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A Techno-Economic Investigation of Advanced Vehicle Technologies and Their Impacts on Fuel Economy, Emissions, and the Future Fleet

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A TECHNO-ECONOMIC INVESTIGATION OF ADVANCED VEHICLE TECHNOLOGIES AND THEIR IMPACTS ON FUEL ECONOMY, EMISSIONS AND THE FUTURE FLEET

A Dissertation

Submitted to the Faculty

of

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by

Richard A. Simmons

In Partial Fulfillment of the

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of

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To my parents

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Simmons, Richard A. Ph.D., Purdue University, December 2015. A Techno-Economic Investigation of Advanced Vehicle Technologies and Their Impacts on Fuel Economy, Emissions, and the Future Fleet. Major Professors: Suresh V. Garimella, School of Mechanical Engineering, and Wallace E. Tyner, School of Agricultural Economics.

A more sustainable transportation energy future for society is the principal motivation of this dissertation. The central purpose of this work is to investigate vehicle technologies that contribute to fuel and emissions reductions while preserving consumer choice, and to evaluate their technological performance and economic practicability as essential aspects of meeting aspirational targets and regulatory requirements associated with the future vehicle fleet.

Innovation in automobiles has been realized at stable and affordable prices for decades, yet efforts to intensify future value creation in the domain of energy efficient technologies are critical. Using analysis of variance and hedonic price modeling techniques, disaggregated contributions of passenger car attributes to vehicle price reveal that consumer valuations of fuel economy move inversely with acceleration performance, and that both are highly correlated to the regulatory context. Novel economic trade-offs among vehicle attributes are introduced, in particular with respect to two foundational premises emphasized by current policies: vehicle classification and weighted sales volume. The implicit value of acceleration is presently greater than that of fuel reduction, with

buyers in the significant mid-size vehicle segment willing to pay more than twice as much for the former than the latter.

Building on these findings, the research explores a suite of fuel- and emission-reducing technologies that have underpinned fuel economy gains and compliance at costs that are at or below levels anticipated by the regulations. However, benefit-cost analyses on 2014 model year compact and mid-size cars reveal that consumers are not yet substantially incentivized to purchase fuel economy under baseline scenarios. A sensitivity analysis reveals that a majority of new technologies become financially attractive to consumers when average fuel prices exceed $5.60/gallon, or when annual miles traveled exceed 16,400. Turbocharged-downsized engines and hybrid powertrains are found to deliver high incremental benefits compared to their costs. The research suggests that the additional cost consumers incur in exchange for a given level of fuel economy improvement in the coming years will need to be steadily reduced compared to current levels, particularly in the context of low fuel prices.

Hybrid and electric vehicles are viewed as enabling technologies, yet their real-world energy consumption is more highly sensitive to driving cycles, ambient temperature, and upstream energy sources than conventional vehicles. Vehicle tractive power, and cabin and battery thermal loads are interactively modeled and simulated for a range of operating conditions among vehicles that employ different energy sources and disparate power and thermal management strategies. Locality-specific system-level energy consumption values are then computed based on characteristics of large U.S. cities such as electricity generation, petroleum refining, and typical weather. The findings quantify the extent to which advanced architectures, though favorable in certain modes, are more energy sensitive to driving cycles and extreme temperatures. Annualized integration of this temperature-dependence reveals that system-equivalent energy consumption varies by locality least for internal combustion and hybrid vehicles, and between 45-70% for electric vehicles. As compared to conventional vehicles, electric vehicle system-equivalent CO_2 emissions range from a 70% improvement to no improvement based on locality. This study suggests that policies and deployment efforts should scientifically account for the strong sensitivity to locality on energy and emissions for advanced vehicles.

Regarding fuel reduction objectives, internal combustion engine vehicle baselines show sustained improvement on both technological and economic fronts without compromising consumer choice. Hybrids perform exceptionally well overall, reducing energy and emissions by levels that appear to justify their incremental cost increases. In terms of fuel switching, vehicles operating on grid-electricity are shown to displace petroleum and yield net energy reductions in certain localities; yet future research must navigate technological and cost challenges to ensure energy and emissions benefits are bankable and that policies are well-aligned. This body of work is intended to promote ways of affordably reducing the impact of transportation on the environment, to stimulate further research toward system-level optimizations, and to help inform subsequent policymaking processes regarding the future vehicle fleet.

CHAPTER 1. INTRODUCTION

Transportation has been responsible for driving modern society to unparalleled limits of mobility and prosperity, with amazing efficiency in a relatively brief period of time. Physical and figurative boundaries once thought insurmountable are now navigated on a daily basis thanks in part to major innovations in nearly every form of transportation. Transportation has propelled untold innovation in other sectors, as modern life has come to depend on the ubiquity, convenience, and potential of today's transportation options. Gasoline and diesel fuel have proven extremely well-suited in providing ample energy, in a dense, portable and low-cost manner. Yet along with the myriad positive impacts fueled by these sources of energy, their virtual dominance has also given rise to significant geopolitical, economic, and environmental consequences. Concerns that technological improvements have not adequately emphasized reductions in fuel consumption or emissions may have merit and warrant deeper investigation.

In the United States, the transportation sector accounts for 28% of domestic energy consumption and 27% of greenhouse gas emissions [1-3]. The United States remains reliant on petroleum for about ninety percent of its transportation needs [2]. This is in stark contrast to domestic stationary electricity supplies, where power generation is derived from no less than ten established sources, including several that are not fossil fuels. No single electricity source accounts for more than 40%, and the total share of renewables has surpassed 13% [4]. The cumulative share of renewables (13%) and nuclear (19%) suggest that nearly one third of U.S. electricity generation is derived from low carbon or zero-carbon sources [4]. So, while the generation of electricity may have certain challenges of its own, diverse, lower carbon and more secure supplies are generally available; whereas the disproportionate reliance of transportation on petroleum represents a more acute concern. In particular, constraints stemming from finite fossil fuel supplies, increasing global demand, price volatility, and adverse environmental impacts are in dire need of long-term solutions. Prolonged efforts aimed at reducing or replacing petroleum and developing more sustainable forms of energy for the transit of people and goods will therefore be critical if the benefits and opportunities brought by transportation are to continue to outweigh their costs and risks.

Reducing oil consumption and emissions in meaningful quantities demands that research, development, and deployment be implemented on a substantially interdisciplinary scale. In particular, focused attention must simultaneously be paid to technological feasibility, economic practicability, and environmental and societal impact. Progress toward optimizing system level outcomes for such multi-faceted challenges calls for more advanced and coordinated methodologies for assessing technological performance in view of economic, environmental and regulatory constraints. Thus it is the central purpose of this work to investigate vehicle technologies that contribute to fuel and emissions reductions while preserving consumer choice, and to evaluate their performance and economic practicability as essential aspects of achieving aspirational targets and regulatory requirements of the future vehicle fleet. This chapter provides an overview of the motivation, scope, definitions, methodologies, key contributions and major objectives relevant to the techno-economic research undertaken in this dissertation.

1.1 The Merits of a Multi-Discipline Approach

In aggregate, this research aims to more completely investigate the strengths, weaknesses, and fuel savings potential of new vehicle technologies by considering multiple perspectives. Consumer preferences for vehicle utility and major attributes, economic benefits and costs, and physics-based simulations of vehicle performance under varying conditions are all employed to more fully characterize vehicle energy efficiency. Technology deployment will certainly be a driving force behind strategies to reduce petroleum and mitigate emission, but disruptive innovation will likely be technologically complex, take time and impose significant costs. Continued improvements to vehicle efficiency, advancements to conventional engine technologies, light-weighting, friction-reduction, and realistic scale-up of hybrid, electric, and advanced vehicles constitute key contributions. This dissertation devotes substantial scope and attention to these primary categories of vehicle technologies because of their strategic intermediate-term impact and potential in bridging toward longer-term solutions. While more aggressive transitions to advanced and alternative fuels may also become technically and economically viable over time, many significant challenges loom. Comprehensive and sector-wide energy and emission solutions are thus reliant upon new vehicle technology as one major element in a suite of strategies. Consumer behavior, intelligent and real-time routing, fuel switching, mass-transit, and modal shifts that may obviate traditional commutes complement the arguably more visible contribution of vehicle innovation, and demonstrate how a campaign towards more sustainable transportation must be cross-cutting. Although several of these are beyond the scope of this research, key aspects of consumer decision-making are considered, such as revealed market preferences, and driving behavior including what, where, when and how people drive.

The automotive marketplace represents a dynamic environment where researchers, automakers, and consumers mutually reinforce or reject change based upon key constraints and a variety of objective and subjective factors. This is the reality of a mature, free yet regulated, market industry where economic practicability is often decided by uncontrollable or uncertain factors. Such dynamic market conditions pose challenges to analytical comparisons of advanced technologies. Neither learning effects, the pace and extent of consumer acceptance of fuel-saving technologies, future fuel costs, nor costs associated with technology development and deployment can be predicted with extreme accuracy. This creates a need for contemporary techno-economic assessment tools that can reduce systemic uncertainty by comparing the effectiveness of competing technologies. To help address this need, this dissertation includes an in-depth assessment of key attributes that contribute to vehicle utility, and their relative weights and valuations for both historical and contemporary time periods. This research further explores uncertainty by studying the sensitivity of energy efficiency and the economic viability of new technologies to variations in key inputs such as the price of fuel, vehicle miles traveled, driving schedules and even locality. In this way, uncertainty is studied from multiple perspectives, facilitating a more accurate overall assessment of practical implications.

Ensuring that viable solutions result in measurable positive impacts on society is non-trivial, but critically important in meeting either the technological or economic objectives defined by the consumer or the manufacturer. Appropriate regulatory measures have been enacted to establish technology-neutral criteria and objectives that provide signals, assurances, and constraints to help encourage suitable societal outcomes. As such, this research accounts for the complex challenge of developing a common basis for defining and valuing vehicle energy consumption as well as associated environmental impacts.

