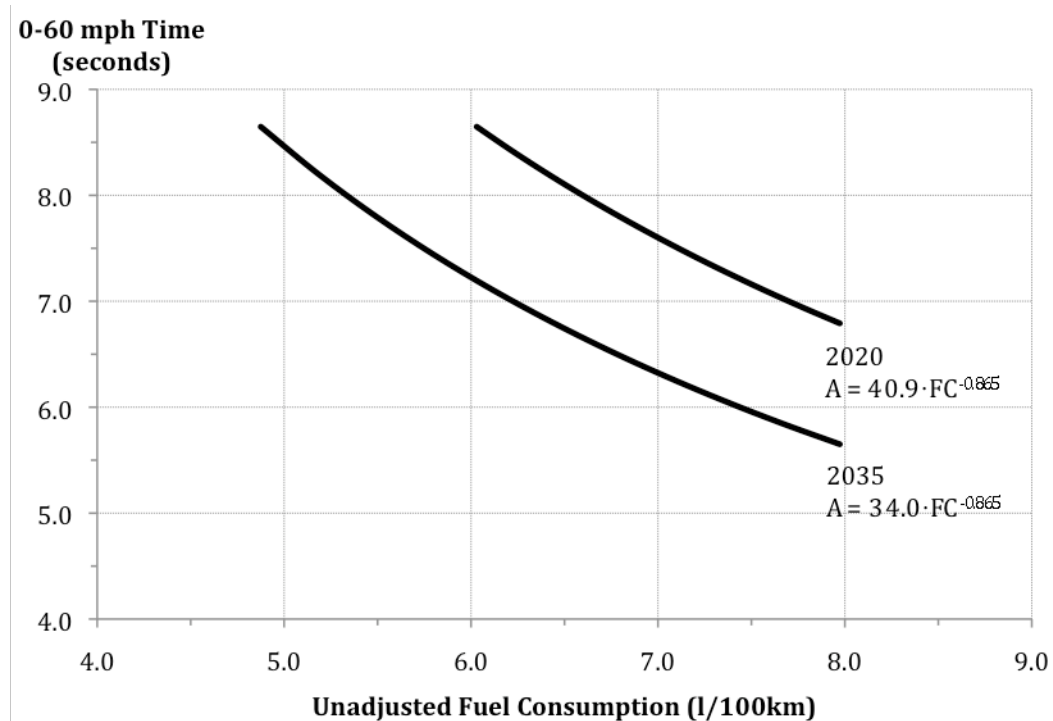
Figure 3-5: Performance - fuel consumption tradeoffs curves for the average new car in 2020 and 2035. Curves were generated using PSFI-based methodology developed in this section and power/weight – acceleration relationship established in Section 3.3.1.

The performance-fuel consumption tradeoff curves generated by the above methodology can be checked against the performance-fuel consumption tradeoff found in the current vehicle market. The 0-60 mph acceleration times of model year 2008 midsize car models (estimated using the relationship developed in the preceding section) are plotted in Figure 3-6 against fuel consumption. Also shown is the tradeoff curve generated using the methodology described in this section, for PSFI equal to that of the average model year 2008 midsize car. There is reasonable

44

agreement between the modeled tradeoff and that represented by the actual mix of midsize cars offered in 2008. Similar plots for small and large cars are provided in Appendix B, and show similar agreement between the PSFI-based methodology and the current vehicle mix.
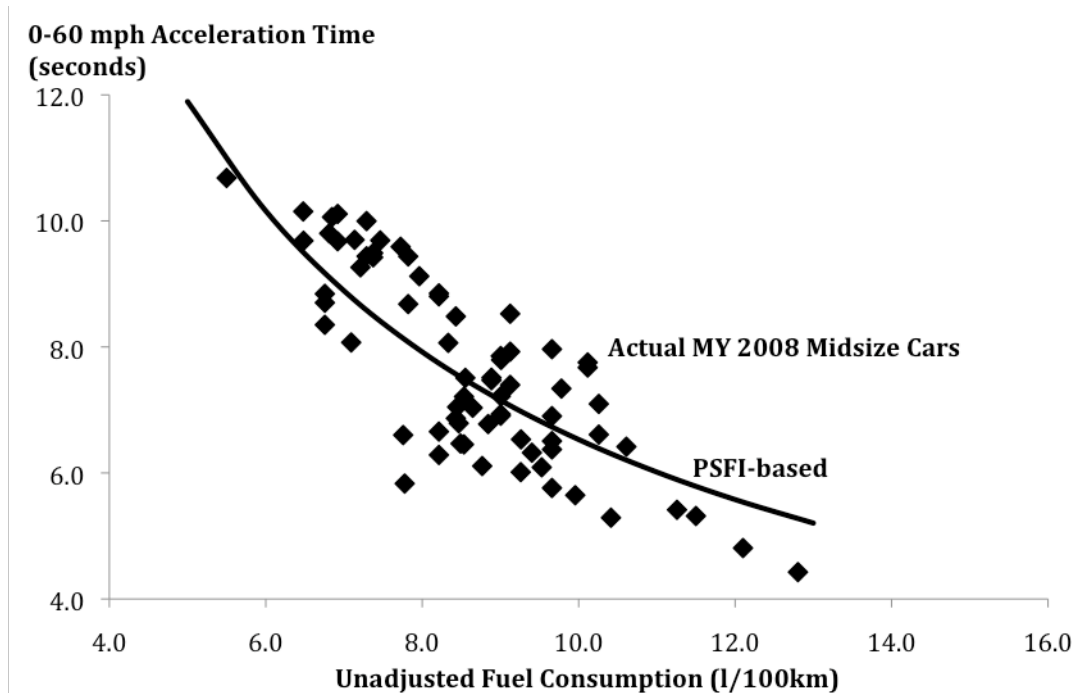
Figure 3-6: Comparison of modeled performance-fuel consumption tradeoff with actual mix of cars offered in the U.S. in model year 2008 (excluding hybrids). (U.S. EPA, 2008; Ward's, 2007; Ward's, 2008; Ward's, 2009)

A second check on the validity of the tradeoff modeling methodology comes from the work of Cheah et al. (2008). Cheah et al. reported results characterizing the tradeoff between 0-60 mph time and fuel consumption for naturally aspirated, spark-ignition cars in 2035. The 0-60 mph times reported were calculated from P/W_I values using the EPA correlation discussed in Section 3.3.1. For purposes of the present work, the 0-60 mph times were recalculated from Cheah et al's P/W_I values using the newer correlation reported in Section 3.3.1 (based on Consumer Reports' values of 0-60 mph times for current cars), in order to ensure consistency with other calculations in this work. The recalculated 0-60 mph times are plotted against unadjusted fuel consumption in Figure 3-7, and are shown with the PSFI-based tradeoff curve for 2035. From Figure 3-7, it is evident that the methodology of

Cheah et al. yields a very similar prediction of the performance-fuel economy tradeoff in 2035 as the PSFI-based methodology, which lends further support to the validity of the PSFI-based methodology.
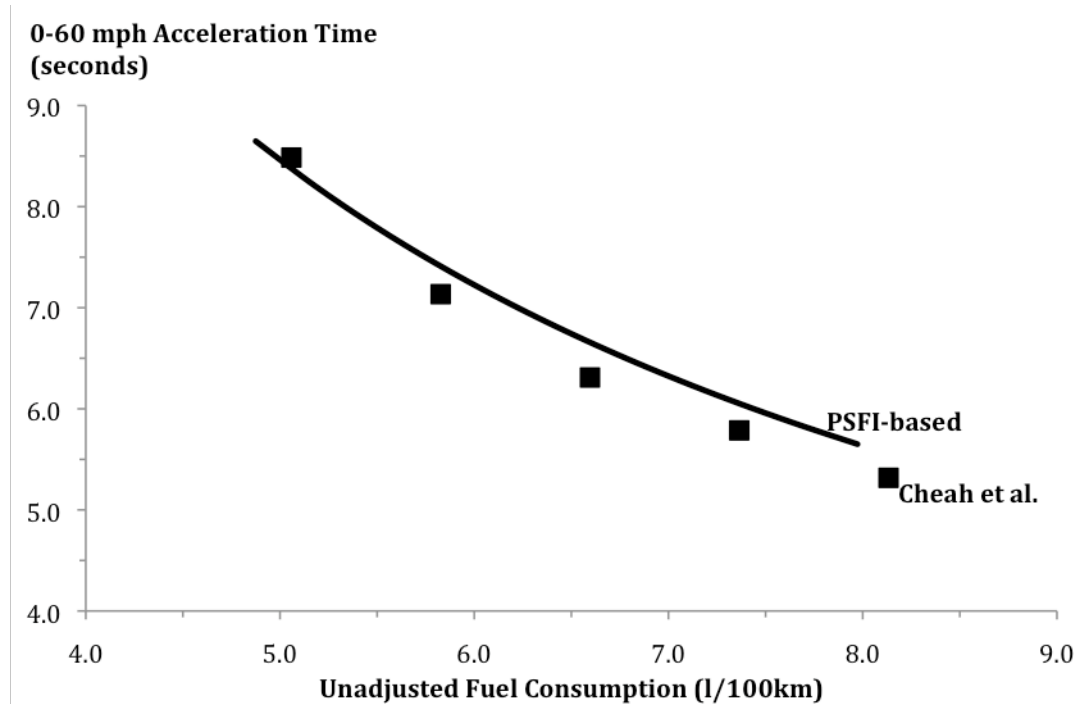
Figure 3-7: The performance-fuel consumption tradeoff modeled using the methodology developed in this section agrees well with the results of Cheah et al. (2008) for 2035.

3.3.3 Willingness to Pay for Fuel Consumption Improvements

A number of authors have estimated consumers' willingness to pay (WTP) for lower fuel consumption in their vehicles, and their results vary widely.

The willingness to pay for fuel consumption is frequently estimated in terms of a payback period, which may be expressed as years of ownership or as miles driven. This raises two important points. First, it should be noted that estimating willingness to pay in terms of a payback period does not imply any presumption that consumers explicitly calculate fuel expenses and weigh these against up-front costs. Quite the contrary, a recent study of car-buyers' decision-making processes found that none of the interviewees had evaluated fuel costs in an objective and quantitative fashion, even in households comprising two "financial service

46

professionals." (Turrentine & Kurani, 2007) Instead, the implication of using a payback period is merely that consumers' willingness to pay is *generally consistent* with such a calculation. (Greene, German, & Delucchi, 2009)

A second key point about using payback period as a basis for willingness to pay is that such an approach implicitly assumes that the willingness to pay for lower fuel consumption is directly proportional to the price of fuel, which is likely a better assumption over the medium to long term than in the short term. Sterman has found that individuals' expectations of future values of a variable (such as price) depend not only on the variable's current value, but on perceived trends as well as the individual's intuitive sense of what the "right" value is. (Sterman, 2000) This suggests that as fuel prices change after a period of stability, consumers may initially expect them to revert to their original values, and later would tend to extrapolate observed price increases into the future. The result is that in the short term, consumers' expectations of fuel prices may differ significantly from actual fuel prices. However, this work is principally concerned with changes in technology allocation over the medium to long term (~10 years or more). Therefore, it is assumed that consumers' willingness to pay for fuel consumption will re-equilibrate to a level proportional to the price of fuel, after a sustained change in fuel prices.

Greene, German, and Delucchi (Greene et al., 2009) and Greene et al. (Greene et al., 2005) make convincing arguments that that consumers value fuel savings only over the first 3 years or roughly 50,000 miles that they will own a vehicle. They rely on a number of sources, including work by the Department of Energy and market research by the auto industry, to reach this conclusion. In addition, Greene, German, and Delucchi offer a model based on bounded rationality and risk-aversion that accounts for consumers' low willingness to pay. Adler et al. found that consumers would demand an undiscounted payback of between 2 and 10 years for up-front investments in fuel savings. (Adler, Wargelin, Kostyniuk, Kalavec, & Occhiuzzo, 2004) While this range appears to reflect the wide variability in the preferences of

the population, it says nothing about where in this range the majority of consumers, or the median consumer, falls.

Other authors have concluded that consumers' willingness to pay is higher than that corresponding to a 3-year payback. Donndelinger and Cook (Donndelinger & Cook, 1997) reported results from a survey of 858 respondents which estimated a value to consumers of $360-$1,230 for each mpg improvement. Expressed in 2007 dollars their results are equivalent to $1,300-$3,000 for each 1l/100km reduction in laboratory fuel consumption. These values are significantly greater than the economic value of the fuel savings over the entire life of the vehicle, even without discounting. McConville and Cook (McConville & Cook, 1996) reported results from a similar, but smaller and admittedly unrepresentative survey. They reported a consumer value increase of $170-$300 per mpg improvement, which is equivalent to $610-$960 for each 1l/100km reduction in laboratory fuel consumption, in 2007 dollars, equivalent to roughly a 6-10 year payback.

In this work, a 3-year payback is used in the development of baseline scenarios. A variety of studies confirm the 3-year estimate from both the consumers' and manufacturers' perspective, and a plausible theoretical explanation for the short payback has been offered. Consumers' willingness to pay for lower fuel consumption, expressed in terms of the dollars they are willing to pay for each 1l/100km reduction, is therefore estimated to be:

Equation 3-10

$$v_{FC} = \frac{n \cdot \frac{VKT}{100} \cdot P_{fuel}}{\alpha}$$

In Equation 3-10, n is the length of the assumed payback period, in years, and P_{fuel} is the expected per-liter price of fuel over the payback period. VKT is the annual distance traveled by the vehicle (vehicle kilometers traveled), which is assumed to be 24,135 km (15,000 miles) per year. This figure is close (within 3%) to the average distance traveled over the first three years of ownership according to

48

Bandivadekar et al. and Greene. (Bandivadekar et al., 2008; Greene, 2001) In addition, 15,000 miles per year is the same distance used by DOE and EPA in estimating annual fuel costs presented to consumers in the annual Fuel Economy Guide. (U.S. Department of Energy & U.S. Environmental Protection Agency, 2008) In Equation 3-10, α is the on-road correction factor that defines the ratio of in-use fuel economy to laboratory test fuel economy. According to estimation procedures recently adopted by the U.S. Environmental Protection Agency, a decreases with increasing fuel economy, and falls between 0.7 and 0.8 for vehicles offered for sale in 2008. (40 CFR 600.210-08) (U.S. EPA, 2009) Within the range of 30-50 mpg, which is of greatest relevance to the present work, a falls between 0.76 and 0.73. In the interest of simplicity, a is assumed to have a constant value of 0.75 throughout this work.

Historic United States gasoline price were shown in Figure 1-5. Prices have been notoriously volatile recently, but were in fact relatively stable and constant for nearly 20 years, between 1986 and 2003. During this time, the price averaged approximately $1.70 per gallon in real terms (2007 dollars).

Assuming a fuel price of $0.45/liter ($1.70 per gallon) and a 3-year payback, Equation 3-10 yields an estimated willingness to pay of $430 for each 1l/100km reduction in (laboratory) fuel consumption. This value is used as the willingness to pay in the business-as-usual, constant fuel price, baseline scenario in Section 4.2. Willingness to pay is readily calculated for other values of payback period and fuel price, and the change in WTP is proportional to the changes in these parameters.

3.3.4   *Willingness to Pay for Performance*

Two main types of data were used to estimate consumers' willingness to pay (WTP) for better vehicle performance. First, literature evaluating consumers' WTP was reviewed. Second, price differentials for 4- and 6-cylinder versions of current car models were calculated.

A number of authors have reported estimates of consumers' WTP for faster acceleration, expressed in terms of a variety of units.[7] The estimates were converted to a common baseline of dollars per 1-second reduction in 0-60 mph time ($/s) and converted to year 2007 dollars, and the resulting estimates are plotted in Figure 3-8 against their year of publication. There is considerable variation in the estimates, which yield both a median and a mean value of $385 for each 1-second reduction. No particular time trend in the WTP is apparent in Figure 3-8.
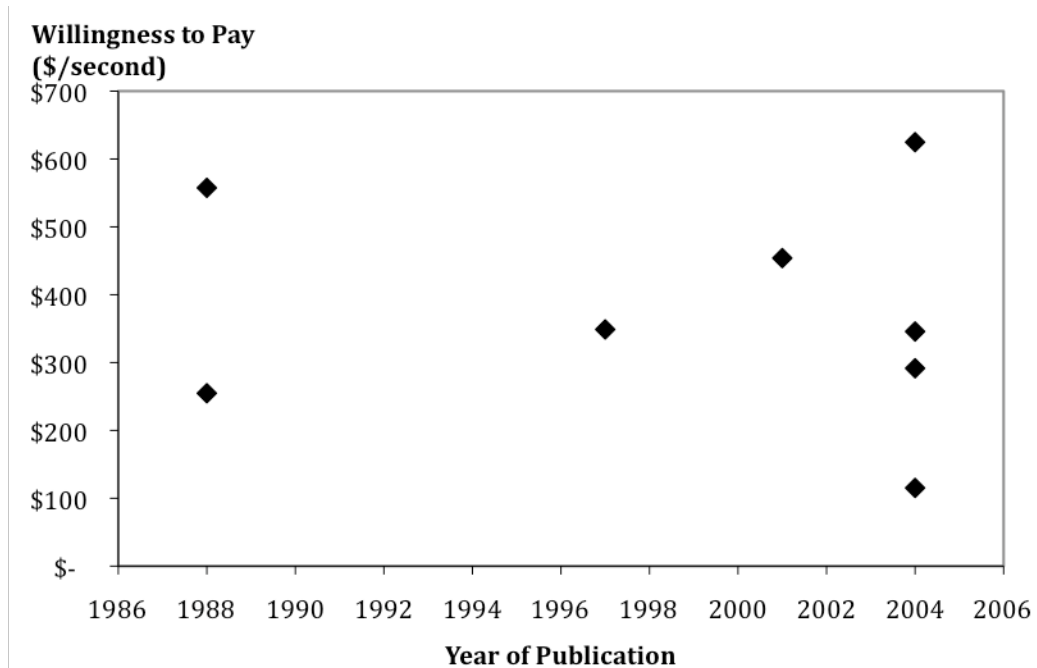
Figure 3-8: Literature estimates of willingness to pay for improved acceleration (2007 dollars per 1-second reduction in 0-60 mph time). (Adler et al., 2004; Bureau of Labor Statistics, 2008; Donndelinger & Cook, 1997; Greene & Liu, 1988; Greene, 2001; Greene, Duleep, & McManus, 2004)

Price data from contemporary vehicle models provide a useful check against the more academic estimates of WTP that are found in the literature, although price differences are not necessarily the same as the WTP values we are seeking. Throughout this work, we are working with the median WTP as the basis of calculating changes in vehicle value, as discussed in Section 3.1. For any given

---

[7] The units reported include the WTP per second reduction in 0-60 mph time, per horsepower, per unit torque, and per unit improvement in engine displacement per pound of vehicle weight.

attribute, there is presumably a distribution in WTP across the population of consumers. If consumers are offered some optional feature at a certain price, and fewer than 50% of them choose that option, then we can safely conclude that the median WTP is less than the price. Similarly, if more than 50% choose the option, we can conclude that the median WTP is greater than the option price. (Monroe & Cook, 1997) Willingness to pay therefore cannot be determined in any meaningful way from price data unless corresponding market share data are also known.

To elucidate manufacturers' perceptions of WTP for acceleration, comparisons were made between comparably-equipped 4-cylinder and 6-cylinder versions of popular U.S. models. Although manufacturer's suggested retail price (MSRP) data are readily available for most vehicles (for example, from Ward's Automotive), the values reported are generally for the base MSRP (the price of the vehicle without any optional equipment). Frequently, a 6-cylinder engine is bundled with several other options that also serve to increase the price. As a result, the difference between the base prices of 4-cylinder and 6-cylinder versions of the same model is driven by more than just the difference in engines.[8] To obtain a more reasonable comparison, prices were obtained using "build and price" tools available on manufacturers' websites. This provides a reliable if time-consuming means of determining the difference in MSRP due solely to switching from a 4-cylinder to a 6-cylinder engine.

Manufacturer's suggested retail prices and 0-60 mph times of 4-cylinder and 6-cylinder versions of several popular U.S. car models were gathered from manufacturers' websites and from Consumer Reports. The full data are presented in Appendix C. For each model, the difference in MSRP was divided by the difference in 0-60 mph time for two versions. In this way, the price premium expected by the manufacturer for each 1-second reduction in 0-60 mph time was estimated. The

---

[8] For example, the 2009 Honda Accord V6 has a base MSRP of $26,605 while the 4-cylinder version has a base MSRP of $20,905. However, even the most basic V6 includes features that are not included on the entry-level 4-cylinder trim, including an automatic transmission, alloy wheels, moonroof, and many others. In this case, it is unreasonable to attribute the entire $5,700 price premium solely to the difference in engines.

resulting price premiums are plotted in Figure 3-9 along with the fraction of each model equipped with V6 engines.[9] For comparison purposes, Figure 3-9 also shows the range of median WTP values reported in the literature, which were discussed above.
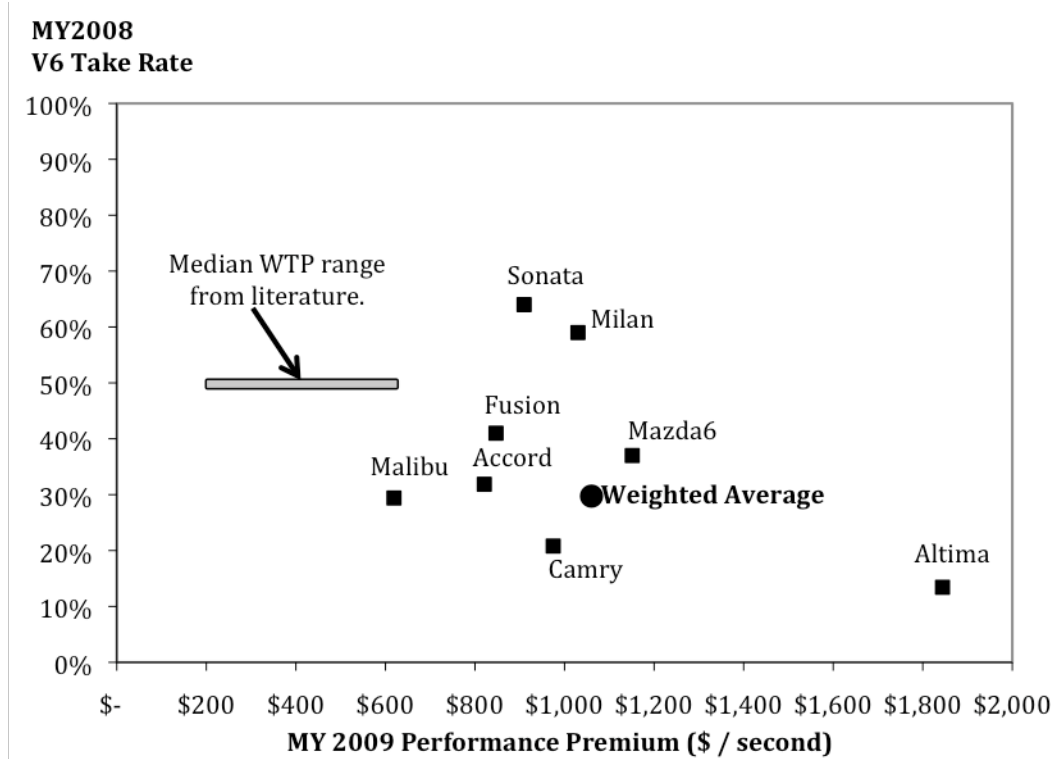
Figure 3-9: Price premiums and take rates for higher-performance engines, compared with literature estimates of willingness to pay for performance. (American Honda Motor Co., ; Consumer Reports, 2009; Ford Motor Company, ; Ford Motor Company, ; General Motors Corporation, ; Hyundai Motor America, ; Mazda North American Operations, ; Nissan North America, ; Toyota Motor Sales, ; Ward's, 2008; Ward's, 2009)

The price premiums calculated from MSRP data are generally consistent with the literature estimates of WTP for performance, despite being somewhat higher. There is considerable variability among the different vehicles investigated, but nearly all of them indicate a price premium greater than the range of WTP values reported in the

---

[9] Price premium data were collected from manufacturers' websites in January-February, 2009, and are for model year 2009 vehicles. Engine market shares were calculated based on Ward's Automotive data for model years 2007 and 2008, because 2009 share data are not yet available. Full data are provided in Appendix C.

52

literature, averaging approximately $1,100 for each 1-second reduction. These two findings are not necessarily inconsistent, however, because fewer than 50% of most models (an average of 30% in 2008) were equipped with the V6, indicating that the median WTP is actually lower than the price premium calculated. In results reported by Adler et al., consumers' WTP for acceleration was found to be $100-$300 per 1-second reduction in 0-60 mph time, but this translated into purchase price increases of $1000 per second. (Adler et al., 2004) Additionally, benefits of the V6 engine may not be limited just to performance improvements. The V6 may provide additional value to the consumer in the form of reduced noise and vibration, which would cause the performance premiums calculated here to be too high. (Magee, 2009)

3.4 Conclusions

In this chapter, the principles, framework, and assumptions underlying the technology allocation model were presented. The model is designed to optimize the allocation of more advanced technologies among the competing attributes of performance and fuel consumption by maximizing the value provided to consumers by these attributes. The range of feasible combinations of performance and fuel consumption is constrained by the availability of technology, which is projected by extrapolating past trends and confirmed by modeling-based work. Consumers' willingness to pay for fuel consumption is estimated to be $430 for each 1l/100km reduction, which corresponds to a three-year payback, assuming a fuel price of $1.70 per gallon, which was the average real price from 1986-2003. Literature estimates of consumers' willingness to pay for performance were reviewed, and found to range from $200 - $600 for each 1-second reduction in 0-60 mph time. The pricing of some of today's most popular U.S. car models reveals a higher premium for performance, but one that is not entirely inconsistent with the literature estimates. In the following chapter, the ranges of estimated WTP will be narrowed further by using historical data, in order develop more useful projections of future technology allocation decisions.

4 Calibration of Baseline Scenario

4.1 Historic Willingness to Pay for Performance and Fuel Consumption

Historic trends in the allocation of technology to performance and fuel consumption can help inform the assumptions underlie predictions of future technology decisions. From a manufacturer's perspective, the optimal allocation of technology to the competing attributes of performance and fuel consumption depends upon the relative value that these attributes deliver to consumers (i.e. "How much will consumers pay for performance versus fuel consumption?"), and the nature of the technical tradeoff between these attributes (i.e. "How much performance do I need to give up in order to improve fuel consumption?"). In the preceding chapter, a model incorporating these factors was developed for predicting the optimal allocation of technologies in the future. In order to narrow the range of plausible values of willingness to pay for performance and fuel consumption, the model was adapted to look at the historic allocation of technology to these two attributes.

It is necessary to obtain more precise estimates of consumers' willingness to pay (WTP) for improvements in performance and fuel consumption. In Section 3.3, WTP for improvements in performance and fuel consumption were estimated, but very broad ranges were found for both parameters. Literature estimates of WTP for performance ranged from $200-$600 per 1-second reduction 0-60 mph time. Price data for actual vehicles was generally consistent with the high end of this range, but was not sufficient to pinpoint WTP precisely. Similarly, broad variability was found in the WTP for improved fuel consumption, with payback periods ranging from two years to more than the life of the car. It will be shown later in this chapter that the variability in these parameters is so broad, and the optimal allocation of technology so sensitive to these values, that it is impossible to make a useful assessment of technology allocation decisions without have a more precise estimate of the relative WTP for performance and fuel consumption.

It is possible to estimate the relative WTP for performance and fuel consumption by examining how these parameters have evolved during historic periods of stable fuel prices. During such periods, it is assumed that consumers' WTP for fuel consumption is relatively constant, that manufacturers are able to elicit this WTP through market research and other "voice of the consumer" tools, and that the actual decisions made by the manufacturers represent the optimal allocations of technology. It is more difficult to assess the relative WTP for attributes during periods of unstable fuel prices, because WTP for fuel consumption is expected to change with fuel price, as discussed in Section 3.3.3. Since manufacturers need 5-10 years to readjust their design priorities and turn over the designs of their vehicles, (Hill et al., 2007) it would be unreasonable to assume that technology allocations made less than 5 years after a shift in fuel prices represent the optimum.

Gasoline prices in the United States were relatively constant in real terms from 1986-2003, (Figure 1-5) so it is to this period that we turn to evaluate the historic trends in the performance-fuel economy tradeoff. The period from 1991-2003 is of particular interest, for two reasons. First, it begins 5 years into the period of stable fuel prices, allowing time for manufacturers to have perceived and reacted to more stable consumer preferences. Second, the Corporate Average Fuel Economy Standard for cars did not change during this period, and changed only slightly during the 5 preceding years (Figure 1-6). (National Highway Traffic Safety Administration, 2004)

Figure 4-1 shows the progression of the average 0-60 mph time and unadjusted (laboratory) fuel consumption for U.S. cars from 1991-2003. The general trend downward and only slightly to the left reflects the generally low emphasis on reducing fuel consumption that was observed during this period. For three years (1991, 1997, and 2003), the performance-fuel consumption tradeoff curves have been added to Figure 4-1, representing the frontier of technically efficient combinations of acceleration and fuel consumption feasible in each year (see Section 1.1). These curves are derived using the performance-size-fuel economy

56

index (PSFI) based methodology that is discussed in Section 3.3.2, and are analogous to the curves in Figures 3-5, 3-6, and 3-7. (The curvature of these relationships is more difficult to discern in Figure 4-1 because of the narrow ranges of fuel consumption and acceleration shown in the plot.)
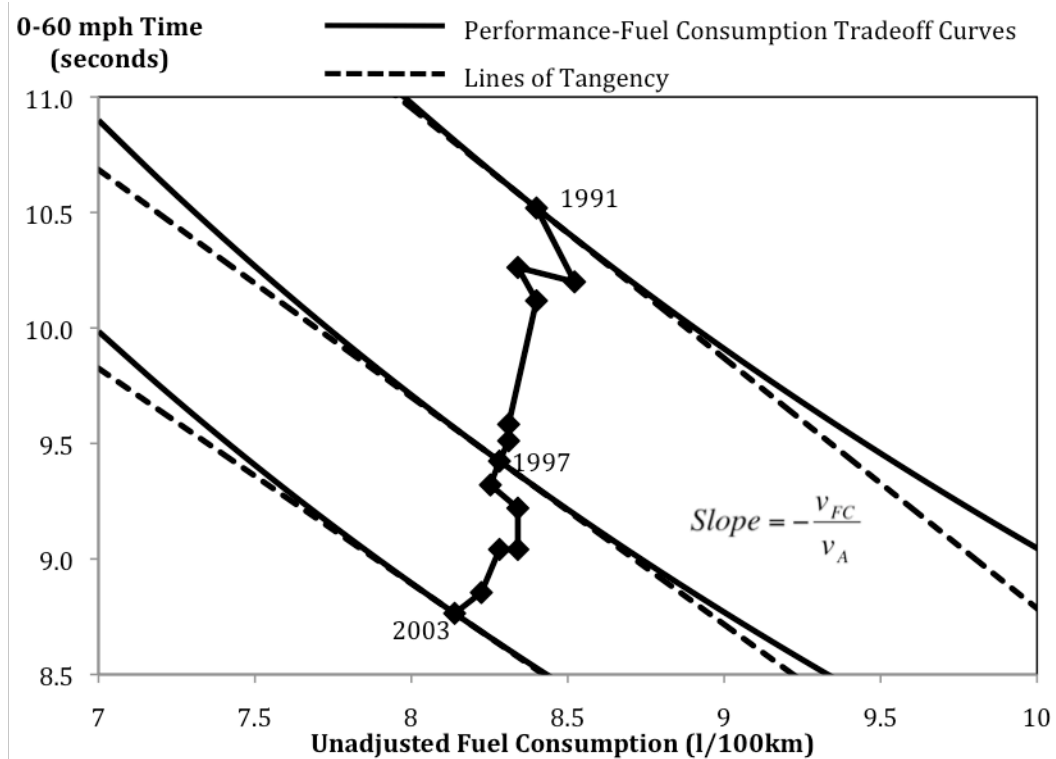
Figure 4-1: Historic tradeoffs between performance and fuel consumption for U.S. cars. The individual points mark the combinations of average 0-60 mph time and average fuel consumption in each year. 0-60 mph times are recalculated from EPA data using relationship developed in Section 3.3.1. The performance-fuel consumption tradeoff curves are of the form given by Equation 3-4 and Equation 3-9. Adapted from (U.S. EPA, 2008).

Also shown in Figure 4-1 are lines tangent to the performance-fuel economy tradeoff curves at the points of actual fuel economy and acceleration, the slopes of which define the ratio of WTP for fuel consumption to WTP for acceleration. Substituting Equation 3-1 and Equation 3-2 into Equation 3-3, and simplifying, yields Equation 4-1, in which C is a constant corresponding to a particular level of consumer value. Thus, Equation 4-1 defines a line representing the set of performance-fuel consumption combinations that yield a particular level of consumer value. When technology allocation is optimized (i.e. when consumers'

value is maximized), this line must be tangent to the performance-fuel consumption tradeoff curve. Similarly, if we assume that the historic allocation of technologies was indeed optimal, then we can conclude that the slope of the tangent is equal to -v_{FC}/v_A, which is the negative of the ratio of consumers' WTP for fuel consumption and acceleration reductions. In this way, it is possible to estimate the historic ratio between WTP for fuel consumption reductions and WTP for acceleration improvements.

Equation 4-1

$$C = -v_{FC} \cdot FC_y - v_{FA} \cdot A_y$$

The relative WTP deduced from historic patterns of performance and fuel consumption is consistent with the literature values reported in Chapter 3. Figure 4-2 shows the ratios of WTP for fuel consumption and acceleration for each year from 1991 to 2003, based on the slopes of the tangents as described above. If it is further assumed that the WTP for fuel consumption improvements was constant over this period and equal to $430 for each 1l/100km reduction,[10] then the corresponding values of WTP for acceleration can be calculated. The values so obtained are shown in Figure 4-3. The estimated WTP increased steadily from 1991 to 2003, ranging from $400-$470 per 1-second reduction. This range is consistent with the range of estimates found in the literature ($200-$600 per second) and discussed in Section 3.3.4.

---

[10] As discussed in Section 3.3.3, the value of $430 is calculated by assuming a 3-year payback, 15,000 miles per year, an average gasoline price of $1.70 per gallon, and on-road fuel economy 25% below the unadjusted laboratory value.
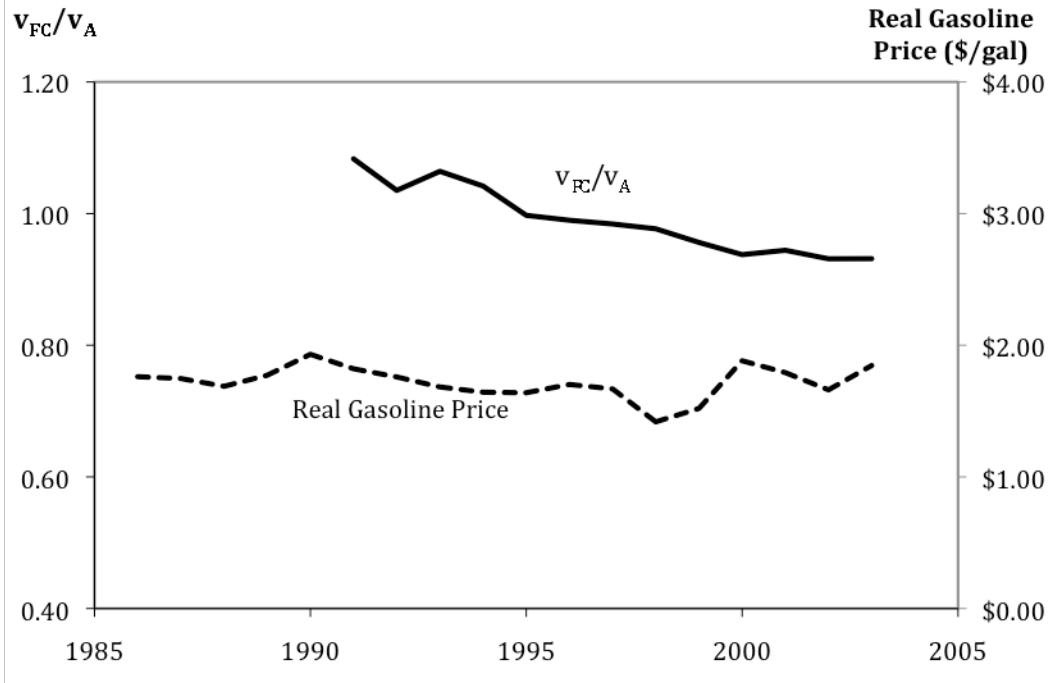
Figure 4-2: Historic ratio of WTP for fuel consumption reduction (v_{FC}) to WTP for acceleration improvements (v_A) during period of stable gasoline prices. Units for fuel consumption are dollars per 1l/100km reduction, and units for acceleration are dollars per 1-second reduction.
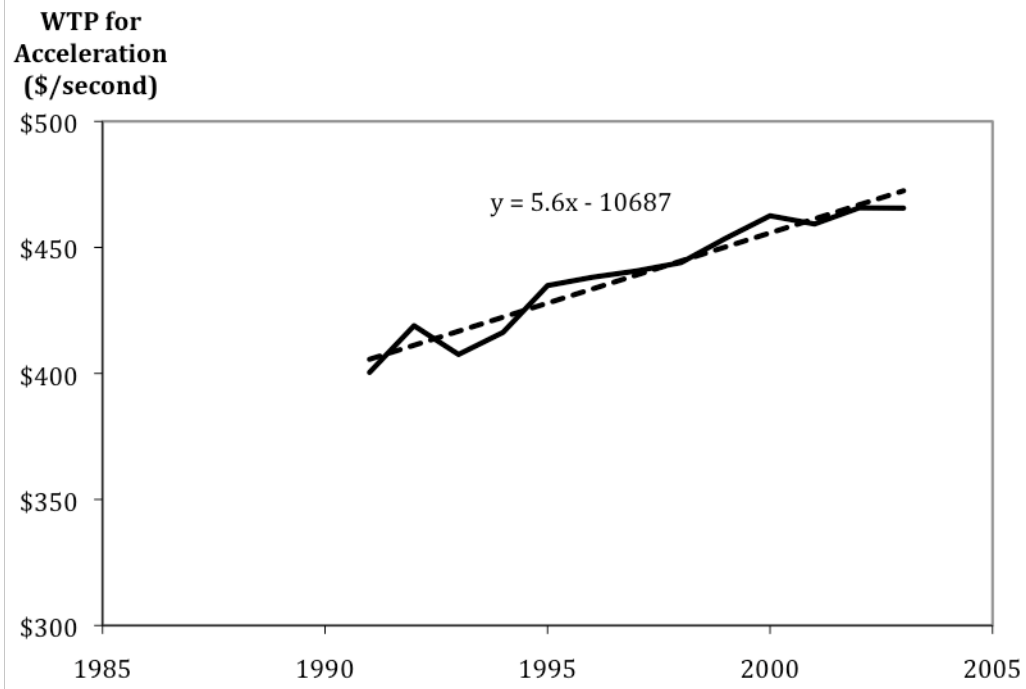
Figure 4-3: Historic WTP for reductions in 0-60 mph time, average U.S. cars. Estimated from v_{FC}/v_A values, assuming constant WTP for fuel consumption of $430 for each 1l/100km reduction. (See Section 3.3.3)

It is assumed that the growth in WTP for acceleration, shown in Figure 4-3, will continue into the future, and the sensitivity of the results to this assumption is explored. If the growth calculated for 1991-2003 is linearly extrapolated through 2020, an estimated WTP of $570 per 1-second reduction in 0-60 mph time is obtained, which is used in the calculation of the baseline scenario. Continuing the linear extrapolation through 2035 yields an estimated WTP for acceleration of $650 per 1-second reduction. A number of explanations can be imagined for continual growth in WTP for acceleration. It is possible that such an increase is driven by income growth; that as car purchasers have more money to spend, they are more willing to spend some of it on attributes like acceleration that make their vehicle more fun to drive. Alternatively, it is possible that consumers want to have a vehicle that performs better than other vehicles on the road, creating a reinforcing loop in which new vehicles must become ever more powerful just to stay ahead of the pack. However, determining the causes of increasing WTP for performance is beyond the scope of this work. Suffice it to say that a trend of increasing WTP for acceleration improvements seems at least plausible. However, extrapolating willingness to pay so far into the future is highly speculative, especially when based on a relatively short historic period. For this reason, the sensitivity of the modeled results to input assumptions is explored in the next section.