Useful and rigorous as they are, single-discipline approaches may tend to be sub-optimal in either deploying solutions or assuring maximum impact toward urgent societal challenges in a prioritized fashion. A technology-centric view may leverage tremendous research and innovation, but may not appropriately address reasonableness of costs or manufacturability. A corporate-oriented, product-centric view may further suffer from commercial bias or lose sight of long-term social consequences. Economically-centered approaches may tend to disproportionately weight financial returns at the possible expense of social well-being. Likewise, social-welfare and regulation-based approaches can fail to appropriately capture the full extent of the technological challenge, or the economic viability of a product, when imposing rules and policies. Obviously then, subjectivity, differing perspectives and conflicted views of ideal outcomes pose threats to ensuring satisfactory or optimal system-wide results. How then, can commonality in purpose be realized for such a diverse set of goals from a myriad of stakeholders?

Strong coordination of technological, economic and regulatory approaches is clearly imperative for a well-functioning strategy to achieve the greatest benefit for the greatest number. The present research facilitates such coordination. Consider that technological progress in the transportation sector can be measured through historical trends, for example in vehicle efficiency. And further consider that the regulated consumer marketplace is a useful macro level tool by which to judge how effectively the three aspects of technology, economic viability, and social consequence interact to affect the modern vehicle fleet. The fleet has evolved dramatically along multiple axes, and this research helps quantify the extent to which consumers today enjoy more functionality and choice at a better value than at any time in history.

Thus, by integrating research approaches across multiple disciplines, a range of improved tools are made available to decision makers from the comparative value proposition of modern fuel saving technologies to the specific energy and emissions profiles of given vehicle types and localities. Though debates ensue over how long fossil fuel supplies may last, it is without doubt that liquid petroleum fuels will fail to provide a permanent, sustainable or environmentally benign supply of energy for transportation needs in the long term. Technology will be a key driver in lasting solutions, but its ultimate success will hinge upon socially conscious and economically reasonable implementation at scale.

A multi-discipline approach is not undertaken without its own set of challenges, however, given the vast array of literature and complicated interactions implied. In brief, it is the intent of this research to model both fundamental components and systems using a necessary and sufficient level of fidelity and mathematical detail. Successful integration of multiple perspectives can lead to timely, unbiased, and academically rigorous insights. These outcomes can simultaneously improve the relevance and accuracy of high-level modeling, a contribution that is greatly needed to add credibility and motivate prioritized and responsive action by all stakeholders.

Given the prevailing sense of urgency, gravity and complexity to address energy and emissions challenges, timely and effective actions are warranted. This research aspires to narrow the gap between often disparate dialogues on transportation technology, economics and policy. The principal motivation of this dissertation is to provide novel interdisciplinary methodologies for investigating vehicle energy consumption toward the broader goal of a more technologically advanced and sustainable energy future.

1.2 Historical Trends and Vehicle Utility

Due to the urgency and multi-faceted nature of efforts to reduce fuel consumption in ground transportation, it is critical to establish a robust framework from which to objectively assess technological innovation with regard to economic practicability and consumer preference. A primary means of achieving this in the present work is to draw from both historical and contemporary data to develop measures of consumer utility in passenger vehicles from representative parameters and to quantify the relationship between technological progress and vehicle prices over time.

By most all measures, new vehicles available today are dramatically superior to those available even 20 years ago. This includes major strides in safety, performance, environmental impact, and even fuel efficiency on a power- and weight-specific basis. Stemming from the reality that consumers buy cars, not features, is the caveat that standard features are bundled by the original equipment manufacturers (OEMs), which can lead to complications in disaggregating feature contribution from overall utility. Power, acceleration time, torque, engine displacement, weight, fuel economy, passenger and cargo space, safety, and price constitute primary factors that contribute to utility and value. While prior studies have done an excellent job characterizing innovation trends and technological trade-offs among vehicle attributes [5-11], the research record is deficient when it comes to analytically connecting such trends and trade-offs with vehicle prices. It is further lacking in utilizing econometrically-determined trade-offs, which may differ substantially from technological trade-off rates, to compare historical and contemporary trends under varying degrees of regulatory constraint.

While it is not surprising that current consumer utility levels are at historical highs, a more comprehensive characterization of the linkage between historical trends in vehicle technology and vehicle price is much needed, particularly at the system attribute level. This has obvious implications on the realistic limitations of pending efforts to reduce oil consumption and emissions in the automotive sector. Advances in data accuracy and availability for both technological and economic metrics underpin the merit and statistical reliability of the approach. Historical perspectives and objective measures of utility are foundational to broader research efforts because they leverage revealed trends and develop a useful interdisciplinary methodology by which to assess future technological advancement.

1.3 Relative Weighting and Willingness to Pay for Vehicle Attributes

Similarly, a temporal sense of the relative weightings of specific vehicle attributes, as determined by implicit pricing methods, has not been adequately investigated in view of fuel economy compliance with future regulatory standards, or with regard to trade-offs between other measures of utility. The techno-economic approach of this study considers the time response of relative weightings among attributes with significant energy implications, such as fuel consumption, acceleration, and weight. One can infer that consumers have become accustomed to both the current attribute levels and conditioned to the upward trends associated with vehicle technologies, in particular by classification. It may be hypothesized that rational consumers will not willingly trade off a given level of utility in a given attribute, unless it is either justified by a related improvement in another; or unless otherwise compelled to do so, for example due to financial or regulatory constraints.

In view of this, hedonic modeling approaches are applied to market-based datasets to determine the partial derivatives of individual attributes with respect to vehicle prices. These partial derivatives, or price elasticities, represent consumers' willingness to pay for individual attributes ceteris paribus, or holding all others constant. The response of these price elasticities over time are substantially influenced by many factors, including notably, fuel economy regulations. Owing to the emphasis of current regulations on sales-weighting and vehicle classification, this study introduces novel statistical means of discretizing price elasticities into bins by vehicle footprint (defined as the projected area of the wheelbase times the average track width). Investigations into correlations between innovation and price, relative weightings among key attributes, and footprint-specific price elasticity trends have considerable technological, economic and policy value. Taken along with established correlations for technological substitution, the results fill a critical gap in quantifying consumer response to regulations and the associated value and uptake of fuel saving technologies in view of other vehicle attributes.

1.4 Advanced Vehicle Technologies

The literature, areas of active research, and commercial market suggest a manageable subset of popular and effective vehicle technologies which demonstrate the greatest potential to reduce oil consumption and emissions in the automotive sector. Many technologies follow an evolutionary path and can be readily incorporated into annual or biannual product “refresh” cycles. This subset includes advanced transmissions, reductions in weight, friction or aerodynamic drag, and certain modifications to the internal combustion engine. Discrete and continuous valve actuation and timing strategies, and cylinder deactivation are examples of relatively minor engine modifications. These technologies deliver modest fuel savings and carry generally lower costs, factors which have spurred their commercial growth. For example, the family of variable valve technologies (VVT) and 6-speed transmissions (AT6) are largely standard equipment from model year 2013 onward, reaching market penetration rates of 96% and 64% respectively [12].

For other technologies, longer redesign cycles (on the order of 2-8 years) often typical of major engine components and other transformational technologies, prevail. This subset includes gasoline direct injection, turbocharging with engine downsizing, as well as hybrid and electric powertrains. It also includes switching from spark-ignited (gasoline) to compression-ignited (diesel) engines. In terms of growth rate, continuously variable transmissions (CVT) and hybrids (HEV) nearly doubled their market penetration between 2008 and 2013, while turbos with downsizing (TRBDS) and gasoline-direct injections (GDI) increased six-fold and ten-fold, respectively during the same period. Though not exhaustive, these technology categories comprise the principal set with the greatest potential to favorably influence fuel economy and emission trends over the next decade. While these technologies represent impressive innovations, comprehensive and integrated efforts to prioritize their impacts, optimize economic practicability, or ensure alignment with the goals of regulatory policy are often insufficient. Furthermore, hybrid and electric vehicles incur additional energy demands imposed by resistive losses, cabin and battery heating and cooling, as well as the need to transport increasingly heavy battery and electronic systems. In view of prevailing regulations, objective techno-economic studies that directly compare the energy, emissions and cost impacts of conventional internal combustion engine vehicles with advanced vehicles are therefore critical.

1.5 Measuring the Energy Efficiency and Emissions Attributable to Vehicles

Fuel economy (FE) and fuel consumption (FC) have been the primary metrics for assessing energy efficiency in passenger cars due to the historical prevalence of petroleum fuels and internal combustion engines. In North America, fuel economy is a familiar vehicle characteristic and is expressed in miles per U.S. gallon (mpg) of gasoline or diesel fuel. The Environmental Protection Agency (EPA) utilizes three different definitions for fuel economy depending on the context and use. These include: the estimate determined by standardized laboratory dynamometer evaluation, the adjusted value to correct for real-world driving, and the value used to calculate regulatory compliance by automaker, respectively [13-15]. In many other regions of the world, including continental Europe, a fuel consumption value, or fuel consumed to travel a given distance, is more commonly reported, often in units of liters per 100 kilometers (L/100km).

Fuel consumption is preferred over fuel economy in technological studies due to the direct objective of reducing fuel. It is also preferable in economic assessments as a measure of consumer utility since it scales linearly with consumer-incurred costs per distance driven (notwithstanding fuel price variability). In this dissertation, fuel consumption is used in actual calculations and derived from or converted to the appropriate EPA fuel economy value as necessary. Since economic and policy aspects of this study are predominantly focused on relative fuel economy improvements over base technologies, since FE is used in current regulations and is familiar among consumers in the United States, and to facilitate comparisons with other studies, fuel economy is often reported. In such cases it will be specified which fuel economy definition is applicable.