4.2   Baseline Scenario Results

The technology allocation model was used to project the revenue-maximizing allocation of technologies to performance and fuel consumption in 2020 and 2035 under a business-as-usual scenario. In this scenario, it was assumed that gasoline prices remained constant at $1.70 per gallon into the future, that consumers' WTP for fuel consumption reductions also remained constant at $430 for each 1l/100km reduction, and that WTP for acceleration continued to increase, as discussed in the preceding section. The use of this baseline scenario does not imply an expectation that gasoline prices will return to $1.70 per gallon. Rather, it is meant to denote what expectations would be if gasoline prices had not spiked beginning in 2004 and if Corporate Average Fuel Economy standards had not been increased. Thus, it

provides a useful starting point from which to evaluate the effects of changes in fuel price and policies affecting performance and fuel consumption. The results of this scenario are summarized in Table 4-1.

Table 4-1: Optimal (revenue-maximizing) technology allocation projections for baseline scenario in 2020 and 2035.

	2005	*2020*	*2035*
WTP for Acceleration ($/second)		*$570*	*$650*
Fuel Consumption (l/100km)	8.0	7.8	7.6
0-60 mph Time (seconds)	8.6	6.9	5.9
ERFC (since 2005)		8%	11%
Value Increase (Fuel Consumption)	-	$70	$150
Value Increase (Acceleration)	-	$980	$1,810
Value Increase (Total)	-	$1,050	$1,960

Under the baseline conditions, the emphasis on reducing fuel consumption would be expected to remain very low through 2035, as consumers continue to be more willing to pay for improvements in acceleration than for reductions in fuel consumption. Although the fuel consumption of the average new car could be reduced from 8.0 l/100km to 6.0 l/100km by 2020 while maintaining the same performance level as in 2005, the optimal outcome from the manufacturers' perspective is for fuel consumption to be reduced by only a small fraction of this amount, while the average 0-60 mph time is reduced by 1.7 seconds, or 20%. The low emphasis on reducing fuel consumption is consistent with historic trends, which have seen most technology directed to improvements in acceleration, and ERFC values generally between 0 and 20%. (see Section 1.2)

The increase in value to consumers due to improvements in acceleration and fuel consumption is generally consistent with the estimated retail price increase associated with the introduction of new technologies. In 2020, it is estimated that the average consumer would be willing to pay a total of $1,050 more for the

improvements in acceleration and fuel consumption enabled by the introduction of new technology. By 2035, this amount would increase to $1,960. For comparison, Bandivadekar et al. estimated a retail price increase of $2,000 due to the introduction of advanced technologies through 2035. (Bandivadekar et al., 2008) The fact that consumers' willingness to pay matches the estimated retail price provides additional confidence in the soundness of the WTP values used here.

4.3   Sensitivity of Model to Assumptions

The sensitivity of the modeled results to underlying assumptions was explored by varying the WTP for acceleration and fuel consumption by 20% above and below their baseline values.

The optimal allocation of technologies as predicted by the model is quite sensitive to the assumed WTP for acceleration. The sensitivity was investigated by varying the WTP between $450 and $680 per second in 2020. A value of $450 per second (20% below baseline) is equal to the estimated WTP in 1999, and so seems to represent a reasonable lower bound on WTP for acceleration in 2020. The sensitivity results are summarized in Table 4-2. If WTP for acceleration is 20% lower than in the baseline case, the optimal ERFC rises from 8% to 53%, while a WTP 20% greater than the baseline shifts ERFC down to -33%.

The negative emphasis on reducing fuel consumption found in the high-WTP case may seem impossible, or at least counterintuitive, and demands explanation. It is necessary to recall the definition of ERFC (Equation 1-1), which is based on the reduction in fuel consumption. In the case of high willingness to pay for acceleration, the revenue-maximizing outcome would be to dedicate not only all new technology toward improving acceleration, but also to accept even worse fuel consumption than in 2005, in order to obtain even deeper reductions in acceleration times. Because of the increase in fuel consumption in this case, the increase in value of fuel consumption is negative, as consumers would expect "compensation" in

exchange for accepting worse higher fuel consumption. This compensation, of course, comes in the form of further reductions in the 0-60 mph time.

Table 4-2: Sensitivity of optimal (revenue-maximizing) technology allocations to WTP for acceleration, with WTP for fuel consumption held constant at $430 per (1l/100km).

	2020		
WTP for Acceleration *$/second*	*$450* *(-20%)*	*$570* *(base)*	*$680* *(+20%)*
Fuel Consumption (l/100km)	6.9	**7.8**	8.6
0-60 mph Time (seconds)	7.7	**6.9**	6.4
ERFC (since 2005)	53%	**8%**	-33%
Value Increase (Fuel Consumption)	$450	**$70**	-$280
Value Increase (Acceleration)	$450	**$980**	$1,560
Value Increase (Total)	$900	**$1,050**	$1,280

The WTP for fuel consumption improvements was varied between $350 and $520 for each 1l/100km reduction, and the results of this sensitivity analysis are shown in Table 4-3. The sensitivity of predicted ERFC to WTP for fuel consumption is similar, but opposite in sign, to the sensitivity to WTP for acceleration. If WTP for fuel consumption were 20% higher, ERFC would by 46% instead of 8%. On the other hand, if WTP for fuel consumption were 20% lower, the optimal ERFC would be -43%.

An interesting question here is why the total consumer value (shown in the last rows in Table 4-2 and Table 4-3) is sensitive to the WTP for acceleration but insensitive to the WTP for fuel consumption, even when ERFC is sensitive to both. This happens because the change is total value (the last row) is driven largely by the value increase due to performance (the second-to-last row), since the biggest changes between 2005 and 2020 are in acceleration times. As a result, a modest change in the WTP for acceleration has significant impact on total value of

acceleration improvements. Since changes in fuel consumption are relatively small in all cases, changes in the WTP for fuel consumption have a smaller effect on the overall value to consumers.

Table 4-3: Sensitivity of optimal technology allocations to WTP for fuel consumption, with WTP for acceleration held constant at $570/second.

	2020		
WTP for Fuel Consumption $ per (1l/100km) reduction	$350 (-20%)	$430 (base)	$520 (+20%)
Fuel Consumption (l/100km)	8.8	**7.8**	7.1
0-60 mph Time (seconds)	6.2	**6.9**	7.5
ERFC	-43%	**8%**	46%
Value Increase (Fuel Consumption)	-$290	**$70**	$460
Value Increase (Acceleration)	$1,370	**$980**	$640
Value Increase (Total)	$1,080	**$1,050**	$1,100

It is also surprising that the total value increase is greater when the WTP for fuel consumption is lower. The reason for this is that in the low-WTP case, the optimal emphasis on reducing fuel consumption is negative and fuel consumption is higher in 2020 than in 2005. As a result, the value due to the change in fuel consumption is negative, since fuel consumption has become worse. However, the lower WTP for fuel consumption also means that the magnitude of the penalty for this inferior fuel consumption becomes smaller. As a result, the gain in value due to faster acceleration more than offsets the loss in value due to higher fuel consumption.

Table 4-4 examines the sensitivity of the model results to simultaneous and identical changes in WTP for fuel consumption and acceleration. If both WTP values are increased or decreased by the same amount, the optimal allocation of technologies does not change, and ERFC remains at 8%. This is because the optimal allocation of technologies depends on the *relative* values of WTP for acceleration

and WTP for fuel consumption improvements, as discussed earlier in this chapter, and as represented mathematically in Equation 3-6.

Table 4-4: Sensitivity of optimal ERFC to WTP for both acceleration and fuel consumption in 2020.

WTP for Fuel Consumption ($ per 1l/100km reduction)	WTP for Acceleration ($/second)		
	$450 (-20%)	$570 (base)	$680 (+20%)
$350 (-20%)	8%	-43%	-89%
$430 (base)	54%	8%	-33%
$520 (+20%)	87%	46%	8%

The cases shown in the upper right and lower left corners of Table 4-4 yield strikingly different results than the baseline assumptions. Such different results are not unexpected given the changes in assumptions, but such large variability may seem to call into question the very usefulness of the model. However, while there is uncertainty in the actual values of WTP for both acceleration and fuel consumption, we can return here to the historical trend in the performance-fuel consumption tradeoff, discussed in Section 4.1. The historic ratio of WTP for fuel consumption and performance, illustrated in Figure 4-2, helps to bound the range of plausible combinations of WTP values. Scenarios in which WTP for acceleration is 20% above the baseline assumption and WTP for fuel consumption is 20% below, or vice versa, would be inconsistent with the historic values and trends seen in Figure 4-2.

4.4 Conclusions

In this chapter, the historic tradeoff between acceleration and fuel consumption was examined for the period of stable gasoline prices from 1991-2003. The historic trend suggests a steady increase in consumers' WTP for acceleration relative to their WTP for fuel consumption. The WTP values implied by the historic trends are

consistent with the literature and price data presented in Chapter 3. Under a baseline scenario with fuel prices constant at pre-2004 levels and no policy intervention, the technology allocation model predicts that emphasis on reducing fuel consumption would remain at approximately 10% through 2035. The model's calculated increase in consumer value of improved acceleration and fuel consumption is consistent with estimates of the retail price increase corresponding to the introduction of advanced technologies.

The optimal ERFC calculated by the model is sensitive to consumers' WTP for performance and fuel consumption. As a result, caution is needed when interpreting model results, since small differences in WTP can produce significantly different estimates of optimal performance and fuel consumption. However, it is important to note that the optimal ERFC depends only on the relative, not the absolute, WTP for acceleration and fuel consumption. Moreover, the historic pattern of technology allocation to performance and fuel consumption tends to support the projections of relative WTP for these two attributes, despite the lingering uncertainty over their precise magnitude.

5 Evaluation of Policies to Influence Performance and Fuel Consumption

5.1 Fuel Price

Higher fuel taxes are one policy option for reducing automotive fuel consumption, and are capable of eliciting a full range of responses from manufacturers and consumers. Higher fuel taxes would motivate consumers to choose vehicles that consume less fuel, and manufacturers to introduce new efficiency-enhancing technologies while placing greater emphasis on reducing fuel consumption. (Evans, 2008) In this section, the effect of a sustained change in gasoline prices on the optimal balance between acceleration and fuel consumption is evaluated for U.S. cars, using the technology allocation model described in the preceding chapters. The modeled fuel consumption and ERFC levels are compared with observed ERFC in Europe, and with fuel consumption calculated based on published values of elasticity of fuel consumption with respect to fuel price. Finally, the effect of higher gasoline prices on consumers' overall value of technology is examined.

5.1.1 Modeled Response to Fuel Price Changes

The long-term, optimal allocation of technologies to acceleration and fuel consumption improvements was modeled by assuming that consumers' willingness to pay (WTP) for fuel consumption reductions is directly proportional to the price of fuel, as explained in Section 3.3.3. For example, a permanent, 50% increase in the average gasoline price from $1.70 per gallon to $2.55 per gallon would be assumed to increase consumers WTP for fuel consumption improvements from $430 to $650 per (1l/100km) reduction, over the long term.

The model results indicate that the optimal balance between performance and fuel consumption is quite sensitive to fuel price. Figure 5-1 shows the optimal emphasis on reducing fuel consumption for the average U.S. car between 2005 and 2020, as a function of gasoline price. It bears repeating that this optimal value represents the

allocation of technologies that would maximize revenues for manufacturers in 2020, based on consumers' willingness to pay for acceleration and fuel consumption improvements. The solid curve, corresponding to the baseline scenario, passes through the point ($1.70, 8%). This represents the baseline, constant fuel price scenario presented in Chapter 4. Also shown are the dashed curves representing the sensitivity cases of higher and lower WTP for acceleration. The results suggest that a sustained increase in the price of gasoline to $2.75 per gallon would make an ERFC of 100% optimal through 2020. In the sensitivity case for high WTP for acceleration, a fuel price of $3.30 per gallon is needed to motivate 100% ERFC, because the higher WTP for acceleration tends to increase the opportunity cost of foregone performance improvements.
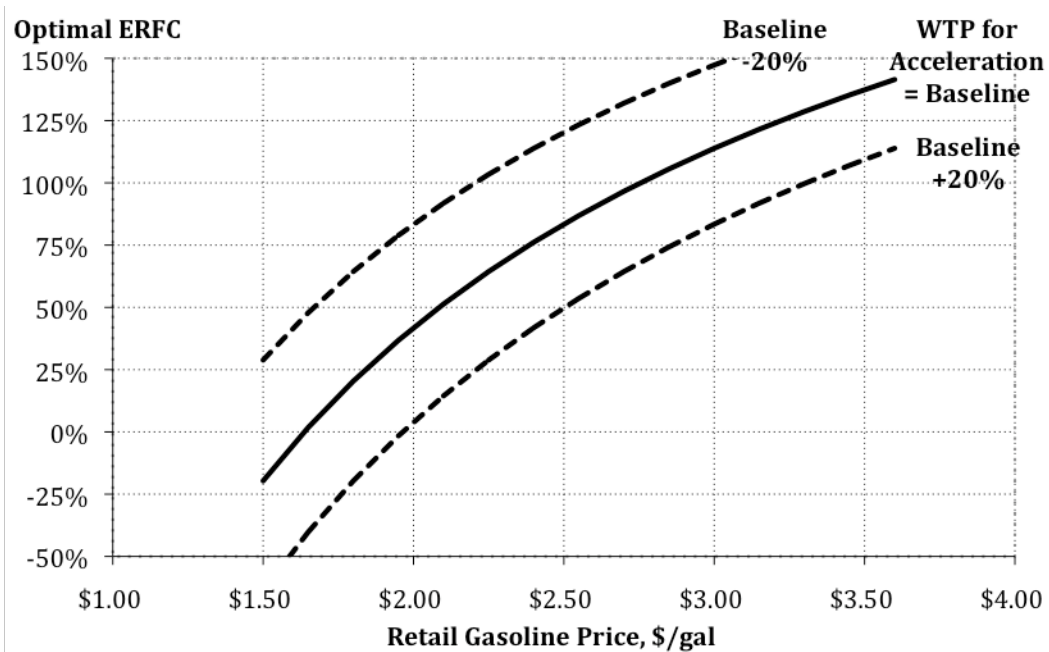
Figure 5-1: Optimal values of emphasis on reducing fuel consumption (ERFC) between 2005 and 2020, as a function of long-term fuel price. ERFC is measured relative to initial fuel consumption and acceleration in 2005. Solid curve represents baseline scenario (WTP for acceleration = $570/second). Dotted curves represent sensitivity cases (WTP for acceleration 20% higher and 20% lower than baseline).

As fuel price increases, the optimal ERFC becomes less sensitive to fuel price. This follows from the nature of the technical tradeoff between acceleration and fuel consumption. As shown in , the curvature of the acceleration-fuel consumption tradeoff curve dictates that as fuel consumption decreases, further reductions in fuel

consumption demand progressively greater marginal sacrifices in acceleration. As a result, the marginal "opportunity cost" of foregone acceleration increases as fuel consumption decreases, and so larger marginal increases in fuel price are needed to drive continued increases in ERFC.

5.1.2   Comparison of Results with European ERFC

Despite higher gasoline prices in Europe, the emphasis on reducing fuel consumption there has not been as high as the results predicted by the technology allocation model and presented in the preceding section. Gasoline prices in major European countries averaged between $4.00 and $5.00 per gallon (2007 U.S. dollars per U.S. gallon) between 1990 and 2003, and increased to $6.00-$6.50 per gallon by 2006. (Energy Information Administration,) During this period, emphasis on reducing fuel consumption was found to be in the range of 50%-80% for gasoline-fueled vehicles. (Cheah et al., 2008) This indicates that the results of the technology allocation model, which suggest that 100% ERFC would result from a sustained gasoline price of just $2.75 per gallon, demand closer scrutiny.

There are two principal reasons that the optimal ERFC calculated for U.S. cars through 2020 is higher than the ERFC historically observed in Europe at comparable fuel prices. First, vehicles are driven fewer kilometers per year in Europe than in the U.S., leading to a lower WTP for fuel consumption at a given fuel price. Second, the calculation of ERFC is dependent upon the initial levels of acceleration and fuel consumption, which are different in Europe and the U.S.

New car buyers in Europe would be expected to have a lower WTP for fuel consumption that U.S. consumers at the same fuel price, because new cars in Europe are driven significantly less in their first few years on the road than those in the U.S. Between 1995 and 2006, the average new gasoline-fueled vehicle in four major European countries was driven between 15,000 and 20,000 km annually in its first three years on the road. (Bodek & Heywood, 2008; Bodek, 2008) This is approximately 20%-40% less than the average vehicle kilometers traveled (VKT) by

a new car in the U.S. over its first 3 years (see Section 3.3.3). The lower VKT can be expected to reduce consumers WTP for fuel consumption reductions, partially offsetting the effects of Europe's higher fuel prices. Table 5-1 summarizes the average VKT over the first three years, average gasoline prices, and corresponding WTP for fuel consumption as calculated by Equation 3-10, for four major European countries.

Table 5-1: Average gasoline prices and annual VKT for new cars in four major European countries, 1995-2003. WTP for fuel consumption is expressed on the basis of U.S. unadjusted fuel consumption measurements, assuming WTP is equivalent to a 3-year payback. Average VKT are from (Bodek & Heywood, 2008; Bodek, 2008). Gasoline prices are reported in nominal U.S. dollars by (Energy Information Administration,) and are adjusted to 2007 dollars using consumer price index data for the respective countries. (Centro diffusione dati, 2009; Institut national de la statistique et des études économiques, 2009; Office for National Statistics, 2009; Statistisches Bundesamt Deutschland, 2009)

	Time Period	Average VKT per year First 3 years	Average Gasoline Price $ / US Gallon	WTP for Fuel Consumption $ per (l/100km)
France	1995-2003	15,500	$4.50	$740
Germany	1995-2003	15,800	$4.20	$700
UK	1995-2001	19,800	$4.50	$940
Italy	1995-2001	14,600	$4.60	$710

Europeans' estimated willingness to pay for fuel consumption reductions at gasoline prices of $4.00-$5.00 per gallon is comparable to that of Americans at prices less than $3.00 per gallon. With the exception of the UK, the WTP for fuel consumption reductions is estimated to be between $700 and $740 per (1l/100km) in the countries listed. If the WTP increased proportionately with gasoline price, without the moderating effects of lower VKT, WTP in the European countries would actually be closer to $1,100 per (1l/100km). Put another way, the range of $700-$740 per (1l/100km) is equivalent to the WTP for fuel consumption expected for U.S. car buyers at a gasoline price of $2.70-$2.90 per gallon and U.S. VKT levels.