For vehicles that operate in “all-electric” or “charge depleting” (CD) modes, substantial unknowns are introduced related to the native energy source employed for electric charging. In order to provide a baseline reference from the standpoint of the vehicle boundary itself, the concept of equivalent fuel economy has been introduced, expressed as miles per gallon equivalent or, “MPGe,” yet can be a source of potential confusion [16-17] because it excludes consideration of energy sources upstream of the vehicle itself. From a thermodynamic perspective, it is essential to evaluate energy consumption (EC) and energy efficiency using consistent system boundaries, methodologies and bases regardless of the upstream energy resource. In respective portions of the comparative analysis, this dissertation considers energy consumed on a vehicle-basis (i.e., considering the fully-fueled or fully-charged vehicle as the boundary), as well as energy consumed on a system-equivalent basis (i.e., in consideration of the upstream energy sources).

Similarly, the measurement of emissions attributable to vehicles should include both tailpipe and upstream sources. For conventional vehicles that consume liquid fuel, DOE and EPA, among others, provide fuel specifications and useful conversion guidelines to estimate equivalent CO2 emissions per mile from fuel economy based upon average gasoline, diesel and ethanol properties [18-21]. With the increasing use of grid-derived electricity in vehicles and interest in comparative studies, the need for accurate system-equivalent emission accounting approaches becomes essential. Source emissions have signatures tied to the relevant energy conversion technologies and can be approximated from sub-region data for domestic utility networks, for example as described in the EPA eGrid 2010 assessment [22]. Given that direct correlations between fuel economy and emissions are no longer categorically applicable, this research undertakes a comparative approach to provide a more complete characterization of the primary emissions associated with advanced vehicle architectures.

Additional definitions and information on fuel economy, equivalent fuel economy, energy consumption and emissions can be found in Appendix A and C.

1.6 Benefit-Cost Assessments

A discounted cash flow rate of return (DCFROR) evaluation is an important financial approach for assessing project worth, and frequently preferred when the time horizon suggests a meaningful sensitivity to the time value of money. Further, benefit-cost analysis is a particular DCFROR which facilitates direct comparisons between multiple options. Benefit-cost analysis can be applied to private, single-party projects such as an individual purchasing an automobile, or an OEM selling millions of them. Similarly, they are often employed to assess the economic viability of a large scale regulatory change, or civil infrastructure project. While it is important to clearly define the scope, relevant perspectives, baseline assumptions, discount rates, valuation methodology, and overall objectives, benefit-cost analyses represent a powerful tool for evaluating transformations that involve energy and emissions reductions. With regard to vehicle technologies, there is good precedent for utilizing incremental retail price equivalents (in $) and fuel economy improvements (in percent change) to both assess historical trends and predict future ones. Some studies develop technology-specific analyses to predict technical readiness and future costs using computer simulations or tear-down approaches [23-24]. A tear-down approach estimates costs and feasibilities associated with the design and manufacture of new products by aggregating constituent components of a larger system in a bottom-up manner. Other studies evaluate pay-back periods or costs and benefits associated with conserving energy using a range of new vehicle technologies [25]. Both methods generally rely upon market-based cost information and reveal timely insight regarding the equilibrium of supply and demand for fuel saving technologies. Given the aggressive rate of statutory improvements that are called for over a more extended period of time, technologies and their costs are changing more quickly than in previous periods of regulatory constraint. The present marketplace is forced to adapt to such fluid conditions, while the governing regulations, by nature, are less flexible, fixing targets that will sometimes be in effect a decade or more into the future. The present work explores benefit-cost analyses toward quantifying the extent to which novel fuel saving technologies are financially attractive to consumers, how their value proposition may evolve in the future, and how technology, consumer choice and regulation work together to affect positive reductions in energy and emissions.

1.7 Current Policy and Compliance

The Renewable Fuel Standard (RFS) and the Corporate Average Fuel Economy (CAFE) standards comprise seminal U.S. policies that regulate the consumption of renewable fuels and fuel economy and emissions standards for new light duty vehicles, respectively [26]. Alternative fuels are a significant aspect of reducing oil consumption and transportation related emissions, and can interact synergistically with new vehicle technologies to ensure more optimal outcomes. Despite this, the primary focus of this research is on the various vehicle technologies themselves, their associated costs and efficiencies, and how they are integrated into a regulated market. The RFS and alternative fuels fall outside this scope. CAFE standards were introduced following the oil crisis of the mid-1970s and were an effective regulatory tool for ensuring that passenger-vehicle (CAFE compliance value basis) fuel economy would double from about 14 to 27.5 miles per gallon by 1990. A revitalized CAFE standard was formally signaled in 2007, under the Energy Independence and Security Act [26], which originally called for CAFE standards to reach a combined car/truck performance of 35 mpg by 2020. This target was effectively pulled ahead to about 2016 with the final 2012-2016 model year (MY) rulemaking [15], followed by annual increases to an equivalent fuel economy of 54.5 mpg by 2025 [27]. Due to CAFE's parallel objectives of improving vehicle efficiency and reducing emissions, U.S. regulatory authority is charged to the Department of Transportation's National Highway Traffic and Safety Administration (NHTSA) and the Environmental Protection Agency (EPA) respectively. To comply with existing regulations, automakers are increasingly bundling fuel-saving innovations into a variety of existing and new vehicle models which have successfully met both consumer and regulatory demands to date. From the 2011 through the 2014 model years, the passenger car fleet has improved from 33.1 to 36.5 miles per gallon (CAFE) on a sales weighted basis, outperforming the Federal standard by 8.0% in 2012, 7.8% in 2013, and 7.0% in 2014 [28]. In a similar fashion, sales-weighted CAFE performance for the entire light duty fleet, which includes all cars and light trucks, increased at a rate of 4.3% in 2011, 3.1% in 2012 and 3.0% in 2013 [29]. The goal of CAFE is to establish robust regulations that carefully balance consumer utility and choice with aggressive goals to reduce the national consumption of petroleum fuels and related emissions. The regulation cites “economic practicability” as an underlying premise noting attention must be given to “the uncertainty surrounding market conditions and consumer demand for fuel economy in addition to other vehicle attributes” [27]. In this fashion, the merit of an interdisciplinary techno-economic investigation so motivated is reinforced by the policy itself.

Through model year 2015, automakers also known as Original Equipment Manufacturers (OEMs), have been able to meet and even exceed the more stringent requirements by pulling ahead existing fuel-saving technologies and by adjusting business strategies and sales portfolios. A great deal of investigation, public-private consultation, and modeling based upon then current information provided the framework for the rules regulating 2012-2016 and subsequently 2017-2025 model year vehicles. That notwithstanding, such processes are admittedly uncertain, particularly with respect to implementation aspects of the final rulemaking over the mid- and long-term. Commodity price volatility and the dynamic nature of the energy and vehicle marketplaces represent additional sources of uncertainty that can affect the modeling predictions and expected outcomes of the policy including the potential to realize targeted levels of fuel and emissions reductions. While continuous feedback for decades-long regulations would be impractical, gaps exist in the research that, if addressed, could ameliorate the overall impact of the policy, and provide the principal stakeholder groups salient, timely and actionable information. A critical mid-term assessment of CAFE 2017-2025 is specified by rule to occur in 2018 [15] supported by federal agencies, OEMs and relevant stakeholders; and promises to assess compliance trends and highlight the actual impacts of the policy. It may also provide a retrospective opportunity to quantify the real-world value that consumers will have obtained from new technologies relative to the more conventional ones they are replacing. Before that, however, timely questions are raised concerning how closely costs, fuel economy improvements and the recently promulgated regulatory standards align. It is the intent of the CAFE policy to promote holistic outcomes as evidenced by specific references of the rulemaking. “In addition to saving consumers money at the pump, the agencies designed their final standards to preserve consumer choice—that is, the standards should not affect consumers’ opportunity to purchase the size of vehicle, with the performance, utility and safety features that meets their needs” [27]. To the extent costs, consumer choice and regulatory standards align well, OEMs can be expected to increase the number of models that comply and be able to attract consumers to purchase the ones that do. Such an assessment of this alignment may prove valuable to a wide range of stakeholders, including researchers in transportation and energy, economics and policy, as well as consumers and OEMs.

1.8 Objectives

The overall objective of this thesis is to study new light duty vehicle technologies that can lead to reduced energy consumption and reduced emissions in the transportation sector, and to investigate cross-cutting implications of their deployment including economic practicability, environmental and social impacts, as well as compliance with regulatory policies. The constituent objectives and approach are as follows:

1. Develop objective measures of consumer utility in passenger vehicles from representative parameters in order to quantify technological progress over time. Compare historical and contemporary trends describing innovation progression as

revealed by correlations between major vehicle parameters such as fuel economy, acceleration time, and weight.

2. Characterize the relationship between passenger car utility as defined by constituent technological attributes and real price response via statistical analysis.
3. Investigate the disaggregated contribution of vehicle attributes to total vehicle price via analysis of variance methods. On a fleet-wide basis, quantify passenger car consumers' willingness to pay for specific vehicle attributes over time via hedonic price modeling.
4. Examine consumers' willingness to pay for reductions in fuel consumption and acceleration time as functions of vehicle classification. Investigate the implications of these findings in view of the sales-weighting and footprint-based aspects of current regulations.
5. Identify and analyze primary vehicle technologies that contribute to improved fuel economy and reduced emissions. Populate a database with vehicle sales by model, engine type, specifications, standard options, other options influencing fuel economy, and all associated costs drawing from research literature, published vehicle specifications and official test results reported by government agencies.
6. Develop a benefit cost model to assess the estimated fuel savings versus costs of new vehicle technologies from a consumer perspective. Estimate differential fuel economy improvements by comparing new technologies to baseline technologies that share identical vehicle platforms. Disaggregate fuel-saving technology costs from total costs by applying an incremental retail price equivalent approach.

7. Characterize the relationship between fuel economy improvement and incremental cost for best-selling passenger car vehicles. Observe the relative value proposition of major fuel saving vehicle technologies as compared to each other and to a breakeven baseline scenario. Perform a sensitivity analysis on the results to determine the significance of both controllable and uncontrollable factors.
8. Develop hierarchical vehicle propulsion and thermal management models for investigating primary and auxiliary energy demands imposed on vehicle energy systems. Simulate the energy consumption response and sensitivity to the combined effects of varying driving cycles and ambient temperatures for a range of representative vehicle architectures.
9. Develop a basis for comparing vehicles that employ different energy sources. Perform a first law thermodynamic investigation of energy consumption per distance traveled first at the level of the vehicle boundary, and subsequently in consideration of upstream factors. Quantify the sensitivities of vehicle energy consumption and emissions to locality in consideration of electricity generation, refining efficiency, temperature characteristics and other geographically-dependent attributes.
10. Introduce tools capable of provisionally estimating anticipated future costs of fuel economy improvements and consumers' future willingness to pay for defined levels of fuel economy gains. Discuss the propensity of the foregoing to align with predictions of future fuel economy costs given by U.S. regulations.

1.9 Organization of the Dissertation

The work presented in this dissertation is organized into six chapters. Chapter 1 introduces the context and the motivation for the research. Primary objectives, approach methodologies, definitions and organization of the work are described. Chapter 2 reviews representative literature for focused efforts to deploy vehicle technologies that reduce fuels and emissions in the transportation sector. Owing to the interdisciplinary approach of this research, a wide variety of literature is relevant to the topic, including technological, economic, environmental, social, and policy perspectives. Such perspectives are naturally drawn from principal stakeholder groups that include the academic research community, automakers and government agencies.

Chapter 3 presents quantitative trends in major passenger car attributes and selling prices over a 37 year period from 1978-2014. It defines a specific objective function for utility, develops a correlation between consumer utility and price, and introduces a methodology whereby the relative weighting of and consumer valuation of vehicle attributes can be determined. Chapter 4 presents a detailed assessment of the benefits and costs associated with new vehicle technologies and fuel economy in the U.S. market. It quantifies the extent to which modern passenger cars comply with stringent regulatory policies. This chapter also provides a review of primary fuel saving technologies, comparing them to one another as well as to a break-even baseline scenario. The uncertainty of the estimates is addressed by virtue of a sensitivity analysis on key economic and vehicle specific factors. Chapter 5 presents a thermodynamic modeling approach to studying vehicle primary energy and auxiliary thermal loads, particularly with regard to new vehicle architectures. Drive cycle and ambient temperature impacts on energy consumption are quantified. The results are leveraged to investigate the locality-dependence of upstream energy and emissions for each vehicle architecture.

Finally, Chapter 6 discusses major conclusions, key perspectives, and implications of the work. It includes a summary of various techno-economic methodologies for characterizing the correlation between consumer costs and future levels of increased fuel economy. These correlations are viewed against regulatory estimates for the purpose of addressing opportunities and challenges associated with future compliance scenarios. The chapter closes with several suggestions for future work including investigations into light duty trucks and enhancing key comparative simulations via parametric modeling of vehicle technologies and their associated costs.

CHAPTER 2. LITERATURE REVIEW

Owing to the interdisciplinary nature of research into vehicle technologies that contribute to fuel and emissions reductions, a substantial set of relevant literature exists. This provides opportunities in the form of numerous independent perspectives and timely research findings, as well as certain challenges associated with the need to establish a manageable and focused scope, to maintain continuity in definitions and to be objective in purpose. This chapter presents a high level overview of the context and major perspectives of the general field followed by a detailed narrative summarizing prior research in three well-defined and thematic areas, related knowledge gaps and the contribution of this dissertation in addressing them. Selected material from Section 2.1 was published in Understanding the Global Energy Crisis, Purdue University Press (2014) 215-239 [30]. Material from Section 2.2 has been submitted for publication in Transportation Research Part D: Transport and Environment [31]. Material from Section 2.3 was published in Applied Energy (157 (2015) 940-952) [32]. Material from Section 2.4 has been submitted for publication in Applied Energy [33].

2.1 Background and Motivation for Reducing Energy Consumption in Transportation

While the oil dependency of major consuming countries varies, the United States is not unique with a transportation sector that accounts for about 28% of total domestic energy consumption and a similar percentage of greenhouse gas (GHG) emissions [2-3]. Increased commercial deployment of advanced vehicle architectures is regarded by major economies as a significant means of reducing fuel use and emissions in the coming decades. A myriad of studies have performed scenario projections based upon energy and climate policies and targets, including works by the International Council on Clean Transportation (ICCT) and the International Energy Agency (IEA). ICCT has projected that vehicle technologies, biofuels and reductions in vehicle miles traveled would need to contribute equally to meet a nearly 30% reduction in fleet petroleum use by 2020 [34]. The analysis also projects the share of petroleum reduction attributable to vehicle technologies should grow to beyond 50% by 2030 to maintain aspirational targets. In its so-called “blue-map” scenario which calls for aggressive deployment of new vehicle technologies [35], IEA projects that while light duty vehicle demand will climb, the market share of conventional gasoline and diesel vehicles will plateau by 2020, and be replaced by increasing shares of hybrid, electric and alternative powertrains as shown in Figure 2.1.

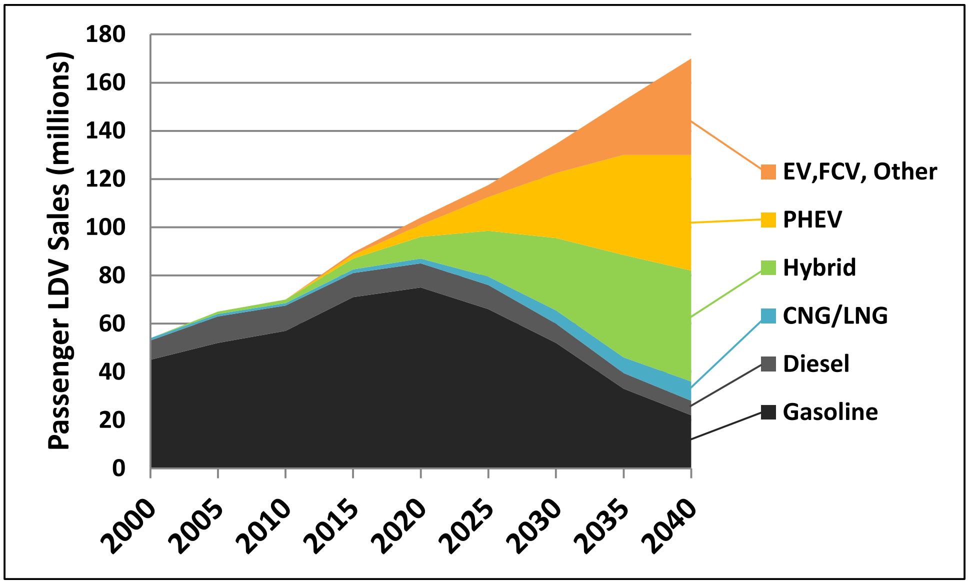

Figure 2.1. IEA "Blue Map" projection of light duty vehicle (LDV) sales through year 2040.

Figure 2.1 Legend: EV=Electric Vehicle; FCV=Fuel Cell Vehicle; PHEV=Plug-in Hybrid Electric Vehicle; CNG=Compressed Natural Gas Vehicle; LNG=Liquid Natural Gas Vehicle. Data source [35].

The U.S. government projects that greenhouse gas emissions from the transportation sector will actually experience slight progressive declines from 2010 baselines in 2020, 2025 and 2030 [36]. Interestingly, this makes transportation unique as the only major U.S. GHG inventory reporting sector expected to experience such reductions. These projections are largely underpinned by substantive technology and policy-making initiatives by major U.S. government agencies, highlighted by RFS and CAFE regulations. In 2011, DOE rolled out its first ever Quadrennial Technology Review (QTR), in which innovation roadmaps toward improved vehicle engines, weight aerodynamics, electrification, fuels and infrastructure were presented [37]. The Energy Information Administration (EIA) reported in its 2013 Annual Energy Outlook that motor gasoline consumption will reflect more stringent fuel economy standards, that renewable fuel use will grow at a much faster rate than fossil fuel use, and that U.S. energy-related carbon dioxide emissions will remain below their 2005 levels through 2040 [38]. For more than a decade, fuel consumption and emissions reductions in transport have been addressed largely by regulatory processes initiated by the executive branch, as opposed to taxes, fiscal legislation, or other market-based approaches. Emphasis on the energy efficiency of homes, buildings and vehicles, as well as on stimulating research and development toward low carbon technologies are in fact two of three major goals of the 2011 White House "Blueprint for a Secure Energy Future." [39]

The focus on transportation energy addresses the twin goals of mitigating petroleum dependence and domestic emissions. Such policies are more palatable domestically, in part because citizens are tax averse, and perhaps also because fuel and emissions reductions have historically been highly correlated and result in mutual benefits. Many researchers correctly point out that climate change is, in general, a "global commons problem" in which "most benefits of mitigation are global and distant, while costs are local and immediate." [40] In some sense, energy used for transportation may be an exception. While the geographic and temporal dimensions may account for inaction in a broad global sense vis-à-vis energy and climate, the 50 United States, both collectively and individually, have tapped and untapped opportunities to benefit from a lower carbon transportation sector and should continue to leverage both national and local policies toward mitigation efforts.