The second reason that the model finds optimal ERFC values for U.S. cars higher than those found in Europe for the same fuel price is that European cars already have lower fuel consumption than U.S. cars, which reduces the calculated ERFC even if the final fuel consumption is the same. This is best understood by referring to Figure 5-2 and Figure 5-3, and is explained in the following paragraphs.

Table 5-2 summarizes the average fuel consumption of news cars sold in four major European countries in 1995, as measured on the New European Drive Cycle (NEDC). Because of differences in the details of the test cycle, the NEDC generally returns higher fuel consumption figures than the U.S. CAFE test cycle (i.e. the U.S. unadjusted laboratory fuel consumption figures used elsewhere in this work). The NEDC fuel consumption figures were converted into U.S. equivalent fuel consumption by multiplying by 1.13. (An & Sauer, 2004)

Table 5-2: Average fuel consumption of new cars in major European countries in 1995, and observed emphasis on reducing fuel consumption post-1995. Fuel consumption rates expressed on the New European Drive Cycle (NEDC) were converted to U.S. CAFE-cycle equivalent by dividing by 1.13. (An & Sauer, 2004; European Commission, 2007)

	Time Period	1995 NEDC fuel consumption (l/100km)	1995 CAFE fuel consumption (l/100km)	ERFC
France	1995-2003	7.5	6.6	54%
Germany	1995-2003	8.2	7.3	51%
UK	1995-2001	8.1	7.2	48%
Italy	1995-2001	7.5	6.6	82%

Figure 5-2 shows the average fuel consumption and 0-60 mph times for U.S. cars in 2005 (point 'A'), and an optimal combination of acceleration and fuel consumption in 2020 (point 'B'). In this case point 'B' was calculated based on a WTP for fuel consumption of $720 per (1l/100km) reduction (consistent with values calculated for Germany, France and Italy between 1995 and 2003, as shown in Table 5-1), and a WTP for acceleration of $570 per second (the baseline assumption used in this work). Under these assumptions, the optimal fuel consumption in 2020 is 6.0

l/100km and the optimal 0-60 mph time is 8.7 seconds (point 'B'). Point 'C' marks the average fuel consumption achievable in 2020 if acceleration were the same as in 2005. ERFC is therefore calculated as 104%, according to Equation 5-1:

Equation 5-1

$$ERFC = \frac{FC_A - FC_B}{FC_A - FC_C}$$

If fuel consumption starts from a lower point, then calculated ERFC will be different, even if the final fuel consumption is the same. Figure 5-3 illustrates a hypothetical situation in which U.S. cars have significantly lower fuel consumption in 2005. The point 'D' corresponds to fuel consumption of 6.9 l/100km, which was typical of European cars in 1995 (Table 5-2). The same assumptions about WTP for fuel consumption and acceleration are used as for Figure 5-2, and the same optimal combination of acceleration and fuel consumption (point 'B') is found for the year 2020. However, ERFC is now calculated according to Equation 5-2, and found to be 57%. Although the model predicts the same optimal fuel consumption and acceleration values, the calculated ERFC is different because the initial fuel consumption and acceleration were different.

Equation 5-2

$$ERFC = \frac{FC_D - FC_B}{FC_D - FC_E}$$

Figure 5-2: Optimal Acceleration, fuel consumption, and ERFC for U.S. cars in 2020, assuming WTP for fuel consumption = $720 per (1l/100km), WTP for acceleration = $570 per second, starting from 8.0 l/100km in 2005.
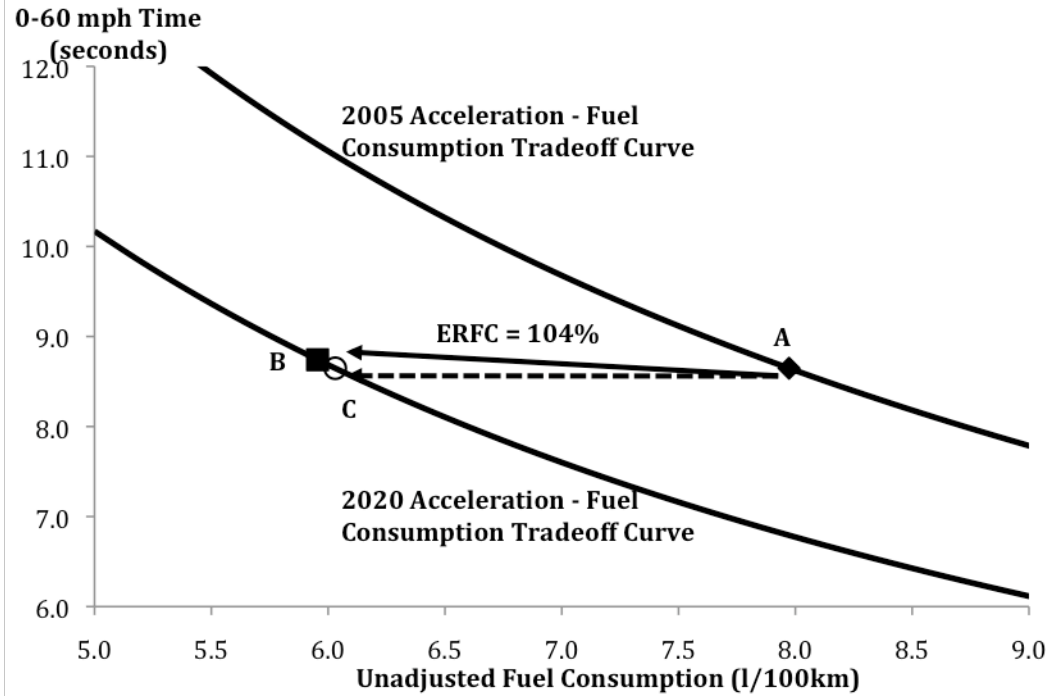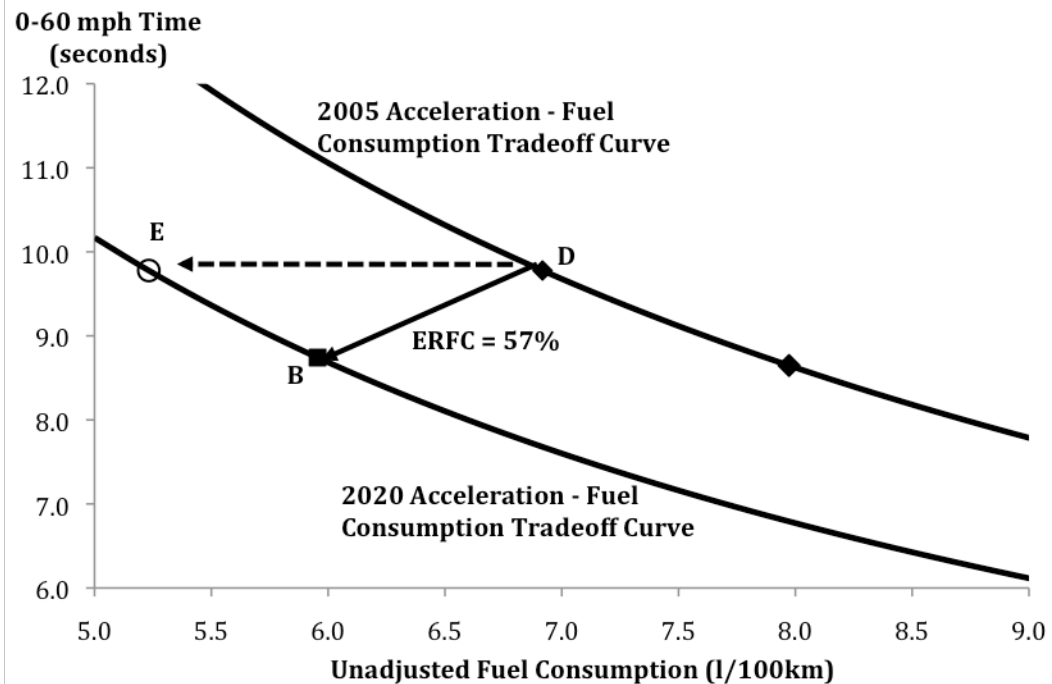

Figure 5-3: Optimal acceleration, fuel consumption, and ERFC for U.S. cars in 2020, assuming WTP for fuel consumption = $720 per (1l/100km), WTP for acceleration = $570 per second, starting from 6.9 l/100km in 2005.

5.1.3   Comparison of Results with Elasticity-based Calculations

The response of average vehicle fuel consumption to a change in fuel price is often characterized using an elasticity – that is, the fractional change in fuel consumption resulting from a certain fractional change in fuel price. The response to an increase in fuel price can be expected to include a shift toward greater emphasis on reducing fuel consumption, more rapid adoption of efficiency-enhancing technologies, and a shift toward classes of vehicles that consume less fuel (i.e. from light trucks to cars, from larger cars to smaller cars). (Evans, 2008) Calculations based on published estimates of elasticity therefore provide a useful comparison for the modeled effect of fuel price changes on ERFC.

The technology allocation model predicts a stronger response to changes in fuel price than that suggested by elasticity calculations using typical values of elasticity. Evans (2008) reviewed a range of published estimates of elasticity of fuel consumption with respect to fuel price and settled on a long-run value of -0.33, while evaluating a range from -0.17 to -0.50. Figure 5-4 compares the optimal fuel consumption values calculated by the model with the fuel consumption as calculated based on an elasticity value of -0.33. The model's response is actually consistent with an elasticity value of -0.53, close to the "more responsive" end of the range investigated by Evans. It should also be noted that the elasticity-based curve in Figure 5-4 represents the overall response of new vehicle fuel consumption, due to shifts in ERFC, technology adoption, and vehicle size. Therefore, it would be expected that the shift in ERFC accounts for only part of the response predicted by the elasticity calculation.
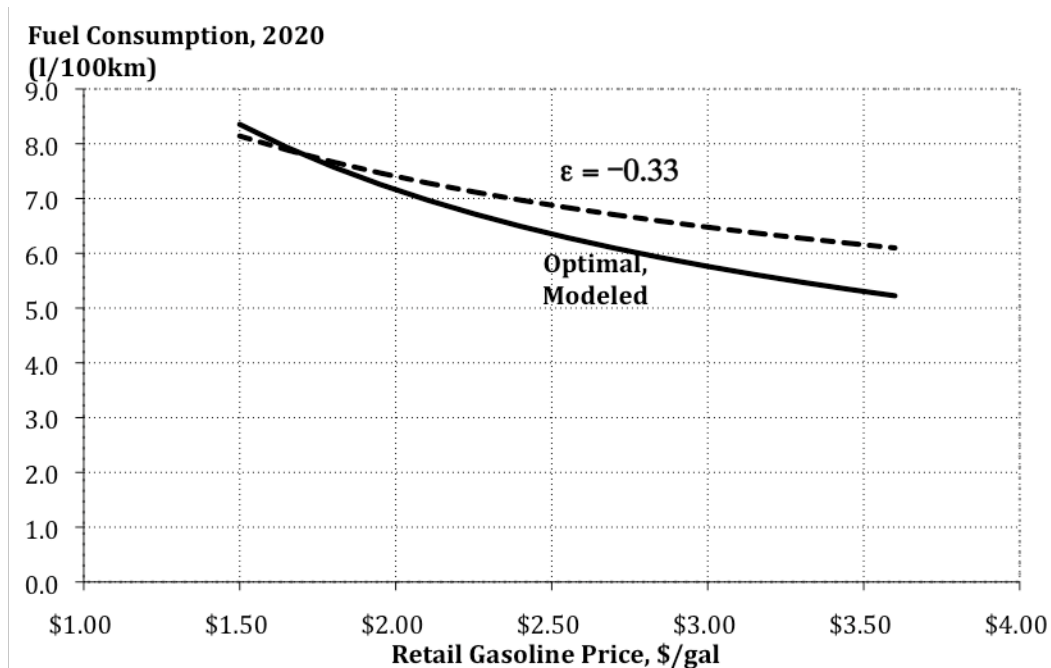
Figure 5-4: Comparison of optimal fuel consumption for U.S. cars in 2020 as calculated by technology allocation model with fuel consumption calculated by assuming elasticity of fuel consumption with respect to price = -0.33.

There are several explanations that may account for the modeled ERFC being higher than the aggregate response based on published elasticities. First, it is possible that consumers' willingness to pay for fuel consumption does not increase proportionally with fuel price. If WTP for fuel consumption increased by less than the increase in fuel price, then the effect of a change in fuel price on fuel consumption (and ERFC) would be reduced, and the modeled response curves in Figure 5-1 and Figure 5-4 would be less steep. Second, it is possible that consumers' WTP for acceleration is not constant, meaning that consumers' total value from acceleration is not linear with respect to the change in acceleration. If reductions in 0-60 mph time produced diminishing returns in consumer value, it would be expected that the marginal cost of foregone acceleration would increase as 0-60 mph times decreased. This would mean that the cost of de-emphasizing performance would increase, which would lead to a smaller fuel consumption response to changes in fuel price. Finally, it is possible that the performance-fuel consumption tradeoff curves used in this work are inconsistent with the historic technical tradeoffs that are embedded in any study of observed elasticity. This

would mean that the sensitivity of the model to changes in fuel price could be different than that which has taken place historically. This suggests that careful study of both historic and projected performance-fuel consumption tradeoffs are important to the reliability of results.

5.1.4 Effect of Fuel Price on Consumers' Value of Technology

Increasing fuel price increases consumers' WTP for fuel consumption improvements, but does not diminish their WTP for acceleration improvements. Figure 5-5 plots the increase in consumer value due to improvements in acceleration and fuel consumption (between 2005 and 2020) as a function of gasoline price. At a gasoline price of $1.70 per gallon (baseline scenario conditions), the total value increase is just over $1,000, assuming a WTP for acceleration of $570 per 1-second reduction in 0-60 mph time. This is chiefly due to reductions in acceleration time, as shown in Table 4-1 and the accompanying discussion. As fuel price rises, the optimal balance between acceleration and fuel consumption shifts in favor of lower fuel consumption (Figure 5-1). As greater emphasis is placed on reducing fuel consumption, the value to consumers of fuel consumption reductions increases while the value of acceleration improvements decreases. At fuel prices greater than $2.75 per gallon, the optimal ERFC is greater than 100%, meaning that the optimal 0-60 mph time in 2020 is greater than its 2005 level. This decrease in acceleration performance is reflected by the value of acceleration changes becoming negative. Similarly, at fuel prices less than $1.65, the optimal ERFC is less than zero, meaning that the optimal fuel consumption is worse in 2020 than in 2005. The value of fuel consumption changes thus becomes negative.
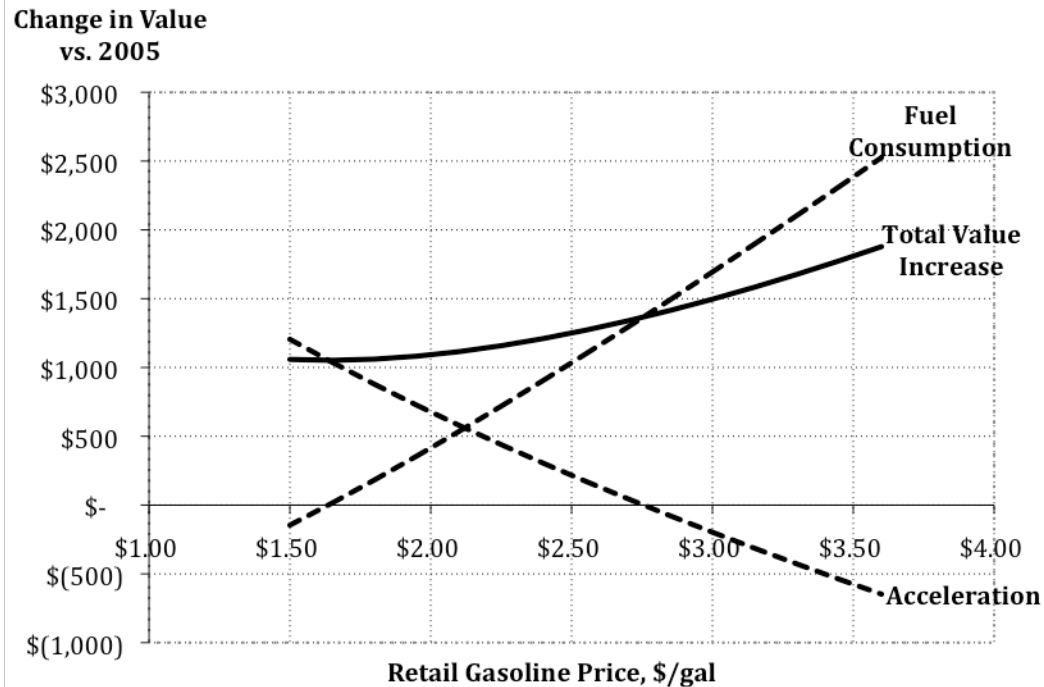
Figure 5-5: Increase in consumers' value of U.S. cars between 2005 and 2020 due to improvements in fuel consumption and acceleration, as a function of gasoline price. Assumes WTP for acceleration = $570 per second in 2020, and WTP for fuel consumption reductions is proportional to gasoline price (and equal to $430 per (1l/100km) when gasoline price = $1.70 per gallon). Value reflects the optimal allocation of technology to performance and fuel consumption for each gasoline price.

An important feature of Figure 5-5 is the upward-curving shape of the fuel consumption value curve. This may at first come as a surprise since fuel consumption is expected to change more slowly at higher fuel prices, as shown in Figure 5-4. However, there are two factors driving the value of fuel consumption at higher fuel prices. First, there is the direct effect of gasoline prices motivating greater reductions in fuel consumption. This is then compounded by the increasing WTP for this better fuel consumption, which itself increases proportionally with fuel price. This behavior is reflected by Equation 3-2 and Equation 3-10, which define the value increase due to fuel consumption reductions.

Perhaps the most interesting conclusion that can be drawn from Figure 5-5 is that higher gasoline prices not only motivate greater emphasis on reducing fuel consumption, but make auto manufacturers' technology considerably more valuable to consumers. Increasing the gasoline price to $3.00 would increase the value that

consumers place on expected new efficiency-enhancing technologies by almost $500, or more than 40%, in 2020. First, by making the technology more valuable, higher fuel prices increase the economic incentive for automakers to develop and deploy more advanced technologies. Over the long term, this would be expected to increase the overall rate of technological improvement in the auto industry.