Because of the magnitude and uncertainty associated with national and global efforts to reduce or replace fossil energy, a large literature exists regarding benefits and costs of energy and emissions reductions across a wide spectrum of sectors and research areas. Efficiency improvements are widely viewed as available technologies, capable of being deployed rapidly, and can therefore result in the greatest economic and environmental benefits in the near term. This focus on the economic potential of efficiency was the subject of two seminal reports by McKinsey, in which benefit/cost analyses and CO2 abatement values were generated for a broad range of efficiency applications in both the electric power and transportation sectors [41-42]. By focusing on specific technologies, paybacks and the effective net present value of comparative options, studies such as these set an excellent precedent for objective techno-economic energy analyses.

Many key technologies currently in development may facilitate progress toward passenger car fuel economies in the 40 mpg range, however wide uncertainty accompanies economic payback estimations. Near term efficiency gains across all vehicle classes will result in the greatest energy and emissions savings, as the incremental improvement over a fixed base value will diminish with each successive year. This aspect of the current policy is potentially problematic since the largest fuel consumption reductions occur in the earlier years, whereas costs may escalate beyond reasonable levels in the latter years [43]. To comply with official CAFE targets within this decade, recent estimates predict that technology upgrades will result in cost premiums in the range of $1600–$4750 (in 2014$) per vehicle at production scales [43-45]. Many believe that these investments are justified, given that they will be offset or exceeded by fuel savings. However, the volatility of gasoline and diesel prices introduces complexities to predicting benefit/cost ratios with certainty [30,46]. As such, a comprehensive investigation of primary technological, economic, consumer and regulatory factors associated with energy reducing vehicle technologies is of considerable value and has broad applicability to a wide range of stakeholders.

2.2 Fuel Economy and Vehicle Attribute Valuation Trends

The availability, utility and value of new automobiles and their constituent features vary widely, have increased steadily over time, and strongly reflect a diverse range of consumer preferences and value propositions. Studies performed by the academic research community, specific OEMs, regulatory agencies, as well as consumer reporting groups may be written with differing objectives for a variety of audiences, but are generally in agreement that considerable technological progress, in quantifiable and objective terms, has been achieved over the past four decades.

2.2.1 Vehicle attributes that contribute to consumer utility

Vehicle buyers generally value an extensive set of both objective and subjective factors. From the more objective traits to the more subjective ones, these include [47-52]:

- Purchase price,
- Resale value,
- Cost to operate,
- Capacity (passenger or cargo space, physical size),
- Performance (power, torque, acceleration, ride),
- Fuel economy,
- Safety (crash worthiness, safety ratings, installed safety equipment),
- Aesthetic value (luxury, comfort, styling),
- Standard or optional equipment,
- Brand reputation,
- Quality,

- Warranty and reliability,
- Environmental impacts,
- Comparative consumer ratings, and
- Personal experience.

Several consumer-review databases provide objective comparisons for many of these parameters, by way of providing overall ratings between vehicles within common classifications [49-50]. Stemming from the reality that consumers buy cars, not features, is the caveat that standard features are packaged together by the OEMs, which can lead to complications in disaggregating feature contribution from overall utility. However, via sophisticated and evolutionary product development processes, OEMs arrive at groupings of characteristics by integrating regulatory, consumer preference, macroeconomic, and competitor benchmark data into new vehicle specifications and design [53]. Thus, consumers and OEMs mutually reinforce product attributes subject to regulatory constraints, including bundles of attributes and relative weightings among attributes that deliver increasing utility [53].

In view of the complexity and potential uncertainty introduced by surveys that reflect stated consumer preferences, revealed behavior has been demonstrated to provide a more accurate reflection of consumer preference [54]. In short, what a consumer actually chooses may be more useful data than what a consumer may say in a survey. Similar research speaks to the nature and applicability of automobile attributes, showing that tangible attributes, such as price and performance, are more consistently revealed and valued in actual consumer choices than intangible attributes, such as prestige or comfort [54]. We therefore track historical and tangible measures of consumer utility through the lens of observed consumer acceptance. One challenge is to select an appropriate subset of objective and appropriately weighted product attributes for which long term data exists, and to subsequently leverage consumer responses and pricing signals in the interest of informing future projections. Since the 1970's, research in this family of topics has been somewhat bifurcated- it has either been studied in a top-down fashion by economists interested in high-level market and fleet-wide policy implications, or from the bottom-up by engineers and product developers focused on the constituent vehicle technologies themselves. One of the aims of this study is to lay a foundation for stronger linkages between the detailed economic and technological considerations of modern vehicles.

2.2.2 Disaggregating bundled vehicle attributes

From an economic and regulatory perspective, several seminal research studies have attempted to disaggregate the specific factors driving consumer preference and product utility since the introduction of the first U.S. fuel economy regulations in the late 1970's. Researchers Lave and Train (1979), observed that then-current models included only price and fuel economy, and therefore proposed a Multinomial Logit (MNL) approach in which characteristics such as weight, external dimensions, passenger space, horsepower, and so on, could be included in the models [47]. Manski and Sherman (1980) utilized Hedonic Demand Modeling (HDM) methods that included five primary attribute categories with the following characteristics: passenger carrying ability, cargo carrying ability, performance, cost and style [55]. A unique emphasis of this study was to consider the combined effects of household and socioeconomic influences along with vehicle attributes on utility. Greene and Liu (1988) used consumer surplus as a primary means of disaggregating the particular contribution of fuel economy in the overall vehicle utility [56].

Ohta and Griliches (1986) used hedonic approaches to investigate the impact of gasoline prices on the tastes of new vehicle buyers [57]. Alcott and Wozny (2014) sought to better quantify this relationship, positing in one scenario that consumers appear to value discounted future gasoline costs only 76% as much as they value purchase prices [58]. Under a variety of scenarios and assumptions, Busse et al (2013) find little evidence of consumer myopia about future fuel costs, suggesting most implicit discount rates range from near zero to less than 20% [59]. However, opinions on this issue are mixed as several researchers have suggested that the market for fuel economy does not function efficiently [58,60-62], with consumers often undervaluing its benefits. Recent studies have further improved upon prior models by considering that certain factors can indeed be endogenous, whereas earlier models assumed all factors were exogenous and therefore did not contribute to internal correlations [63-64].

Since the relatively recent implementation of more stringent U.S. Corporate Average Fuel Economy (CAFE) standards begun in model year 2012 [15,27], few studies have detailed the impacts of new regulations on the rates of consumer acceptance, technology adoption, or corresponding prices [65]. What remains under-researched are analyses that quantify the extent to which the prescribed tighter fuel economy standards affect other vehicle characteristics, and importantly, the market price impact of such technological trade-offs into the coming decade. Given the emphasis of the new regulations on vehicle footprint and sales weighting [15], characterizations of consumer preferences and attribute valuations as functions of vehicle class are extremely limited, yet are critical to future compliance strategies.

Early studies motivated by system level economic analysis eventually gave rise to the use of aggregated vehicle utility modeling as a means of studying the weighting and impact of a particular attribute or set of attributes. Regardless of the method used or the underlying motivations, "utility" as defined in either economic or technological terms is an admittedly complicated "function" to parse into individual components. Precise prediction of attribute contribution to the aggregate is difficult, in part because numerous factors are involved and in part because some attributes are strongly correlated with others, or are jointly determined [7]. For this reason, rigorous technological perspectives are invaluable and complementary to economic and policy modeling.

Several examples from the literature have introduced simplified objective functions and models that predict binary technological trade-offs among attributes with remarkable accuracy. Variations on these approaches have been used, for example, to assess the impact of Federal Motor Vehicles Safety Standards over time, or to quantify the relationship between safety, cost and weight as performed by the National Highway Traffic Safety Administration (2004) [66]. One recent application of related research was a 2012 study of the German automobile sector where vehicle technologies and attributes were tracked against major OEMs to better explain key drivers of trends in market share [48].

Coinciding with revitalized legislation regarding U.S. energy policy [26], An and DeCicco (2007) introduced the so-called "performance-size-fuel economy index" (PSFI) [5], suggesting a sustained and linearly increasing trend of long-run technological innovation by the auto industry. PSFI is the product of three equally weighted objective measures of utility:

- Performance (engine power in horsepower divided by vehicle inertia weight in lbs, where vehicle inertia weight is defined by EPA to be vehicle curb weight plus 136 kgs.)
- Size (interior volume of the passenger compartment in cubic feet), and
- Fuel Economy (U.S. EPA laboratory rated combined city/highway fuel economy in miles per U.S. gallon, mpg).

By using sales-weighted vehicle attribute data from the EPA [13] as plotted in Figure 2.2, PSFI is an effective first-order indicator of utility in the U.S. market. For example, computing PSFI for the period of 1978-2014 for U.S. passenger cars suggests a 2.7% linear increase with an R^2 of 0.979 as illustrated in Figure 2.3 [5,13]. Please note that when introduced in 2007, PSFI used then-current definitions for EPA combined city/highway Fuel Economy (FE). In 2008, EPA introduced revised rules and definitions to better reflect real-world fuel economy as per [14]. As such, the 2.7% average compound annual rate of increase applies the original PSFI formula but uses new EPA FE definitions for adjusted fuel economy accordingly.