A second important insight is that higher fuel prices over the medium to long term may be beneficial to the auto industry. This is a counterintuitive result, given the popular view that high gasoline prices have exacerbated the recent problems faced by the auto industry (particularly the Detroit companies). However, the key distinction here is between the short-term effects of fuel prices and the medium- to long-term effects. In the short term, manufacturers can respond to shifts in fuel price mainly by adjusting prices and the mix of their existing product line. This deviation from their existing product plan can be costly. In the medium term, however, manufacturers can re-optimize their allocation of technologies to place greater emphasis on reducing fuel consumption, and in the long term they can ramp up their deployment of technologies. (Klier & Linn, 2008) This observation can also be viewed in an economic sense, considering efficiency technologies and fuels as substitutable. As the price of fuel rises, consumers can purchase more efficiency technologies in order to be able to meet their mobility demands with less fuel. At the same time, higher prices of fuel drive higher prices for the substitute: advanced technology.[11]

The above observations may help to explain why the auto industry and its supporters are so enthusiastic about using gasoline taxes to drive improvements in

[11] An additional effect of higher fuel prices is a reduction in VKT (Evans, 2008). Lower annual VKT would be expected to extend the lifetime of vehicles, and therefore could have the effect of reducing sales volume, which would not be good for auto manufacturers. If an increase in gasoline price from $1.70 to $3.00 per gallon (a 76% increase) would reduce fuel consumption by 26% (Figure 5-4), then the fuel cost per kilometer would increase by 30%. Evans assumed an elasticity of VKT with respect to the fuel cost per kilometer of -0.1, which suggests a decrease in VKT of less than 3% for new vehicles. If VKT for new vehicles decreases by less than 3%, then the reduction in sales should be commensurately small as well.

fuel consumption. (Garthwaite, 2009; Lopez, 2009; Murphy, 2008) This analysis shows that gasoline taxes are far from a neutral policy from the perspective of automakers. To the contrary, increasing the price of fuel increases the value of one of the auto industry's key assets and capabilities: the development and deployment of advanced technology.

5.2 Incentives to Influence ERFC

Incentives or disincentives linked to the fuel consumption or performance attributes of a vehicle provide an alternative means of influencing manufacturers' decisions on the allocation of technologies to these attributes. In this section, the incorporation of incentive systems into the technology allocation model is described, and the effects of different incentive systems on the performance-fuel consumption tradeoff are evaluated.

5.2.1 Modeling of Incentives

In this section, the incorporation of a fuel consumption incentive into the technology allocation model is described. The logic and equations behind the incorporation of a performance-focused incentive system are similar, but are not provided here. Equation 5-3 shows how an incentive amount would be calculated for a linear (constant-rate) fuel consumption incentive. I_{FC} represents the incentive amount, with positive values of I_{FC} corresponding to a reward being paid. The incentive is linear with respect to fuel consumption, with rate r_{FC}, and FC^P denotes the pivot point fuel consumption level.

Equation 5-3

$$I_{FC} = r_{FC} \cdot (FC^P - FC_y)$$

The incentive amount can be added to the inherent value that consumers place on the improvements in the vehicle, as calculated according to Equation 3-2. In this way an incentive-adjusted value to consumers can be calculated, as shown by Equation 5-4.

Equation 5-4

$$V_{FC} = v_{FC} \cdot (FC_0 - FC_y) + V_{FC,0} + r_{FC} \cdot (FC^P - FC_y)$$

By using the expression in Equation 5-4 and substituting into Equation 3-1, it is possible to solve for the optimal fuel consumption level, as was done in Section 3.2.3. In this way, it can be shown that the optimal fuel consumption under an incentive program is given by the following equation, in which p and q are as defined in Chapter 3:

Equation 5-5

$$FC_{Optimal} = \left(-\frac{v_{FC} + r_{FC}}{v_A \cdot p \cdot q} \right)^{\frac{1}{q-1}}$$

Equation 5-5 reveals an important property of a linear incentive system: the optimal allocation of technologies to performance and fuel consumption depends on the incentive rate, but not on the pivot point. This is because the optimal allocation of technologies depends on the derivative of the incentive amount with respect to the attribute of interest. For linear incentive systems, this is equal to the incentive rate. The implication of this is that penalty-based, reward-based, and mixed incentive system should all be equally effective for influencing ERFC; all that matters is the incentive rate. Greene et al. have confirmed that for a system in which a constant incentive rate is applied to all vehicles, the selection of the pivot point does not affect the resulting fuel economy level. (Greene et al., 2005)

The incentive pivot point does have important consequences. First, as shown in Equation 5-3, the incentive amount for a given vehicle is proportional to the difference between the pivot point and the vehicle's fuel consumption. The higher the pivot point is, the larger is the reward (or smaller the penalty) on each vehicle. Systems that emphasize rewards over penalties, by having pivot points above the average fuel consumption, will effectively subsidize industry by paying out more than they collect. On the other hand, penalty-focused incentive programs, with low

pivot points, would effectively tax the automotive market by collecting more than they pay out. Revenue-neutral systems would neither tax nor subsidize industry.

A final important point is that in a revenue-neutral system with a constant feebate rate, the pivot point must be equal to the average fuel consumption, by definition. (If it did not, the system could not be revenue-neutral.) If the pivot point is equal to the average fuel consumption, then the average incentive amount is zero, and so the incentive adds no value for the average consumer. This is apparent from Equation 5-4. Put another way, under a revenue-neutral incentive system, each vehicle that benefits from a reward must be balanced out by a vehicle that is charged a penalty. Therefore, the benefits to one consumer must be offset by losses from another consumer(s).[12]

5.2.2 Fuel Consumption Incentives

The effect of a fuel consumption incentive program on the average fuel consumption of new U.S. cars was modeled by adding the incentive rate to consumers' WTP for fuel consumption and solving for optimal fuel consumption according to Equation 5-5. The optimal ERFC values obtained are plotted as a function of incentive rate in Figure 5-6, for a constant gasoline price of $1.70. When the incentive rate is zero (the baseline scenario), the optimal ERFC is 8%, as discussed in the preceding chapter. The optimal ERFC increases rapidly with incentive rate, reaching 100% for an incentive rate of $275 per (1l/100km).

The incentive rate needed to motivate 100% ERFC for new U.S. cars through 2020 is considerably less than the incentive rate employed in the U.S. gas guzzler tax (approximately $730 per (1l/100km)), or the feebate system recently adopted in France (equivalent to approximately $650 per (1l/100km) on the U.S. CAFE cycle).

---

[12] In reality, if incentive rates or pivot points are set in advance, it is extremely unlikely that the fees collected will perfectly offset the rebates. Even in a system intended to be revenue-neutral, there will be too many uncertainties for policymakers to predict in advance the exact mix of vehicles that will be sold. However, it is assumed that over time, policymakers will be able to make reasonably accurate predictions, informed by past experience with the system.

The incentive rate needed to motivate 100% ERFC is in fact closer to the stringency of the CO_2-based tax policies in Germany and the U.K., assuming a three-year valuation of ownership taxes. (see Chapter 2 for an analysis of the stringencies of current fuel consumption and CO_2 policies in the U.S. and Europe) This suggests that the feebate rates currently in use should be more than adequate to motivate 100% ERFC. However, the U.S. gas guzzler tax applies only to cars with fuel consumption greater than 10.5 l/100km (i.e. fuel economy less than 22.5 mpg). (U.S. EPA, 2006) The French feebate system is based on a series of bins, so the effective marginal rate will vary from zero to very large, depending on a vehicle's fuel consumption relative to the bin boundary. Because neither system provides a uniform, constant-rate incentive, they do not affect all vehicles in the same way and will not deliver the most cost-effective reductions according to the equimarginal principle. (Field, 1994)
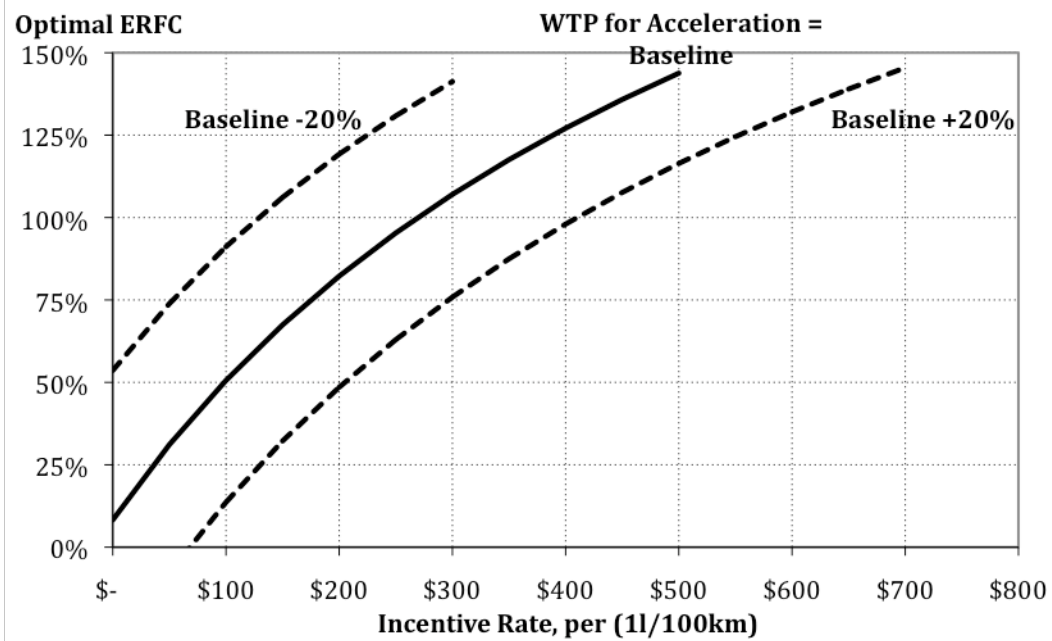
Figure 5-6: Optimal values of emphasis on reducing fuel consumption (ERFC) in 2020, as a function of fuel consumption incentive rate. ERFC is measured relative to initial fuel consumption and acceleration in 2005. Solid curve represents baseline scenario (WTP for acceleration = $570/second). Dotted curves represent sensitivity cases (WTP for acceleration 20% higher and 20% lower than baseline). Gasoline price is assumed to be constant at $1.70 per gallon, and consumers' WTP for fuel consumption is assumed to be constant at $430 per (1l/100km) in all cases.

Recently, preliminary data have indicated a shift in trends in the French car market since the bonus-malus system was introduced. In 2008, the average new car sold in France was reportedly 2 cm shorter than in the year prior, with a 3% reduction in weight and a 3.5% reduction in power. Also, the average price dropped by nearly €2,700. These shifts were attributed to the combination of the bonus-malus system and high fuel prices. (Navarro, 2009) More time and data will likely be needed to disentangle the effects of the bonus-malus system, high fuel prices, and a slowing economy on the car market. However, it is worth noting that these findings are not inconsistent with the results reported here.

Greene et al. evaluated the effect of feebate systems on new vehicle fuel economy at rates of $210 and $425 per (1l/100km), using a technology adoption framework. (Greene et al., 2005) Their key results are summarized in Table 5-3 and compared with the results predicted by the technology allocation model. Evans (2008) reviewed a number of other studies of feebates and found that they reported results generally similar to those of Greene et al.

The technology allocation model predicts a significantly larger fuel consumption response than was reported in Greene. This is likely due to the difference in modeling approaches. Whereas Greene et al. employ a technology adoption model, in which they hold constant all vehicle attributes other than fuel consumption and price, the technology allocation model takes a certain level of technology as given. In the scenario of a $425 per (1l/100km) incentive rate, the fuel consumption figures predicted by Greene et al. correspond to an increase of 25% in performance-size-fuel economy index over 10-15 years, and considerably less under the lower-rate scenario (assuming, as Greene et al. do, that size and performance remain constant). In comparison, the present work assumes an increase in PSFI of 32% over 15 years, regardless of the incentive rate.

Table 5-3: Comparison of modeled effects of fuel consumption incentives with results reported by Greene et al. (2005). Incentive rates have been converted to 2007 dollars. (Bureau of Labor Statistics, 2008)

	Greene et al. (2005)	*Technology Allocation Model*
Base Year Fuel Cons. (l/100km)	8.3	8.0
Future Fuel Cons. (l/100km) *No Policy*	8.3	7.8
Future Fuel Cons. (l/100km) (% reduction vs. No Policy) *Rate = $256 per (1l/100km)*	7.4 (11%)	6.1 (22%)
Future Fuel Cons. (l/100km) (% reduction vs. No Policy) *Rate = $512 per (1l/100km)*	6.7 (20%)	5.1 (34%)

5.2.3   Acceleration (Dis-)Incentives

An alternative way to influence the performance-fuel consumption tradeoff is to create disincentives for the production and sale of higher-performing vehicles. Rather than pulling technology toward fuel consumption improvements, these disincentives would push it away from improvements in acceleration. The effect of disincentives for acceleration on ERFC was evaluated by subtracting the incentive rate from consumers' WTP for acceleration. In this way, the optimal ERFC shown in Figure 5-7 was obtained as a function of the disincentive rate.[13] While performance incentives might not be linked directly to acceleration (as shown in Chapter 2, they may target engine size or engine power), acceleration does provide a useful basis of comparison for different performance-linked incentives currently in use. As discussed in Chapter 2, existing policies targeting engine displacement and power in

---

[13] The disincentive is defined such that a positive disincentive rate corresponds to a larger fee being charged (or a smaller reward offered) on vehicles that have lower 0-60 mph times.

several European countries would impose incentive rates much higher than those examined here and presented in Figure 5-7, ranging from $500 to $4,000 per marginal 1-second reduction in 0-60 mph time for the average new U.S. car.

If the goal of imposing an incentive program is purely to reduce fuel consumption, then targeting the incentive on moderating performance is an inferior approach to imposing a fuel consumption incentive. Incentives targeting fuel consumption directly would be expected to elicit all manner of responses that reduce fuel consumption, including increasing ERFC, ramping up technology adoption, and shifting toward smaller vehicles. On the other hand, a policy aimed at discouraging performance increases would only indirectly influence fuel consumption, and only through one of these responses (increasing ERFC).
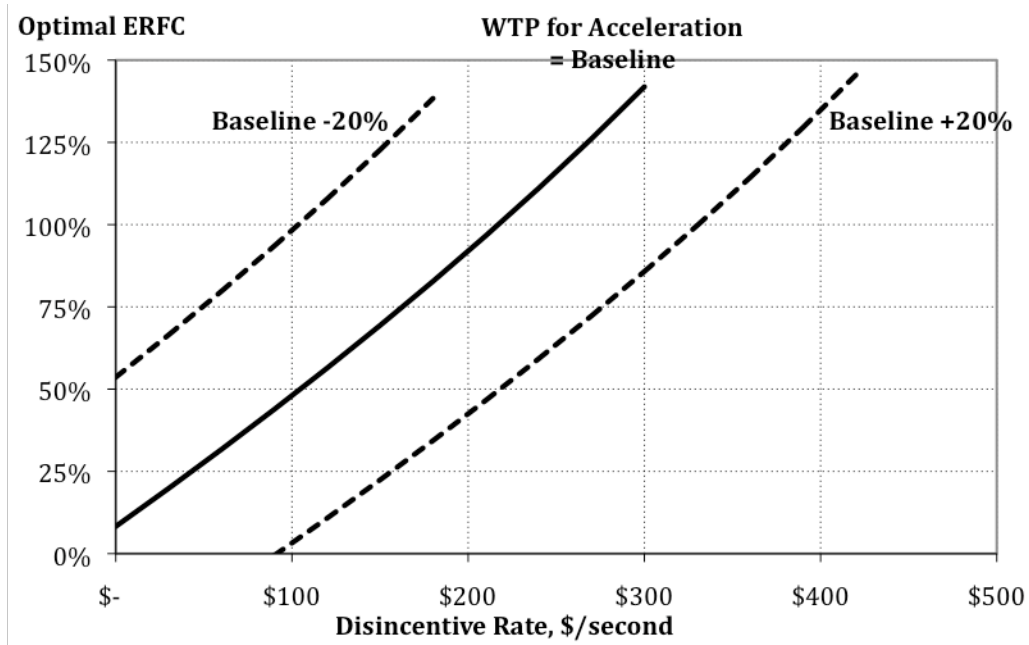
Figure 5-7: Optimal values of emphasis on reducing fuel consumption (ERFC) in 2020, as a function of acceleration disincentive rate. ERFC is measured relative to initial fuel consumption and acceleration in 2005. Solid curve represents baseline scenario (WTP for acceleration = $570/second). Dotted curves represent sensitivity cases (WTP for acceleration 20% higher and 20% lower than baseline). Gasoline price is assumed to be constant at $1.70 per gallon, and consumers' WTP for fuel consumption is assumed to be constant at $430 per (1l/100km) in all cases.

A further problem with performance disincentives is the practical feasibility of implementing them. Acceleration time is the performance metric used here, but it is

far from being the only metric available. It is more likely that that some performance-related attribute such as power or power/weight ratio would be made the target of the incentive program, as is done in many European countries (and discussed in Chapter 2). This would open the door to more problems, however. For example, if a displacement-based incentive program were developed, manufacturers might simply turn to turbocharging to increase vehicle performance while keeping engine size low. Or, if a horsepower-based incentive were adopted, manufacturers might switch to diesel engines, in order to obtain superior torque while reducing peak power. In neither case would the manufacturer have an incentive to emphasize lower fuel consumption in their new designs.

None of the preceding discussion is meant to imply that reducing vehicle performance is an inherently unworthy goal in its own right. Indeed, it is possible that there would be safety benefits from moderating the performance capabilities of future cars. If this were considered a policy priority, then policies addressing performance directly might be appropriate. However, if the goal of policymaking is to reduce fuel consumption, then this goal can be most effectively served by incentives focused more directly to fuel consumption.

5.3   Corporate Average Fuel Economy (CAFE) Standards

Corporate Average Fuel Economy (CAFE) standards can increase ERFC by mandating that the average fuel economy of the fleet of vehicles sold by each manufacturer meet at least a prescribed minimum (i.e. the standards prescribe maximum levels of average fuel consumption). Because CAFE standards do not increase the price of fuel, or impose an explicit price signal on fuel consumption, they do not affect the revenue-maximizing allocation of technology between performance and fuel consumption. Instead, they simply compel manufacturers to produce a fleet of vehicles with characteristics that deviate from the unregulated, revenue-maximizing characteristics. Therefore, one way to estimate the cost of a CAFE standard is to measure the difference between the maximized (optimal) value

of new vehicle attributes and their value of those attributes at the mandated conditions.

CAFE standards have been in place in the United States since the late 1970s, but were essentially unchanged until the Energy Independence and Security Act of 2007 (EISA 2007) was passed in December, 2007. (Energy Independence and Security Act of 2007, 2007; National Highway Traffic Safety Administration, 2004) EISA 2007 requires that the combined fleet of cars and light trucks sold in the United States achieve an average fuel consumption of not more than 6.7 l/100km by 2020, a reduction of approximately 30% from the 2005 level of 9.5 l/100km.

Preliminary evidence suggests that cars will be subject to a CAFE standard of 6.0 l/100km in 2020. In the preliminary rule for the years 2011-2015, the fuel consumption standard for cars averages about 19% less than that mandated for light trucks. If the car/truck sales split is assumed to be 50/50 in 2020,[14] then the maximum fuel consumption standards in 2020 would have to be 6.0 l/100km for cars and 7.4 l/100km for light trucks in order to meet the 6.7 l/100km overall average. As shown in Figure 3-5, an average fuel consumption rate of 6.0 l/100km corresponds to a 100% emphasis on reducing fuel consumption between 2005 and 2020.

Figure 5-8 shows the relationship between ERFC and consumers' value of vehicle attributes, assuming constant WTP for acceleration and fuel consumption, under baseline scenario assumptions. The solid curve represents the net increase in consumers' value of performance and fuel consumption between 2005 and 2020. It is equal to the sum of the two dashed curves, which represent the increases in value due to acceleration improvements and fuel consumption reductions, as shown in Equation 3-1. As ERFC increases, the value of the associated fuel consumption

---

[14] The fraction of cars in the new vehicle fleet fell from 84% in 1980 to 48% in 2004, the rebounded and held steady between 50% and 53% from 2005 to 2008. (U.S. EPA, 2008)

reduction increases proportionately. However, increased ERFC also means smaller reductions in acceleration times, so the value of acceleration declines as ERFC increases. An ERFC of zero indicates no improvement in fuel consumption over time, so the value of fuel consumption improvements is zero and the net value to consumers is equal to the value of acceleration improvements. On the other hand, an ERFC of 100% represents the case in which there is no change in acceleration, so the value of acceleration improvements is zero, and the net value increase is due entirely to the improvement in fuel consumption.
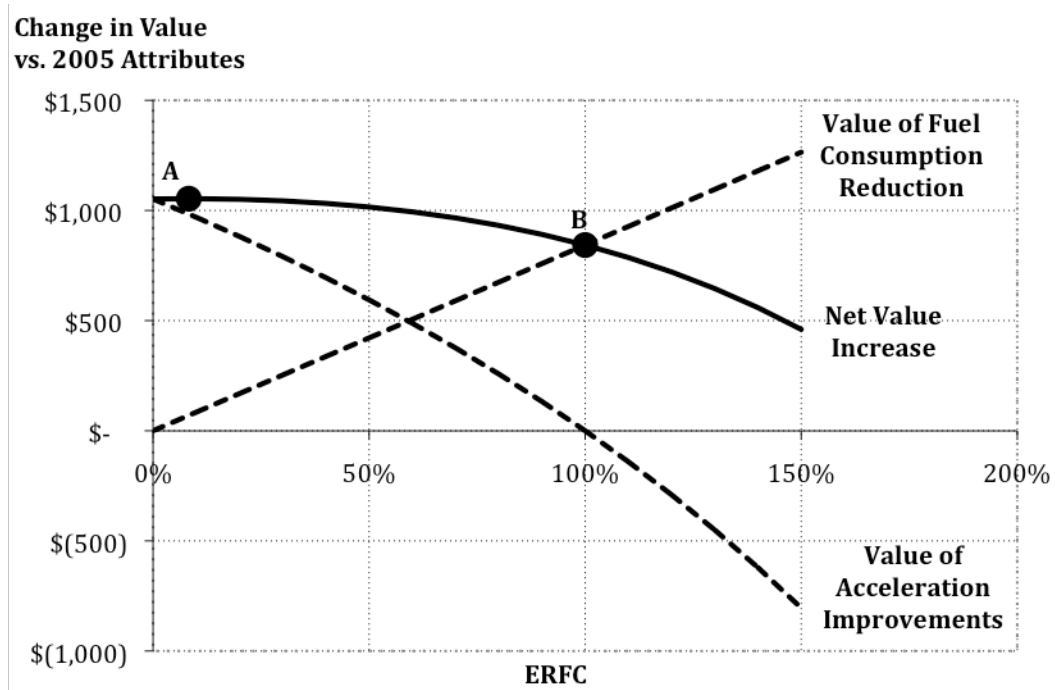
Figure 5-8: Consumers' value of fuel consumption and acceleration improvements as a function of ERFC. WTP for fuel consumption improvements is assumed to be constant at $430 per (1l/100km) reduction, and WTP for acceleration is assumed to be constant at $570 per 1-second reduction in 0-60 mph time.

Figure 5-8 suggests that if the CAFE standard were met entirely by shifting ERFC, the cost imposed by the standard would be on the order of $200 per car, when averaged across the entire fleet of new cars. Point 'A' marks the optimum ERFC under the baseline scenario conditions, for which the increase in consumers' combined value of acceleration and fuel consumption is maximized (ERFC = 8%, total value = $1,050). If the CAFE standard of 6.0 l/100km in 2020 were met entirely

by trading off performance (rather than through additional technology introductions or downsizing of vehicles), an ERFC of 100% would be needed between 2005 and 2020 (as discussed in the preceding paragraphs and shown by Figure 3-5). Consumers' value of performance and fuel consumption in this case would be represented by point 'B' in Figure 5-8 (100%, $840). Although consumers do value the fuel consumption reductions, the value of acceleration improvements declines more rapidly, leading to a reduction in net decrease in value to consumers. The value that consumers place on the reduction in fuel consumption at point 'B' is $840 under baseline assumptions, or roughly $200 less than the value they place on combined improvements in performance and fuel consumption at the optimum ERFC of 8%.

The estimated cost of just over $200 per car for meeting the CAFE standard of 6.0 l/100km (39 mpg) in 2020 is substantially less than many estimates that have been reported publicly. For example, General Motors' Vice Chairman, Bob Lutz, predicted in 2008 that GM would spend an average of $6,000 per vehicle to meet the 35 mpg combined car/truck standard. (Murphy, 2008) The consulting company Global Insight estimated the cumulative cost at $46 billion through 2015 for the top six companies in the U.S. market (equivalent to approximately $600 per vehicle, assuming 15 million vehicles sold per year over 5 years), and pegged the expected increase in sticker prices at 5-15% in 2020. (Greimel, 2008; Squatriglia, 2007) Based on the average base MSRP of $22,000 for new cars in 2008 (Ward's, 2007; Ward's, 2008; Ward's, 2009), a 5-15% increase would be approximately $1,100-$3,300. The National Highway Traffic Safety Administration, responsible for implementing CAFE standards, estimated a price increase of $650 per car just to meet its proposed standard of 6.8 l/100km (34.7 mpg) in 2015. (National Highway Traffic Safety Administration, 2008)

The large difference in cost estimates is due to the way in which technology decisions are modeled and the way in which costs are measured, which combine to significantly overstate the true costs of the regulations. All of the above estimates

rely on a "technology adoption" framework, in which vehicle size and performance are set exogenously and held constant while additional technologies are added in order to reduce fuel consumption.[15] The corresponding increase in retail prices is then reported as the cost of complying with the regulation. Although this is one way to define "cost," it overlooks the possibility of trading off performance for improvements in fuel consumption, with no change in the normal pattern of technology adoption. A more realistic assessment of the cost to manufacturers is obtained by measuring the difference between the revenues that can be realized in the absence of regulation, and the revenues that can be realized by employing the same suite of technologies (at the same manufacturing cost) in the presence of regulation. Because consumers do place some value on reductions in fuel consumption, manufacturers are able to recoup most of prospective revenues lost through foregone performance, especially for modest reallocations of technology from offsetting performance increases to reducing fuel consumption. Although CAFE standards do impose real costs on manufacturers, the true costs are substantially lower than those commonly reported.

5.4 Technology Development and Deployment Incentives

So far, the analysis and discussion in this chapter have focused on policies that would shift the allocation of efficiency-enhancing technologies in cars toward greater emphasis on reducing fuel consumption, while assuming that the overall rate of technological progress is fixed. A somewhat different approach to decreasing automotive fuel consumption is to implement policies intended to lower the costs and accelerate the deployment of more advanced technologies into the new vehicle

---

[15] In setting CAFE standards, NHTSA assumes certain costs and fuel-saving potential for each technology, and then adds technologies in order of cost-effectiveness until the marginal cost of adding new technologies matches the marginal benefit they deliver, from a societal standpoint. (National Highway Traffic Safety Administration, 2008) Global Insight concluded that to meet the CAFE standards, "Two-thirds of the U.S. fleet will have to change to direct injection. One-third of the total market will be diesel, and half of those will be diesel-electric hybrids. Everyone is pursuing a strategy of smaller engines with direct injection and turbochargers." (Squatriglia, 2007) GM's Lutz based his estimate of costs on an assumption of "maintaining the fleet mix basically as it stands today." (Murphy, 2008)

fleet. The effectiveness of such policies for reducing fuel consumption is wholly dependent upon the decisions made by manufacturers to apply the new technologies to lowering fuel consumption or to offsetting performance increases. In this section, the effectiveness of these policies is explored by using the technology allocation model to estimate the allocation of technologies to performance and fuel consumption, under different levels of future technological capability.

A variety of policies have been proposed or adopted with the goal of increasing the rate of development and deployment of efficiency-enhancing technologies, or stimulating the adoption of leap-ahead technologies. In the 1990s, the Partnership for a New Generation of Vehicles was intended to facilitate the development of technologies that could triple new vehicle fuel economy while meeting consumers' and government expectations of safety, criteria pollutant emissions, and price. (Sperling, 2002) The energy bill passed by the U.S. Congress in 2005 included provisions directing the Secretary of Energy to accelerate R&D efforts on batteries, power electronics, and other enabling technologies for hybrid vehicles (Sec. 711); establishing a grant program to support the manufacture of hybrid electric and diesel vehicles in the U.S. (Sec. 712); and establishing a consumer incentive program to encourage the purchase of hybrid, diesel, and fuel cell vehicles (Sec. 1341). (Energy Policy Act of 2005, 2005) The 2007 energy bill added loan guarantees for manufacturers of advanced components and for batteries, and direct loans for the retooling of manufacturing plants to produce "advanced technology vehicles." (Energy Independence and Security Act of 2007, 2007) Some of these programs and provisions have specifically linked eligibility for incentives to the production of vehicles that achieve lower fuel consumption, while others have simply focused on the development or deployment of efficiency-enhancing technologies (either evolutionary or revolutionary).

A successful policy for accelerating the adoption of more advanced technologies can be modeled in a general way by increasing the rate of growth in the performance-size-fuel economy index (PSFI). This is illustrated in Figure 5-9. Historically, PSFI

has grown linearly at a rate of 3.5 (hp/lb)(ft³)(mpg) per year. The baseline scenario presented in Chapter 4 and all of the preceding analyses in this chapter have assumed continued linear growth in PSFI at the same rate, which yields projections of future technological capabilities consistent with engineering judgment-based assessments. (An & DeCicco, 2007; Cheah et al., 2008) This is illustrated by the lower line in Figure 5-9. The effect of a policy that doubles the rate of technological improvement is represented by the upper, dashed line.
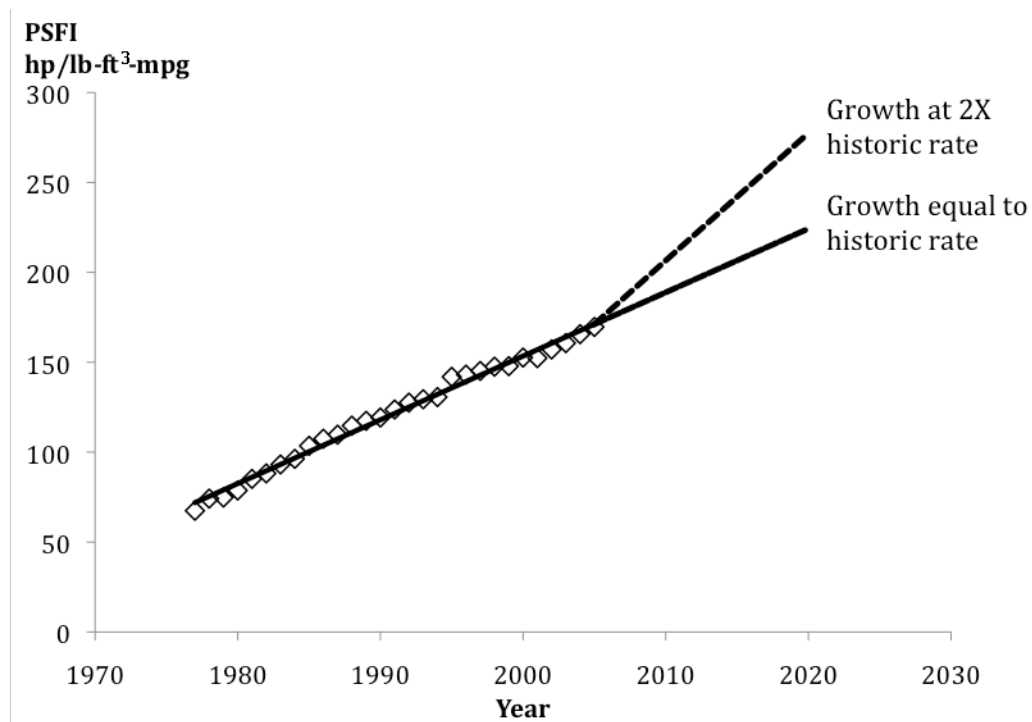
Figure 5-9: Projected performance-size-fuel economy index (PSFI) of new U.S. cars, at growth rates equal to historic trend and at double the historic rate. (An & DeCicco, 2007; U.S. EPA, 2008)

It is beyond the scope of this work to evaluate whether particular policies are actually capable of stimulating an increase in the rate of new technology deployment. Rather, the purpose of this work is simply to examine the effect that such increases might have on the allocation of technologies to performance and fuel consumption. In the following paragraphs, we explore these effects for ranges in growth between 100% and 200% of the historic growth rate (i.e. for growth rates bounded by the two lines in Figure 5-9).

When the rate of adoption of more advanced technologies is increased, both performance and fuel consumption can be expected to improve. Figure 5-10 shows the optimal reductions in acceleration time and fuel consumption rate for the average new U.S. car between 2005 and 2020, as a function of the rate of technological improvement. The far left of the graph represents the baseline scenario, under which the optimal 0-60 mph time is reduced from 8.6 seconds in 2005 to 6.9 seconds in 2020, and the optimal fuel consumption is reduced from 8.0 l/100km to 7.8 l/100km. The far right size of the graph represents the case in which the rate of PSFI growth has been doubled (corresponding to the upper, dashed line in Figure 5-9). The increasing values for both the improvement in fuel consumption and the improvement in acceleration time indicate that the incremental technology improvements are being split between these two attributes.
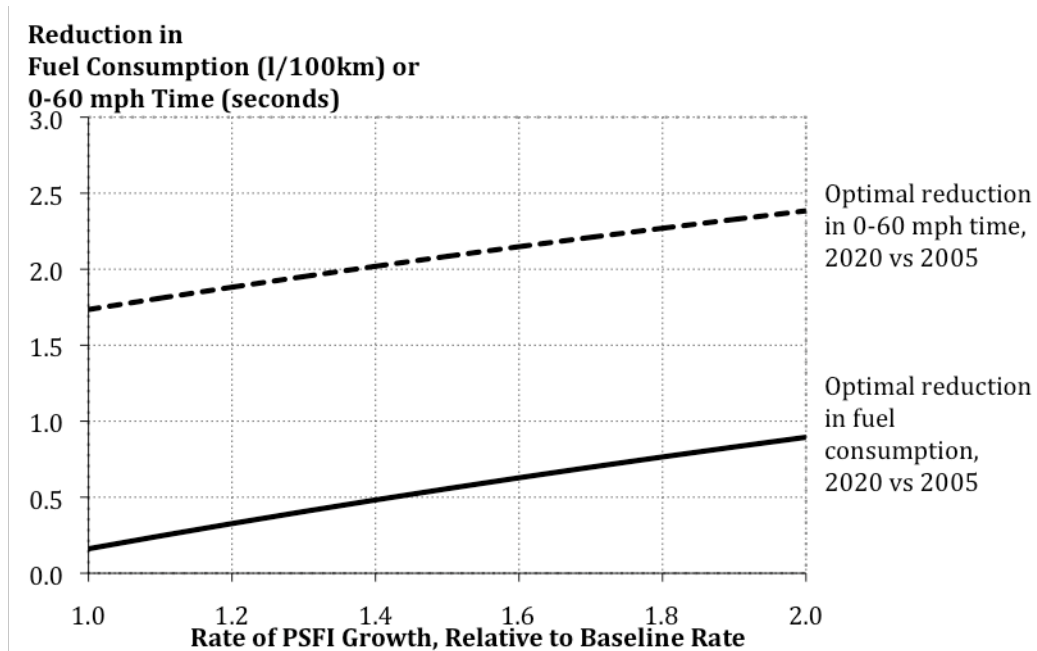
Figure 5-10: Optimal reductions in fuel consumption (unadjusted) and 0-60 mph time for average new U.S. car in 2020, relative to 2005 levels. As rate of technology adoption increases, both performance and fuel consumption can be expected to improve. Rate of technological improvement is characterized by the annual growth in PSFI, indexed to the baseline (historic) rate of growth.

The optimal value of ERFC is expected to increase modestly as the rate of adoption of more advanced technologies is increased, assuming WTP for performance and fuel consumption remain unchanged. As discussed in Chapter 4 and shown in Figure

5-11, the optimal ERFC between 2005 and 2020 under baseline conditions, including historic rates of technology adoption, is 8%. If the rate of adoption of efficiency-enhancing technologies in increased such that PSFI increases at double its historic rate, the overall ERFC between 2005 and 2020 is expected to increase to nearly 30%. Although this is greater than under baseline conditions, it indicates that a majority of the potential improvement in fuel consumption would be "lost" to increased performance.
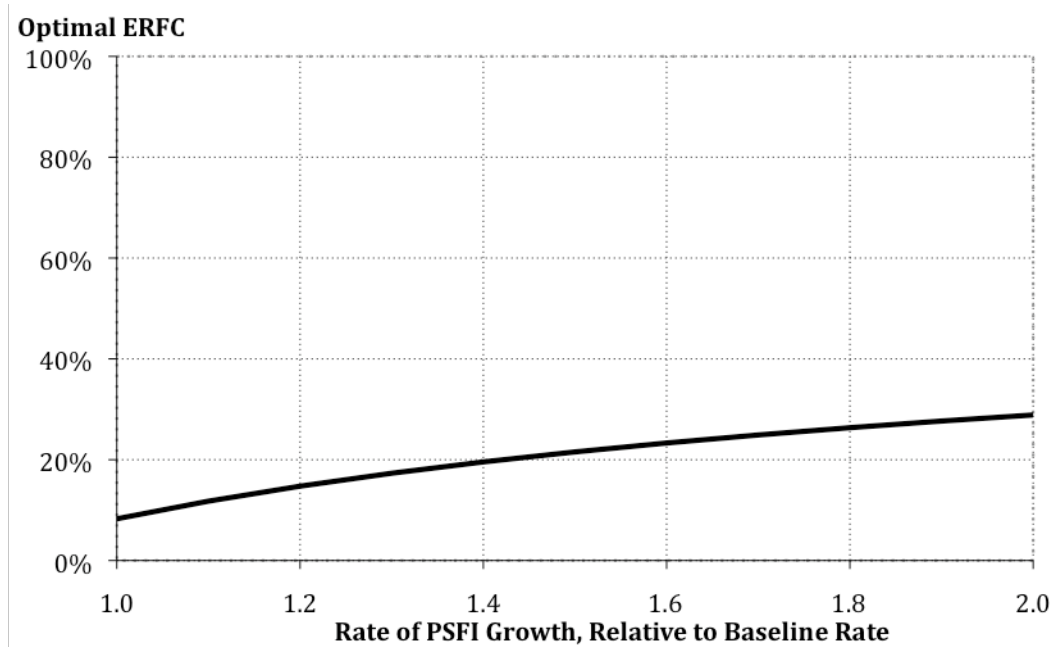
Figure 5-11: Optimal emphasis on reducing fuel consumption increases slightly as the rate of technology adoption (modeled by a faster increase in PSFI) increases.

The finding that increasing the rate of adoption of more advanced technologies leads to improvements in both performance and fuel consumption has important consequences for policymaking. If reducing fuel consumption is a policy goal but improving vehicle performance is not, then policies aimed only at accelerating the deployment of more advanced technologies will not be fully effective.[16] Although ERFC increases somewhat as the rate of technology adoption increases, a large

---

[16] The same likely holds true for leap-ahead technologies too (such as hybrids) as long as the efficiency improvements they deliver are readily convertible between fuel consumption reductions and performance improvements.

share of the new technology continues to be allocated to performance improvements, as shown by the dashed line in Figure 5-10. If policymakers were to use government money to accelerate the introduction of more advanced technologies, with the goal of improving fuel consumption, they might be disappointed to learn that they had effectively subsidized a significant increase in vehicle performance. If policymakers have a goal of accelerating the deployment of more advanced technologies to reduce fuel consumption, they should couple any programs aimed at accelerating technology adoption to complementary policies aimed more directly at increasing ERFC, like those discussed in the preceding sections.