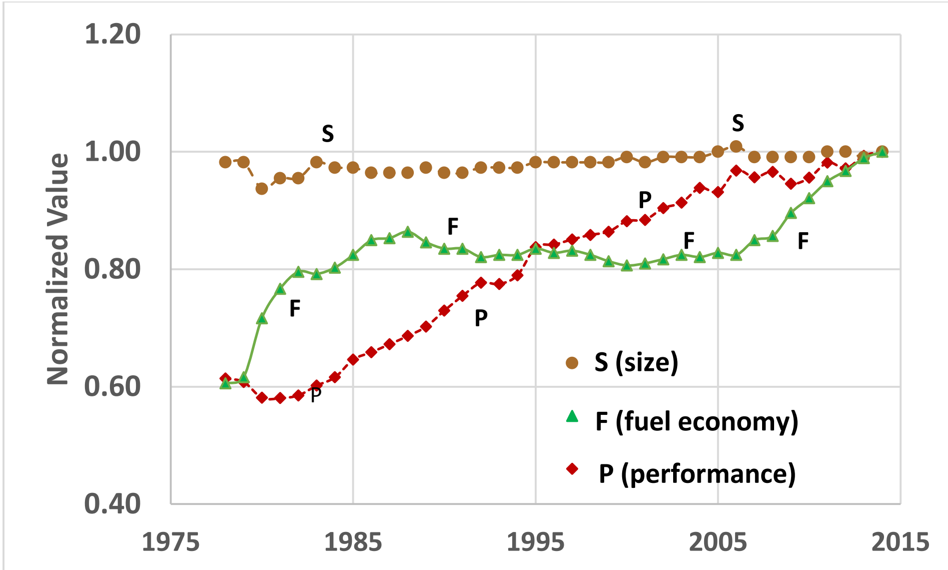

Figure 2.2. Trends in individual attributes of performance, size and fuel economy as per [5,13], 1978-2014.

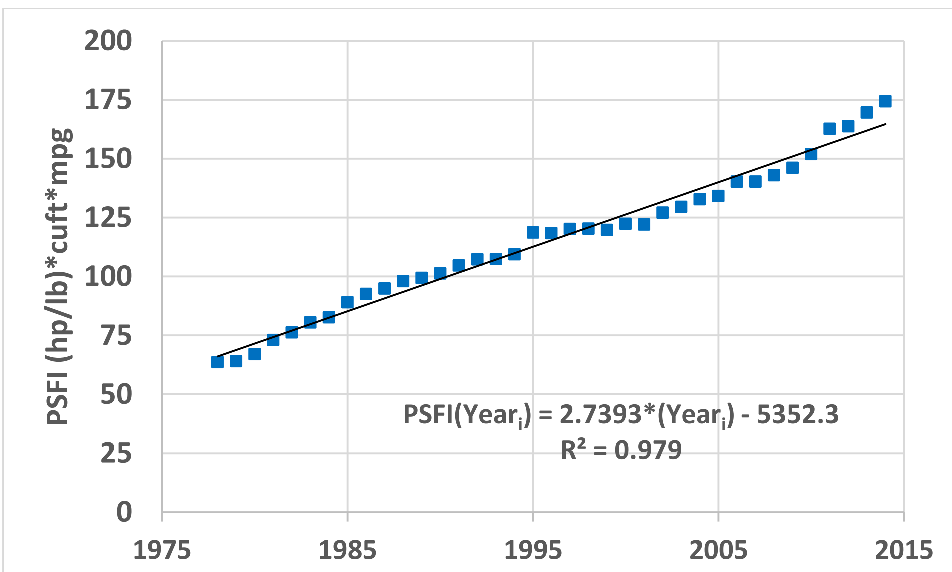

Figure 2.3. Performance-Size-Fuel Economy-Index (PSFI) Trends, 1978-2014.

2.2.3 Characterizing trade-offs among vehicle attributes

One of the potential shortcomings in PSFI is its allocation of equal weighting to the performance, size and fuel economy parameters. Knittel (2011) [7] and MacKenzie and

Heywood (2015) [8] have applied empirical models to historical records to estimate the elasticity of fuel consumption with respect to engine power, acceleration and weight confirming the trade-offs are not 1:1, suggesting that the parameters are “not of equal weight.” Kasseris and Heywood (2007) conducted system-level analyses to explore fuel saving powertrain modifications and suggest comparative advantages of future engine, aspiration, transmission and vehicle architecture technologies [9]. Cheah et al (2008) explored technological trade-offs among attributes with a focused view toward quantifying the extent to which fuel consumption reduction could be emphasized [10]. In follow up, Cheah and Heywood (2011) point out that prior CAFE compliance feasibility assessments do not detail or do not constrain deployment rates of new vehicle technologies; and do not appropriately account for technology improvement rates over time [6]. Prior studies also assume the performance and utility of vehicles will remain unchanged in the future, contrary to established history [6]. Both [5] and [6] helped inform an improved understanding of the constraints on future technological frontiers and implicitly or explicitly acknowledged that future consideration of economic impacts (not undertaken in their works) would have merit. Indeed, technological trade-offs not appropriately informed by the associated economic consequences have marginal applicability in realistic projections of future market trends. Given that CAFE standards are based on sales-weighted averages, both technological and economic aspects of attribute trade-offs add value to informing compliance feasibility.

In addition to sustained technological progress overall, it is obvious that innovation has manifested itself through specific attributes during specific periods of time, as Figures 2.2 and 2.3 illustrate. A more concrete and detailed view of temporal trade-offs, however, is warranted. As noted in Chapter 1, concerns that past technological innovation did not directly result in fuel or emissions reductions are profound and are a major driver behind renewed federal regulations. In a 2012 report on the evolution of specific vehicle attributes in view of historical trends, EPA observed:

> From model year 1987 through model year 2004, on a fleet-wide basis, automotive technology innovation was generally utilized to support market-driven attributes other than CO2 emissions and fuel economy, such as vehicle weight, performance, and utility. Beginning in MY 2005, technology has been used to increase both fuel economy (which has reduced CO2 emissions) and performance, while keeping vehicle weight relatively constant [67].

The present study aims to definitively capture the interplay between economic, technological and regulatory considerations by evaluating vehicle characteristics in context with trends in vehicle prices and regulatory constraints. It expands the prior work in significant ways by considering recent data up to and including 2014, a period of substantial flux with regard to fuel prices, the global economy, the health of the U.S. automotive sector, and regulations affecting new vehicle fuel economy and emissions. It captures innovation in critical technologies heretofore under-represented in previous studies, such as hybrids. By comparing historical vehicle fleet aggregate price elasticities with contemporary trim-level elasticities, it provides timely insight into the economic practicability of fuel economy across a spectrum of vehicle footprints. The characterization of linkages between technological progress and economic analyses leads to an improved understanding of the relative weighting and price elasticities for key vehicle attributes for which both long-run historical and near-term contemporary trends have timely implications.

2.3 Benefit-Cost Approaches to New Vehicle Technologies and Fuel Economy

As noted in Chapter 1, federal fuel economy policies are designed to simultaneously address key challenges and deliver tangible benefits to consumers, the economy, and the country as a whole. Fuel economy and emissions regulations along with other efforts to reduce oil dependence have indeed accelerated the global deployment of advanced vehicle technologies. Recent U.S. trends indicate that OEM compliance with CAFE standards is largely being attained, the policy has thus far been successful, and progress is on track [13,68]. A great deal of investigation, consultation, and modeling based upon then current information provided the framework for the rule regulating 2012-2016 model year vehicles. The Department of Transportation's National Highway and Traffic Safety Administration (NHTSA) and the Environmental Protection Agency (EPA) issued the Draft Joint Technical Support Document (TSD) specifically to document relevant technology performance and cost data available prior to rule issuance [69]. Such processes are admittedly uncertain, in part because subject estimates of technology, costs and fleet evolution are based upon projections drawn from 2008 and 2010 model year information [15], yet implementation of the regulations extends more than a decade into the future. Technologies are assumed to penetrate the market based upon a cost-effectiveness algorithm that compares the technology cost to the discounted stream of fuel savings and the value of performance to the consumer [70]. Though the source data detailed technology specificity [71] and delineated assumptions about fuel prices and discount rates, projections of fleet-wide impacts and vehicle sales by technology type were aggregated, making it difficult to explicitly determine the relative performance and cost-effectiveness of fuel savings technologies. In view of the need to validate economic practicability of compliance efforts in advance of the 2018 mid-term review, benefit-cost analysis can be viewed as an invaluable tool for making public or private assessments. This approach can be employed to assess the economic viability of specific technologies against absolute criteria as well as to compare them against other competing technologies.

2.3.1 Status and outlook for progressive fuel economy standards

Sustainably achieving compliance over a period of a decade or more, whether in the United States or elsewhere, requires that regulations be based upon the most current scientific and market-based data available, and appropriately address sources of uncertainty over time. While numerous studies quantify the benefits of fuel economy standards and project the composition of future vehicle fleets in 2035 or 2050 [72-76], researchers have suggested that the market for fuel economy does not function efficiently [58,60-62,77], with consumers often undervaluing its benefits. Given the sales-weighted emphasis of most policies, Greene suggested that “policy analysis must be based upon how real world markets actually function,” noting that costs and benefits may vary accordingly [77].

Due to the long lead-times typical of automotive design and the lengthy rulemaking process signaled under the Energy Policy Act of 2005 [78], OEMs began to increase internal CAFE metrics beyond the required level, even before the issuance of the 2012-2016 rule. This is illustrated in Figure 2.4 by the superior performance of the “Actual fleet” as compared to the “Avg Fed Std” fuel economy levels in the year 2010. One reason automakers have continued to exceed the minimum requirements in recent years is that they can generate credits for over-compliance within the current policy, and have the option of carrying them forward or backward, or trading them with other OEMs [27]. From the 2011 through the 2014 model years, the passenger car fleet fuel economy has improved about 10% to 36.5 miles per gallon (NHTSA/CAFE) on a sales-weighted basis, outperforming the Federal standard by 8.0% in 2012, 7.8% in 2013, and 7.0% in 2014 [28]. In a similar fashion, sales-weighted CAFE performance for the entire light duty fleet, which includes all cars and light trucks, increased at a rate of 4.3% in 2011, 3.1% in 2012 and 3.0% in 2013 [29].