5.5 Conclusions

In this chapter, the optimal allocation of technologies to performance and fuel consumption under different policy regimes was investigated. Policies investigated included raising gasoline prices, purchase incentives for vehicles with lower fuel consumption, disincentives for vehicles with higher performance, fuel economy standards, and policies aimed at stimulating technology deployment.

Sustained increases in gasoline prices are expected to increase emphasis on reducing fuel consumption (ERFC) by increasing consumers' willingness to pay (WTP) for improvements in fuel consumption. If gas prices were to remain near $2.00 per gallon instead of returning to their pre-2003 level of $1.70 per gallon, the optimal ERFC would be expected to increase from less than 10% to approximately 40% for the average new U.S. car through 2020. Sustained prices of $2.75 per gallon would be expected to motivate a 100% ERFC through 2020. Despite recent price spikes to well above these levels, ERFC has not increased to the levels predicted by the model, because manufacturers are limited in their ability to adjust vehicle designs in the short term.

Higher gasoline prices make efficiency-enhancing technologies more valuable to consumers, as they seek to substitute vehicle technologies for fuel consumption in

satisfying their mobility demands. Sustained gasoline prices of $3.00 per gallon are estimated to increase consumers' value of more advanced technologies by approximately $500 for the average new car in the U.S. in 2020. Over the medium to long term, higher gasoline prices should increase the incremental revenues that manufacturers can derive by deploying more advanced technologies.

Incentive programs shift the optimum balance between performance and fuel consumption by imposing a penalty for higher fuel consumption or performance, and/or offering a reward for lower fuel consumption or performance. Modeled results indicate that a 100% ERFC would be motivated through 2020 by an incentive rate of less than $300 per (1l/100km). This is considerably less than the incentive rates already implemented through the U.S. gas guzzler tax, and in France's new bonus-malus system, which has reportedly had a significant influence on the French car market in just one year.

Fuel economy standards are an effective means for increasing ERFC. A 100% ERFC for new U.S. cars between 2005 and 2020 would likely be adequate to satisfy the requirements of the Energy Independence and Security Act of 2007 (6.7 l/100km for new cars and light trucks combined). Fuel economy standards do impose costs on manufacturers, but these costs are substantially less than figures commonly cited by industry, analysts, and in the press. It is estimated that even if gasoline drops back to $1.70 per gallon, the cost of meeting the CAFE standard through reallocation of technologies from performance to fuel consumption would be approximately $200 per car in 2020. This amount is the difference between the opportunity cost of foregone performance and consumers' value of the reduced fuel consumption. In contrast, industry, analysts, and the Department of Transportation frequently peg the cost at anywhere from 3 – 30 times this figure, by failing to account for the potential to reallocate evolutionary technologies to fuel consumption instead of performance, or for consumers' willingness to pay for fuel consumption reductions.

Policies that focus only on increasing the rate of technological improvement will not deliver good "bang for the buck" in reducing fuel consumption. Absent

complementary policies to increase ERFC, such policies may end up subsidizing significant increases in performance, as well as some reductions in fuel consumption. It is estimated that even if the rate of growth in technological capabilities (as measured by the performance-size-fuel economy index) could be doubled, ERFC would likely remain below 30%. Therefore, policies to accelerate technology development or adoption should be accompanied by policies focused more directly on increasing ERFC.

6 Conclusions

In this work, a technology allocation model was developed to assist in understanding automobile manufacturers' decisions on allocating efficiency-enhancing technologies between the competing goals of lowering fuel consumption and offsetting performance improvements. The model maximizes the value that consumers will derive from such technologies, based on their willingness to pay for improvements in these two attributes. It is assumed that manufacturers will aspire to maximize the value that their products offer to consumers, in order to maximize their own market share and profits. In other words, the model seeks to identify the optimal balance between performance and fuel consumption from the perspective of the auto manufacturers. The model was calibrated using studies reported in the literature, manufacturers' price data, and historic trends in performance and fuel consumption.

In the absence of any policy intervention or the recent spike in gasoline prices, it would have been reasonable to expect the majority of more advanced technologies to continue flowing toward offsetting performance improvements. Under such a scenario, in which U.S. gasoline prices remained at $1.70 per gallon (they were fairly constant at this level from 1986-2003, in real terms), it would be expected that the 0-60 mph acceleration time of the average new U.S. car would decrease from 8.6 seconds to 6.9 seconds between 2005 and 2020. Over the same period, fuel consumption of the average new U.S. car would drop only slightly, from 8.0 l/100km to 7.8 l/100km. However, these results are sensitive to consumers' relative willingness to pay for improvements in performance and fuel consumption, and average 0-60 mph times of anywhere between 6.4 and 7.7 seconds could have been reasonably expected in 2020 (corresponding to fuel consumption between 8.6 and 6.9 l/100km).

Of course, there has in fact been a recent spike in gasoline prices and a significant policy intervention in the market. Gasoline prices departed significantly from their

long-term averages beginning in 2004. Sustained increases in fuel price would be expected to shift the optimal allocation of technologies more toward reducing fuel consumption, because consumers become more willing to pay for reductions in fuel consumption when fuel is more costly. The results of this work indicate that the optimal balance between performance and fuel consumption shifts substantially with even modest changes in gasoline price. If fuel prices stabilized at $2.00 per gallon long-term, instead of their pre-2004 average of $1.70 per gallon, it would be expected that the average new U.S. car in 2020 would have a 0-60 mph time of 7.5 seconds, instead of 6.9 seconds (but still well below the 2005 average of 8.6 seconds). Fuel consumption of these cars would be expected to average 7.2 l/100km in this case, instead of 7.8 l/100km. Considering even larger increases in gasoline price, a sustained price of $2.75 per gallon would lead to the average 0-60 mph time in 2020 being the same as in 2005, with all new efficiency-enhancing technologies being directed to lowering fuel consumption.

Also of note, increases in gasoline price increase consumers' willingness to pay for fuel consumption reductions, which increases the total value that consumers place on more advanced technologies. In effect, higher gasoline prices motivate consumer to seek substitutes for fuel for meeting their mobility needs and wants, and fuel-saving technologies are a substitute for fuel. Thus, over the medium to long term, higher gasoline prices may prove beneficial to the auto industry, as they increase the value of one of the auto industry's key products: more advanced technologies.

The second recent event likely to influence the performance-fuel consumption tradeoff is the passage by Congress of increases in Corporate Average Fuel Economy (CAFE) standards, which may impose modest costs on the auto industry. The industry can be expected to adopt evolutionary technologies while placing greater emphasis on reducing fuel consumption as part of its strategy for meeting CAFE standards. The tradeoff between performance and fuel consumption will be especially important in the future, since Congress instructed the Department of Transportation (DOT) to promulgate attribute-based standards. (Energy

100

Independence and Security Act of 2007, 2007) If DOT adopts size-based standards for cars, as it did for light trucks in 2006 (National Highway Traffic Safety Administration, 2006) then the downsizing of vehicles could prove less effective, or indeed counterproductive, as a CAFE compliance strategy.[17] However, if manufacturers choose to sell vehicles with lower fuel consumption and slower acceleration than the revenue-maximizing optimum, they will effectively be incurring an opportunity cost in the form of the lost performance. (Evans, 2008)

The technology allocation model indicates that at the pre-2004 average gasoline price of $1.70 per gallon, meeting the 2020 CAFE standard would reduce the combined value of performance and fuel consumption of the average new car by approximately $200 in 2020, if manufacturers complied with CAFE entirely by trading off performance for fuel consumption. Although consumers' valuation of fuel consumption would be enhanced by the reduction in fuel consumption, the decline in consumers' valuation of performance would outweigh this increase by approximately $200 for the average new car. Therefore, $200 per car is an estimate of the true cost imposed by the 2020 CAFE standard.

Several points need to be considered when interpreting the cost of the CAFE standard. First, although $200 is significant, it is far less than the values frequently offered by the auto industry and DOT, which run into the thousands of dollars per vehicle. Those estimates are extremely high because they assume that even more costly advanced technologies will have to be adopted in order to meet CAFE standards, and they measure only the up-front costs of these technologies, rather than considering how much consumers are willing to pay for fuel consumption and performance. Second, although consumers may be willing to pay only $800 for the reductions in fuel consumption mandated by CAFE, these reductions will actually

---

[17] Under size-based CAFE standards, manufacturers that produce smaller vehicles will be held to higher CAFE standards. Depending upon how quickly the CAFE target increases as vehicle size decreases, it may be self-defeating for manufacturers to improve their fuel economy by selling more small vehicles, because doing so would only raise the CAFE standard that they must meet.

save approximately $1,800 in fuel expenses over the life of an average car.[18] Thirdly, increases in gasoline price reduce the opportunity cost of foregone performance, since consumers are more willing to pay for the mandated reductions in fuel consumption. A sustained gasoline price of $2.00 per gallon instead of $1.70 per gallon would halve the per-vehicle cost to $100. Finally, it must be remembered that like many public policies, the CAFE program is concerned not only with the profits of the industry concerned, but with achieving a balance between a number of competing societal goals, which in the case of CAFE are explicitly identified in the law. (49 U.S.C. 32902(f))

The model was also used to evaluate incentive programs targeting either performance or fuel consumption, both of which were found to be effective for shifting the balance between these attributes. Fuel consumption incentives considerably less stringent than those already implemented in the U.S. (the gas guzzler tax) and in various European countries (e.g. the CO_2-based bonus-malus system adopted in France) were found to motivate almost a full emphasis on reducing fuel consumption through 2020, which would see performance remain constant and the fuel consumption of the average new U.S. car reduced from 8.0 to 6.0 l/100km. However, these incentives must apply to all vehicles in order for them to be effective. Similarly, existing European policies targeting engine displacement and power would place a very high price on performance if applied to the average new U.S. car, sufficient to motivate a large swing away from higher performance.

The model results also highlight the fact that a revenue-neutral incentive system would have the effect of decreasing the total value that consumers place on the attributes of new cars, on average. Incentive systems effectively put a price on fuel consumption, shifting the optimum balance between these attributes. But they do

---

[18] For a reduction in fuel consumption from 7.8 l/100km to 6.0 l/100km. Assumes 15,600 miles driven in the first year, declining at 4.5% per year, for a 15-year life. Assumes on-road fuel economy is 25% less than unadjusted, laboratory fuel economy. Future fuel savings discounted at 10% per annum.

not, on average, increase the value that consumers perceive in vehicles. This is a result of the revenue-neutral character of the system: every consumer eligible for a rebate (and thus more willing to pay for a lower-consuming vehicle) must be offset by another consumer paying a fee (who is commensurately less willing to pay for that higher-consuming vehicle). On net, therefore, revenue-neutral incentive systems can increase the marginal value of lower fuel consumption, but decrease the combined value of performance and fuel consumption, in much the same way that CAFE does. This effect could be offset if the incentive system were not revenue-neutral, and instead more rebates were paid than fees were collected.

The model helps to illuminate the different magnitudes and distributions of costs associated with using gas taxes versus CAFE standards to achieve the same shift in ERFC. Higher gas prices may be good for auto manufacturers over the longer term, but cost consumers dearly. The model indicates that a sustained gasoline price of $2.75 per gallon is needed to motivate 100% ERFC (reaching 6.0 l/100km in 2020). Compared with the baseline results (7.8 l/100km in 2020 when gasoline is $1.70), the higher gasoline price will lead to an increase in lifetime fuel expenditures of nearly $2,000, even after accounting for the fuel consumption response.[19] In addition, the consumers will be willing to pay the auto manufacturers roughly $300 more per vehicle for the reduction fuel consumption, which is good for the industry but bad for consumers.

In contrast to higher gasoline prices, CAFE standards reduce fuel expenses over the life of the vehicle, but impose costs at the time of purchase. Increasing ERFC to 100% to meet CAFE standards imposes an estimated cost of $200 if gasoline prices are averaging $1.70 per gallon, but the standards will reduce fuel expenses by many times this amount over the life of the car.

---

[19] Assumes 15,600 miles driven in the first year, declining at 4.5% per year, for a 15-year life. Assumes on-road fuel economy is 25% less than unadjusted, laboratory fuel economy. Future fuel savings discounted at 10% per annum.

The effectiveness of policies aimed at accelerating technology adoption for reducing fuel consumption was also explored using the model. It was found that although these policies can lead to lower fuel consumption, they can be expected to also lead to higher performance, unless accompanied by policies that can direct the technology improvements toward lower fuel consumption. In effect, these policies on their own would subsidize an increase in vehicle performance in addition to come improvement in fuel consumption, and so may represent poor value as a public investment if the goal is to reduce fuel consumption.

The high sensitivity of the optimal balance between performance and fuel consumption to consumers' willingness to pay for these attributes points to two important lessons for automakers. First, it reinforces the importance of manufacturers staying abreast of their customers' preferences, a priority already well appreciated within the industry. (Hill et al., 2007) Second, and perhaps more importantly, it also highlights a risk. If consumers' willingness to pay for fuel consumption moves in step with fuel prices – or with their expectation of future fuel prices, based on price trends – then the optimal balance between performance and fuel consumption has the potential to shift much more rapidly than automakers can redesign their products. Automakers therefore may stand to benefit if they can shorten the cycle time needed to bring a new product to market, or if they can more easily readjust the balance between performance and fuel consumption in existing products through mid-cycle changes.

6.1 Future Work

This work has applied a modeling framework based on *technology allocation* to the problem of automotive performance and fuel consumption. Unlike *technology adoption* modeling frameworks commonly used to evaluate this system, the technology allocation framework recognizes the significant inertia in the automotive industry, which makes it difficult to rapidly increase or decrease the rate of technology deployment. Rather than focusing on which technologies can be adopted to reduce fuel consumption, this framework takes the introduction of more

advanced technologies as a given, and looks instead at what must be done to direct those technologies toward to policy goal of lowering fuel consumption. While the model presented in this work provides a useful way of looking at the performance-fuel consumption tradeoff, there are significant opportunities to make it more robust, as well as more comprehensive.

The model currently does not segment the vehicle market by class, nor consumers by their preferences. The model delivers useful understanding of the general drivers of the performance-fuel economy tradeoff, but cannot make detailed predictions about market mix. The model could be expanded to include light trucks, instead of just cars, in order to capture this large and important part of the U.S. vehicle market. In addition, cars and trucks could be disaggregated into segments in order to capture differences in the performance-fuel economy tradeoff across these classes. Along with a segmenting of the vehicle market, it would make sense to incorporate heterogeneities in consumers' WTP for performance and fuel consumption, especially for purchasers in different segments.

The model is intended to examine optimal tradeoffs over the medium to long term, meaning periods of ten years or more. It cannot produce meaningful results for, nor be reasonably compared with, trends over shorter time periods. Such periods may be too short to allow for automakers to identify shifts in consumer preferences and public policies, and to adjust their design priorities accordingly. The model would be more useful if it could provide insights into the dynamics of fuel prices, shifts in consumers' willingness to pay, and the vehicle development and production process. This would allow it to be used to estimate shorter term effects of policy changes, as well as longer-term effects.

Many attributes beyond performance and technology influence the fuel consumption of vehicles, and may be valued by consumers. For example, fuel consumption is decreased by increasing size, or adding safety equipment or other accessories that increase vehicle weight. The model could be expanded to include

more attributes related to fuel consumption, though modeling the associated tradeoffs becomes significantly more complex.

Finally, the model is sensitive to assumed values of WTP for performance and fuel consumption, and to the shape of the performance-fuel consumption tradeoff curve. These sensitivities underscore the need for well-characterized tradeoffs and a good understanding of consumers' WTP for attributes. Good data should underlie any other improvements to the model.

References

ACEA. (2008). *ACEA tax guide 2008*

Adler, T., Wargelin, L., Kostyniuk, L., Kalavec, C., & Occhiuzzo, G. (2004). *Experimental assessment of incentives for alternate fuel vehicles.* TRB Annual Meeting.

American Honda Motor Co. Retrieved January 15, 2009, from www.hondacars.com

An, F., & DeCicco, J. (2007). Trends in technical efficiency trade-offs for the U.S. light vehicle fleet. *SAE Technical Paper Series, 2007-01-1325*

An, F., & Sauer, A. (2004). *Comparison of passenger vehicle fuel economy and greenhouse gas emission standards around the world.* Arlington, VA: Pew Center on Global Climate Change.

Bandivadekar, A., Bodek, K., Cheah, L., Evans, C., Groode, T., Heywood, J., et al. (2008). *On the road in 2035: Reducing Transportation's petroleum consumption and GHG emissions* No. LFEE 2008-05 RP). Cambridge, MA: Massachusetts Institute of Technology.

Bank of Canada. (2009). *10-year currency converter.* Retrieved May 7, 2009, 2009, from http://www.bankofcanada.ca/en/rates/exchform.html

Berry, I. (2010). *Master's thesis.* Unpublished S.M., Massachusetts Institute of Technology, Cambridge, MA.

Bodek, K. (2008). *EU fleet mode*l. Cambridge, MA: Massachusetts Institute of Technology.

Bodek, K., & Heywood, J. (2008). *Europe's evolving passenger vehicle fleet: Fuel use and GHG emissions scenarios through 203*5 No. LFEE 2008-03 RP). Cambridge, MA: Laboratory for Energy and Environment, Massachusetts Institute of Technology.

Bureau of Labor Statistics. (2008). *Consumer price index: All urban consumers.* Retrieved November 23, 2008, from ftp://ftp.bls.gov/pub/special.requests/cpi/cpiai.txt

Centro diffusione dati. (2009). *ConIstat on line.*, 2009, from http://con.istat.it/amerigo/inizio.asp?id=56490&lg=E

Cheah, L. W., Bandivadekar, A. P., Bodek, K. M., Kasseris, E. P., & Heywood, J. B. (2008). The trade-off between automobile acceleration performance, weight, and fuel consumption. *SAE Technical Paper Series, 2008-01-1524*

Consumer Reports. (2009). *Performance comparison*. Retrieved March 24, 2009, from http://www.consumerreports.org/cro/cars/types/sedans/performance-comparison.htm

Donndelinger, J. A., & Cook, H. E. (1997). Methods for analyzing the value of automobiles. *SAE Technical Paper Series, 970762*

Energy Independence and Security Act of 2007, H.R. 6, 110th Congress. (2007).

Energy Information Administration. *Annual energy review 2007.*, 2008, from http://www.eia.doe.gov/aer/inter.html

Energy Information Administration. (2009). *January 2009 monthly energy review*. Retrieved February, 2009, from http://www.eia.doe.gov/mer/prices.html

Energy Policy Act of 2005, H.R. 6, 109th Congress. (2005).

European Commission. (2007). *Database to monitor the average specific emissions of CO2 from new passenger cars*

Evans, C. (2008). Putting policy in drive: Coordinating measures to reduce fuel use and greenhouse gas emissions from U.S. light-duty vehicles. (S.M., Massachusetts Institute of Technology).

Federal Highway Administration. (2008). *Highway statistics 2007.http://www.fhwa.dot.gov/policy/ohpi/hss/index.cfm*

Field, B. C. (1994). *Environmental economics : An introductio*n. New York: McGraw-Hill.