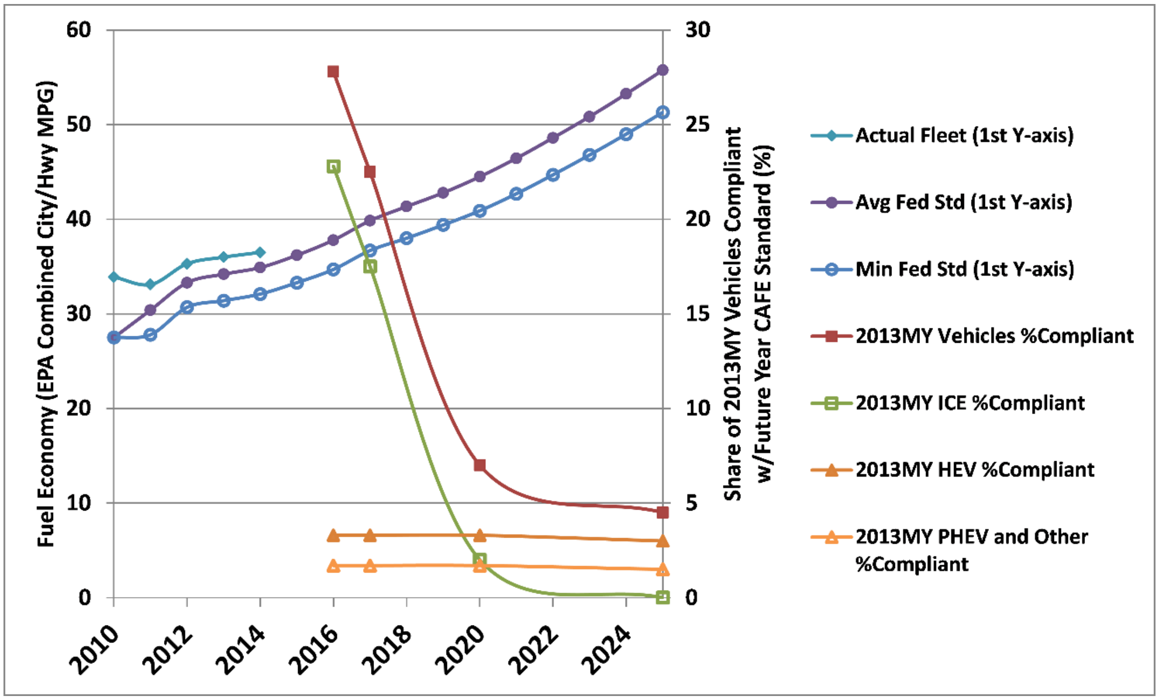

Figure 2.4. Passenger Car Corporate Average Fuel Economy (CAFE) actual fleet performance vs. Federal standards (left Y-axis); and approximate share of 2013 MY vehicles that are compliant with the Federal standard in future years (right Y-axis).

Figure 2.4 Legend: ICE denotes internal combustion engine; HEV denotes hybrid electric vehicles; PHEV denotes plug-in hybrid electric vehicles; “Other” includes electric vehicles (EV) and compressed natural gas (CNG) vehicles. Data sources: [28,68].

As mentioned, EPA and NHTSA regulations differ slightly. In Figure 2.4, an equivalent CAFE fuel economy standard that estimated an average of the two is shown, labeled “Avg Fed Std.”

A December 2013 EPA report indicates that 28% of MY2013 vehicles meet the 2016 standard [68], which varies slightly among the two regulatory agencies due to the regulation of CAFE vs. CO_2 emissions (34.1 mpg is NHTSA's CAFE goal for passenger cars, whereas 35.5 mpg is EPA's "CO_2 equivalent" goal) [15]. It should be noted that the exact regulatory standard is variable within annual limits due to the unknown sales mix and the footprint-specific approach, and also because the authority of NHTSA and EPA requires them to regulate fuel economy and GHG emissions respectively [15,27]. However, the standards on passenger cars roughly follow a 4.3% increase through 2016, and then a 4 to 5% annual increase beginning in 2017 and extending until 2025.

With this steady increase in requirements through 2025, the share of 2014 models that will be able to comply in that terminal year without further modification falls precipitously toward the end of the decade. Only 5% of all light duty MY 2013 vehicles appear to be compliant with the 2025 standards (which include CO_2 equivalent emission targets as well as fuel economy targets) [68]. Aside from today's hybrids, a portion of those that do are currently low volume, partially or fully-electrified platforms such as plug-in hybrid or electric vehicles which rely on a multiplier of the miles-per-gallon equivalent (mpge) to comply. CAFE regulations consider the vehicle itself, fully fueled or fully charged (using an energy conversion equal to the full calorific value of 33.7 kWh/gallon gasoline equivalent), as the system boundary. In other words, tailpipe emissions and on-board equivalent energy are the only variables considered in fuel economy estimates used in computing CAFE under the policy. For the purposes of fuel economy accounting under the rule, no consideration is therefore given to upstream electricity production, net system efficiency, or lifecycle energy-emissions. When running on all-electric mode, EV and

PHEV vehicles get CAFE credit for fuel economy values that are elevated even beyond the mpge basis, which is important to note as results are compared. The Department of Energy (DOE) studied U.S. average fossil-fuel electricity generation efficiency in 2000, determining it to be approximately ≈ 0.328 [79] and suggesting a method for calculating a petroleum-equivalency factor (PEF) that would provide an incentive to vehicles that employ electricity. The PEF is equal to 1/0.15, or about 6.7, as is intended to incentivize OEMs to produce and sell electric vehicles, and provide opportunities for significantly boosting CAFE compliance. The factor, however, does not accurately reflect the energy intensities of electric vehicles vs. internal combustion engine vehicles, nor does the mpge rating. Additional credits are assigned within CAFE regulations for alternative vehicles such as PHEV and EV to incentivize OEMs to sell them. Though the details of this accounting are beyond the scope of the present work, it is an important consideration in view of the impacts and implications of the various vehicle technologies addressed within the policy. Additional detail on fuel economy can be found in Appendix A.

Thus, two critical, but distinct, near-term challenges facing the industry today are approaches to increase the number of models that comply, and to attract consumers to purchase the ones that do. Regarding the first, the commercial introduction and deployment of an increasingly wide range of advanced technologies will be needed (see Chapter 4). Regarding the second, if the consumer is to benefit financially from stricter standards, costs must be offset by an equal or greater level of benefits to the consumer, and not just to society as a whole (see Chapter 4). As mentioned, in addition to striving to ensure technological feasibility, conserve energy and reduce emissions, the policy has a requirement to ensure "economic practicability." This has implications on the financial capability of the industry, jobs, and consumer demand for fuel economy in addition to other vehicle attributes [27].

The present assessment analyzes critical technologies in today's marketplace, discusses revealed consumer preference, and explores associated benefits and costs under a range of potential conditions. By taking a consumer perspective and analyzing specific vehicle models and technologies, the study provides insight into current-day economic practicality that has been lacking in previous studies focused on fleet-wide averages [72-76], or based upon past model years [15,45,74]. Uncertainty is addressed by means of a straightforward sensitivity analysis on economic and application-dependent parameters. The primary scope of this study is the U.S. passenger car market in 2014, with an emphasis on compact and midsize vehicles. This detailed study is confined to these segments because they are a representative subset of new car sales and, owing to their nature, basic design, and market demands, tend to incorporate a comparatively large number of fuel-saving technologies. This analysis includes 14 of the highest-selling passenger cars in the U.S. market for the period 2012-2014, or about 55% of the entire passenger car market. The data supporting this study are aggregated, and to the greatest practical extent, references to specific makes, models or proprietary technologies are limited so as to avoid any unintended bias toward or against a particular vehicle technology or brand.

2.3.2 Key fuel economy technologies and their estimated costs

An exhaustive review of all fuel-saving technologies introduced in U.S. cars is well beyond the scope of this paper. However, the literature and market suggest a manageable subset of the most popular and effective solutions that have now become commercially available. The process for revitalizing CAFE standards was formally initiated in 2007, under the Energy Independence and Security Act [26], which originally called for CAFE standards to reach a combined car/truck performance of 35 mpg by 2020. This target was effectively pulled ahead to about 2016 with the final 2012-2016 MY rulemaking [15], as illustrated in Figure 2.4. For some technologies, long redesign cycles (on the order of 4-8 years) often typical of engines and other transformational technologies, such as hybrid and electric powertrains, are the reality. Other technologies follow a more evolutionary path, can be more readily incorporated into annual or biannual design cycles, and include advanced transmissions, reductions in weight, friction or drag, and valve actuation strategies, for example [28,45,71]. These carry generally lower costs, but proportionally lower fuel savings as well.

Table 2.1 provides an overview of several major vehicle technologies that contribute to increased fuel economy. The methods and underlying detail for estimating 2014 MY costs emerging from the author's study are discussed in Chapter 4. The table includes data drawn from a comprehensive report on the subject prepared by the National Research Council [45]. In that study, which constituted one of many inputs to the Federal policy, ranges and average values for estimated fuel economy improvements and their associated incremental costs were presented by technology type and vehicle class based upon then-current technology and baseline fleet characteristics. Here, the NRC cost estimates are expressed in 2014 dollars, having been converted from a 2008$ basis via the consumer price index, or CPI [80]. Depending on the context, source and application, "incremental cost" can have multiple meanings. In order to reduce confusion, it is defined here to mean the value which equates to the consumers' retail equivalent price difference between a base technology and an upgraded one. In other words, it is the price difference due solely to the fuel economy technology.