Ford Motor Company. (a). Retrieved January 16, 2009, from www.fordvehicles.com

Ford Motor Company. (b). Retrieved February 26, 2009, from www.mercuryvehicles.com

Garthwaite, J. (2009). *Why bill ford (yes, that ford) wants a gas tax hike.http://earth2tech.com/2009/04/20/why-bill-ford-yes-that-ford-wants-a-gas-tax-hike/*

General Motors Corporation. Retrieved January 16, 2009, from www.chevrolet.com

Spiegel Online International (2009) *Germany joins EU in tying car fees to emissions*. January 27. *http://www.spiegel.de/international/germany/0,1518,603798,00.html*

108

Greene, D. L. (2001). *TAFV alternative fuels and vehicles choice model documentatio*n No. ORNL/TM-2001/134). Oak Ridge, TN: Oak Ridge National Laboratory.

Greene, D. L., Duleep, K. G., & McManus, W. (2004). *Future potential of hybrid and diesel powertrains in the U.S. light-duty vehicle marke*t No. ORNL/TM-2004/181). Oak Ridge, TN: Oak Ridge National Laboratory.

Greene, D. L., German, J., & Delucchi, M. A. (2009). Reducing climate impacts in the transportation sector. *Biennial Asilomar Transportation and Energy Conference; 11th,* 181-229.

Greene, D. L., & Liu, J. (1988). Automotive fuel economy improvements and consumers' surplus*. Transportation Research. Part A, General., 22*A(3), 203.

Greene, D. L., Patterson, P. D., Singh, M., & Li, J. (2005). Feebates, rebates and gas-guzzler taxes: A study of incentives for increased fuel economy*. Energy Policy, 33*(6), 757-775.

Greimel, H. (2008, May 23, 2008). Forecast: CAFE will cost Detroit 3 double that of Japanese*. Automotive News,*

Hill, K., Edwards, M., & Szakaly, S. (2007). *How automakers plan their products: A primer for policymakers on automotive industry business planning*. Center for Automotive Research.

Hyundai Motor America. Retrieved February 26, 2009, from www.hyundaiusa.com

Institut national de la statistique et des études économiques. (2009). *Indice des prix à la consommation - IPC - Ensemble des ménages - Métropole + DOM - par fonction de consommation - Indice d'ensemble.*, 2009, from http://www.indices.insee.fr/bsweb/servlet/bsweb?action=BS_SERIE&BS_IDBANK=000639196&BS_IDARBO=06010000000000

Klier, T., & Linn, J. (2008). *New vehicle characteristics and the cost of the corporate average fuel economy standard.* Unpublished manuscript.

Lopez, M. (2009). Congress dangerous to Detroit*. Detroit News,* March 25, 2009.

Magee, C. L. (2009). *Personal communication.*

Malliaris, A. C., Hsia, H., & Gould, H. (1976). Concise description of auto fuel economy and performance in recent model years*. SAE Technical Paper Series, 760045*

Mazda North American Operations. Retrieved February 26, 2009, from www.mazdausa.com

McConville, G. P., & Cook, H. E. (1996). Examining the tradeoff between automobile acceleration performance and fuel economy*. SAE Technical Paper Series, 960004*

Monroe, E. M., & Cook, H. E. (1997). Determining the value of vehicle attributes using a PC based tool. *SAE Technical Paper Series, 970763*

Murphy, T. (2008). *The new face of CAFE.* Ward's AutoWorld, February 1, 2008. http://wardsautoworld.com/ar/auto_new_face_cafe/

National Highway Traffic Safety Administration. (2004). *Automotive fuel economy program: Annual update, calendar year 200*3. U.S. Department of Transportation.

National Highway Traffic Safety Administration. (2006). *Average fuel economy standards for light trucks model years 2008-2011* National Archives and Records Administration.

National Highway Traffic Safety Administration. (2008). *Preliminary regulatory impact analysis: Corporate average fuel economy for MY 2011-2015 passenger cars and light truck*s. U.S. Department of Transportation.

National Research Council (U.S.). Committee on the Effectiveness and Impact of Corporate Average Fuel Economy Standards, National Research Council (U.S.). Board on Energy and Environmental Systems, & National Research Council (U.S.). Transportation Research Board. (2002). *Effectiveness and impact of corporate average fuel economy (CAFE) standard*s. Washington, D.C.: National Academy Press.

Navarro, X. (2009, May 1, 2009). CO_2-based tax has already affected the average French car. Message posted to http://www.autobloggreen.com/2009/05/01/co-sub-2-sub-based-tax-has-already-affected-the-average-french/

Nissan North America. Retrieved January 16, 2009, from www.nissanusa.com

Office for National Statistics. (2009). *National statistics online: Consumer price indices.*, 2009, from http://www.statistics.gov.uk/statbase/tsdtables1.asp?vlnk=mm23

Sperling, D. (2002). Updating automotive research. *Issues in Science and Technology, 18*(3)

Squatriglia, C. (2007, December 20, 2007). How Detroit will reach 35 mpg. Message posted to http://www.wired.com/autopia/2007/12/how-detroit-wil

Statistisches Bundesamt Deutschland. (2009). *Consumer price index and index of retail price.*, 2009, from [http://www.destatis.de/jetspeed/portal/cms/Sites/destatis/Internet/EN/Navigation/TopNav/AboutUs.psml;jsessionid=0D16EA9D9C907559F8C68519C7D8A119.internet2](http://www.destatis.de/jetspeed/portal/cms/Sites/destatis/Internet/EN/Navigation/TopNav/AboutUs.psml;jsessionid=0D16EA9D9C907559F8C68519C7D8A119.internet2)

Sterman, J. (2000). Business dynamics : Systems thinking and modeling for a complex world. (pp. 631). Boston: Irwin/McGraw-Hill.

Toyota Motor Sales, U. S. A. Retrieved January 15, 2009, from www.toyota.com

Turrentine, T. S., & Kurani, K. S. (2007). Car buyers and fuel economy*? Energy Policy, 3*5(2), 1213-1223.

U.S. Department of Energy, & U.S. Environmental Protection Agency. (2008). *Fuel economy guide 200*9 No. DOE/EE-0325)

U.S. Environmental Protection Agency. (2009). *Inventory of U.S. greenhouse gas emissions and sinks: 1990 – 200*7 No. EPA 430-R-09-004). Washington, DC: U.S. Environmental Protection Agency.

U.S. EPA. (2006). *Program overview: Gas guzzler ta*x No. EPA420-F-06-042)

U.S. EPA. (2008). *Light-duty automotive technology and fuel economy trends: 1975 through 200*8 No. EPA420-R-08-015)Office of Transportation and Air Quality, U.S. Environmental Protection Agency.

U.S. EPA. (2009). *Green vehicle guide.* Retrieved April 11, 2009, from http://www.epa.gov/greenvehicles/Download.do

Ward's. (2007). *'08 model U.S. car and light truck specifications and price*s Ward's Automotive Group, a Division of Penton Media Inc.

Ward's. (2008). *% Engine installations on '08 model U.S. domestic cars and light truck*s Ward's Automotive Group, a Division of Penton Media Inc.

Ward's. (2009). *% Engine installations on '08 model U.S. import cars and lt. truck*s Ward's Automotive Group, a Division of Penton Media Inc.

Wetzstein, M. E. (2005). Microeconomic theory : Concepts and connections. Mason, OH: Thomson/South-Western.

Acronyms, Abbreviation, and Symbols

|		
A	0-60 mph acceleration time	seconds
c	Coefficient in acceleration vs power/weight function	
C	A constant incorporating consumers' baseline value of performance and fuel consumption	dollars
CAFE	Corporate Average Fuel Economy (standards)	mpg
d	Exponent in acceleration vs power/weight function	
ERFC	Emphasis on reducing fuel consumption	%
FC	Unadjusted 55/45 city/highway combined fuel consumption	liters/100km
FE	Unadjusted 55/45 city/highway combined fuel economy	mpg
I	Amount of incentive	dollars
k	A constant (value = 235.2) used to convert between fuel economy and fuel consumption space. $k = FE*FC$	mpg-l/100km
MSRP	Manufacturer's suggested retail price	dollars
n	Payback period for calculating WTP for fuel consumption	years
P	Engine peak horsepower	hp
p	Coefficient in performance-fuel consumption tradeoff function	
P_{fuel}	Price of fuel	dollars per liter
PSFI	Performance-size-fuel economy index	$(hp/lb)(ft^3)(mpg)$
q	Exponent in performance-fuel consumption tradeoff function	
r	Incentive rate per unit change in attribute of interest	dollars per unit attribute
S	Interior Volume (Size)	ft^3
v_A	Willingness to pay per unit reduction in 0-60 mph acceleration time	dollars/second
v_{FC}	Willingness to pay per unit reduction in fuel consumption	$\frac{dollars}{l/100km}$
ΔV_A	Consumers' valuation of reduced acceleration time	dollars
ΔV_{FC}	Consumers' valuation of fuel consumption reduction	dollars
ΔV_{tech}	Consumers' valuation of new efficiency technology	dollars
VKT	Vehicle kilometers traveled	km
W_I	Inertia weight (curb weight + 300 lbs.)	pounds
WTP	Willingness to Pay	dollars per unit of attribute
α	On-road correction factor, ratio of in-use fuel economy to laboratory fuel economy	

Appendices

A. Engine Displacement and Power

Estimated 0-60 mph Acceleration Time (seconds)

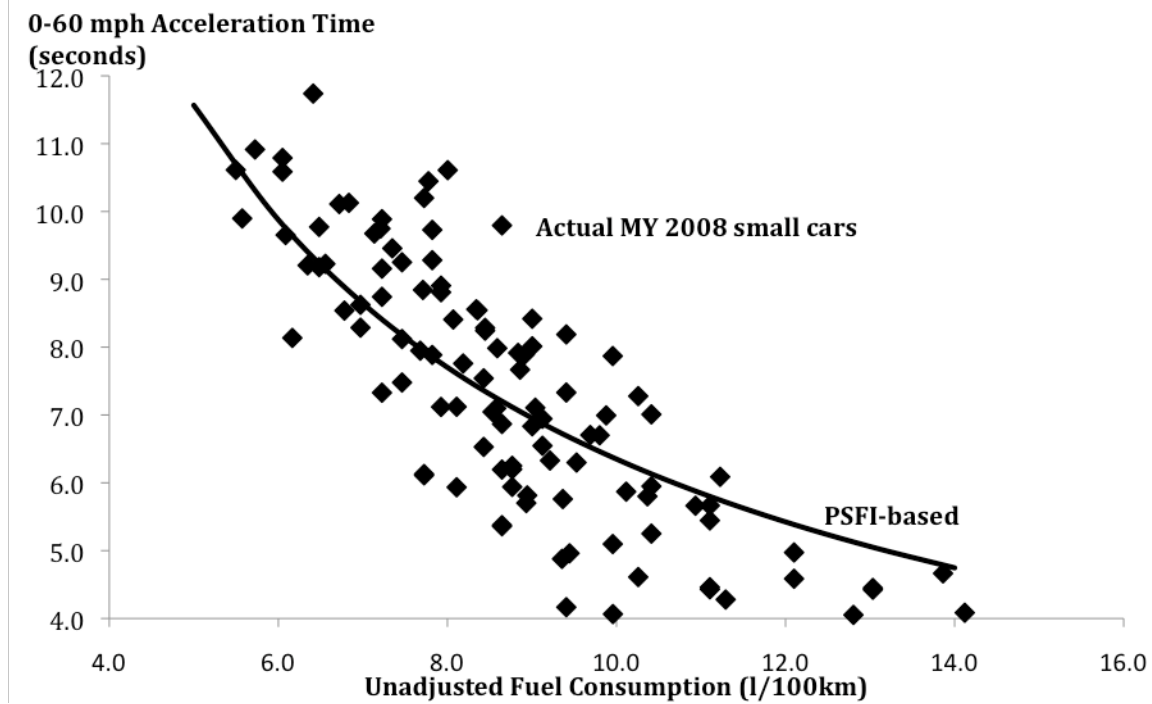$$y = 515x^{-0.528}$$
$$R^2 = 0.59$$
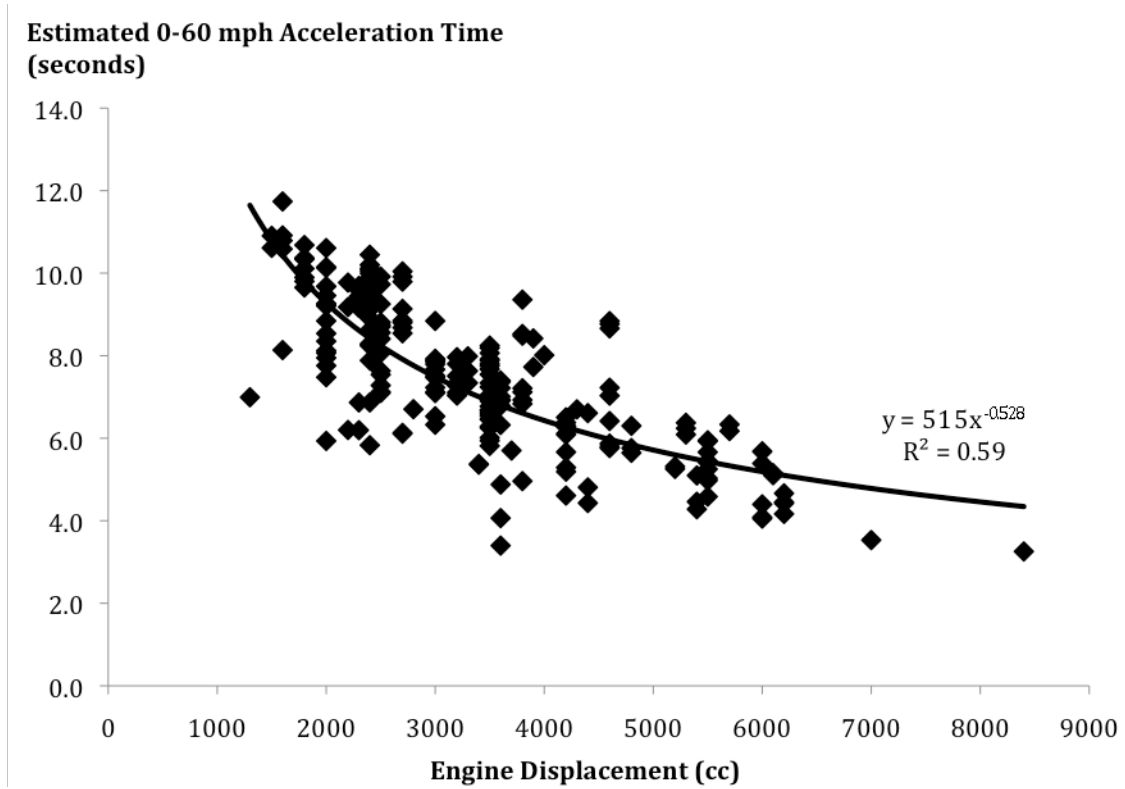
Relationship between engine displacement and 0-60 mph time for model year 2008 U.S. cars.

B. Current Tradeoffs Between Performance and Fuel Consumption
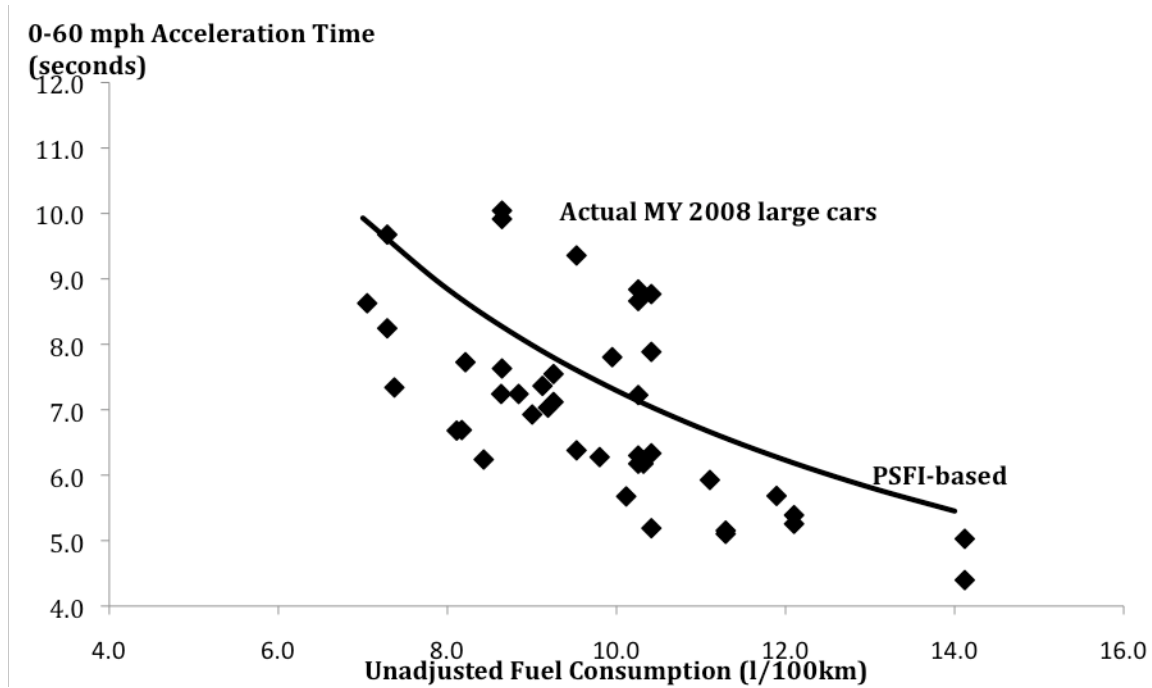
Comparison of modeled performance-fuel consumption tradeoff with actual large cars offered in the U.S. in model year 2008 (excluding hybrids). (U.S. EPA, 2008; Ward's, 2007; Ward's, 2008; Ward's, 2009)

Comparison of modeled performance-fuel consumption tradeoff with actual small cars offered in the U.S. in model year 2008 (excluding hybrids). (U.S. EPA, 2008; Ward's, 2007; Ward's, 2008; Ward's, 2009)

C. V6 Price Premiums

Manufactuers' suggested retail prices for comparably-equipped 4- and 6-cylinder versions of popular U.S. car models. (American Honda Motor Co., ; Consumer Reports, 2009; Ford Motor Company, ; Ford Motor Company, ; General Motors Corporation, ; Hyundai Motor America, ; Mazda North American Operations, ; Nissan North America, ; Toyota Motor Sales,)

	Price		0-60 mph Time		
Year, Model & Trim	4-cylinder	6-cylinder	4-cylinder	6-cylinder	Performance Premium ($/sec)
2009 Camry LE	$22,370	$24,935	9.6	7.1	$1,030
2009 Camry SE	$25,615	$28,290	9.6	7.1	$1,070
2009 Camry XLE	$28,435	$30,505	9.6	7.1	$830
2009 Accord EX	$25,355	$27,275	9.8	7.4	$800
2009 Accord EX-L	$27,355	$29,375	9.8	7.4	$840
2009 Malibu 2LT	$25,375	$27,170	9.4	6.5	$620
2009 Fusion SE	$19,545	$20,829	9.5	8.0	$860
2009 Fusion SEL	$20,668	$21,925	9.5	8.0	$840
2009 Altima SL	$27,220	$30,210	8.1	6.4	$1,760
2009 Altima SL (2)	$29,900	$33,180	8.1	6.4	$1,930
2009 Sonata GLS	$18,595	$21,145	9.8	7.4	$1,060
2009 Sonata SE	$20,745	$22,745	9.8	7.4	$830
2009 Sonata Limited	$23,245	$25,245	9.8	7.4	$830
2009 Mazda6 Touring	$23,520	$26,130	9.0	6.8	$1,190
2009 Mazda6 Grand Touring	$26,780	$29,235	9.0	6.8	$1,120
2009 Milan	$21,340	$22,970	9.5	8.0	$1,090
2009 Milan Premier	$23,385	$24,845	9.5	8.0	$970
2009 G8	$29,730	$32,440	7.0	5.3	$1,590