One can get a sense for the recent commercial growth of these selected technologies by comparing their respective market shares among all new light duty vehicles (LDV) in the 2008 model year with the 2013 model year [68]. It is not surprising that the lowest-cost, most "evolutionary" technologies, such as variable valve technologies (VVT) and 6-speed transmissions (AT6), reflect the highest market shares overall (96% and 64%, respectively). However, in terms of growth *rate*, one notes that continuously variable transmissions (CVT) and hybrids (HEV) have nearly doubled, while turbos with downsizing (TRBDS) and gasoline-direct injections (GDI) have increased six-fold and ten-fold, respectively. Quantifying future market penetration, while estimated by previous studies [6,69,71,81], is inevitably uncertain, but can be in part be illuminated by revealed preferences in current model-year sales, adding to the relevance and timeliness of this study's approach.

Table 2.1. Overview of selected vehicle technologies that contribute to improved fuel economy, their approximate market share growth, their benefits and costs [45,68].

		Market Share (%LDV[1], est.)		**Fuel Econ Benefits** (average % diff)		**Incremental Costs** (est., in $2014)	
	Source:	[68]		[45] NRC[3] 2011	Authors	[45] NRC 2011	Authors
Technology Description [2]	Abbr.	MY2008	MY2013		**MY2014**		**MY2014**
Wt reduction (2 - 5%)	WT	-	-	2.5		280	
Aero. & frict. reduct.	AERO	-	-	2.6	**9.7**	133	**1,233**
Variable Valve Tech.	VVT	58.0	96.0	3.7		279	
Auto Trans. (6 sp)	AT6	19.0	64.0	2.6	**5.6**	510	**817**
Cont. Variable Trans.	CVT	7.0	13.0	4.3		266	
Gasoline Direct Inj.	GDI	3.1	30.0	3.1	**10.2**	324	**1,301**
Turbo & Downsizing	TRBDS	2.5	15.0	5.3		814	
Conversion to Diesel	Diesel	< 1.0	1.0	35.7	**21.8**	3,974	**4,005**
Hybrid	HEV	1.9	3.5	58.1	**58.1**	4,982	**4,098**
Plug In Hybrid[4]	PHEV	< 1.0	< 1.0	N/A	**91.1**	14,723	**8,849**

The notional data reflected in Table 2.1 for both fuel economy improvement and cost represent average values from both the NRC study and a preview of some of the results of the author's analysis in Chapter 4. Regarding technology definitions, in most cases the

[1] %LDV means % of the light duty vehicle fleet that includes some aspect of the given technology. These numbers are estimates from [68].

[2] Baseline technologies from the NRC study [45] are drawn from 2007 to 2010 era production vehicle data. For the purposes of comparing advanced fuel economy options, baseline technologies are not significantly different in 2014, though it is imperative to be cognizant of the base level of technology against which improvements are compared.

[3] The NRC study reported fuel savings in terms of % reductions in fuel consumption. These have been converted to % improvements in fuel economy, though the relationship is inversely proportional. Costs have been converted from 2008$ to 2014$ [45,80].

[4] NRC study considered a single PHEV with a 40 mile range, although this study includes PHEVs with all electric ranges from 10 to 40 miles. All-electric range is linearly proportional to battery cost and therefore incremental price. Also, NRC did not report on the % fuel economy improvement typical of a PHEV, possibly because it is largely application-dependent and the two modes of energy (electricity and gasoline) make this non-trivial to report on the same basis. For this study, a Federal subsidy applies to certain PHEV vehicles (>5kWh battery) and has therefore been included [82], whereas the policy had not taken effect when NRC performed its study. CAFE regulations consider mpg and mpge (for certain PHEV) equivalently, and are therefore included accordingly in this study. [15,27]

technology descriptions are self-explanatory. In some cases, a preceding technology is often required in a later evolution, such as is common with gasoline direct injection, downsizing and turbocharging. A second example of bundling is the availability of "fuel economy" packages whereby OEMs may include reductions in weight, friction, rolling resistance and/or aerodynamic drag for some premium charge. Thirdly, in most all new models with advanced fuel economy technologies, such as hybrids, advanced transmissions are being used. Therefore, it may be assumed that the benefits of an automatic transmission with an increased number of speed ratios or a continuously variable transmission (CVT) are normally embodied in such vehicles (even if not so stated). This study combines relevant pairings accordingly as indicated. The relationship between incremental cost and corresponding fuel economy improvement is a complicated, though critical, one with important implications on consumers and regulatory compliance. While each technology is unique, studying them collectively and drawing upon timely market-based data offers unique insights into current fuel economy trends and the comparative value of technology improvements to consumers.

The literature is remarkably consistent in its inclusion of these primary technologies over an extended period of time. For example, a 1994 study names nearly all of the above families of technology options as most impactful, though understandably from a different starting point and cost basis [83]. These are not the only technologies, but are the most prevalent in the selected vehicle classes. Among those excluded are two that are commercially available: stop-start (also known as idle-off) and cylinder-deactivation. Stop-start technology has evolved considerably but has not taken off as quickly in the U.S. due to a perception of limited benefits owing to the simplified 2-cycle EPA fuel economy test, in which the vehicle spends little time idling. In real-world driving, stop-start has proven to reduce fuel consumption substantively, with studies reporting improvements on the order of 4 to 5% under various conditions [45,84]. Cylinder deactivation is more commonly applied in engines having six or more cylinders, whereas many of the vehicles in the compact and midsize classes feature inline 4-cylinder engines.

2.3.3 Predicted benefits and costs of compliance from other studies

Incremental retail price equivalents (in $) and fuel economy improvements (in percent change) are commonly used metrics to assess historical trends and predict future ones [61]. Since 2002, the National Research Council (NRC) has compiled technological performance and costs data as a means of tracking their correlation, informing automotive research and design decision-making, and providing input to the policymaking process [45,52,85,86]. Some studies evaluate pay-back periods or costs and benefits associated with conserving energy using a range of new vehicle technologies [25]. Others develop sophisticated technology-specific analyses to predict technical readiness and future costs using computer simulations or tear-down approaches [23-24]. A tear-down approach estimates costs and feasibilities associated with the design and manufacture of new products by aggregating constituent components of a larger system in a bottom-up manner. Both the market-based and technology-specific studies help inform future trends. However, given the aggressive rate of required improvements over a more extended period of time, technologies and their costs are changing more quickly than in previous periods of regulatory constraint. One comparative assessment performed by the National Renewable Energy Laboratory (NREL) evaluated technological and market assumptions utilized by EPA in 2009 [69], suggesting that more specific analyses of technology characterization, current usage and expected 2016 usage of selected technologies would be useful [87]. While highlighting technology variances compared to initial EPA assumptions, the NREL study did not include a financial assessment of economic viability. As noted, many high-level policy analyses aggregate vehicle trends on a fleet-wide basis for future extrapolation [72-76]. For many of these, costs and benefits, if investigated, are typically assessed from a *social, economy-wide perspective* [15,27,88]. While obviously important in the formulation of public policy, two important factors reinforce the merit of analyzing benefits and costs from a *consumer perspective*. First, determination of economic practicability is ultimately a consumer choice that is revealed in the disaggregated sales data. Second, the first-order cost is incremental technology cost, and the first-order benefit is incremental fuel savings. Secord-order social benefits (such as social cost of carbon, increased consumer surplus, and petroleum market externalities) and second-order costs (such as the rebound effect from additional vehicle miles driven, congestion, and accidents) are generally an order of magnitude lower than first-order effects [15,27].

To address the loss of resolution due to aggregating, other studies have investigated specific categories of technologies, such as an investigation into hybrid and diesels by Lutsey [89] which suggested that due to uncertainty and rapid evolution in costs and performance, future market shares are pivotal to compliance but complicated to assess. Lutsey acknowledged that cost reductions for hybrids and diesels are critical for mainstream deployment, but did not elaborate on the relative value of these technologies as compared with other fuel-saving technologies or as compared against a break-even condition. A study by Cheah and Heywood integrated a broader range of technologies, but focused more on compliance scenarios and technological readiness, than relative benefits and costs [6]. The Cheah and Heywood study suggests that the 2016 standards are aggressive and may be difficult to attain, even with full emphasis on seeking reduction in fuel consumption. Uncertainty affects 2016 targets differently than longer-term targets. Near-term redesign inflexibility, depreciation of existing capital, and historical reliance on performance over fuel savings could adversely affect consumer compliance by 2016. Conversely, while longer lead times will help facilitate transitions to fuel saving technologies over the course of the coming decade, the uncertainty of exogenous factors will play an increasingly vital role. The present study therefore includes a market-based, real time assessment of revealed response to CAFE 2012-2016 and can serve to highlight the comparative value that consumers are actually obtaining from new technologies relative to more conventional ones. This may prove valuable in view of the scheduled 2018 mid-term CAFE policy review to involve major stakeholders. Finally, it bears repeating that consumers do not buy fuel economy, or even horsepower; they buy cars. As in every year prior, their preferences are largely revealed in the sales record of the current model year, a year which arguably includes more fuel saving technologies than ever.

2.4 Energy Consumption and Emissions Sensitivity of Advanced Vehicle Architectures

Hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), and electric vehicles (EV) have been introduced to commercial automotive markets due to their potential for favorable energy efficiencies and low tailpipe emissions compared to traditional gasoline- or diesel-powered vehicles. Though advanced vehicle architectures incur greater upfront investment costs, energy operating costs are reduced as a result of fuel conservation enabled by HEV and PHEV technologies, and from the substitution of electricity for liquid fuel made possible by PHEV and EV. Key factors that affect vehicle fuel and energy consumption include driving conditions, ambient temperatures, and the need for auxiliary power such as that imposed by heating or cooling demands [90-91]. Numerous studies have demonstrated that HEV, PHEV and EV have greater sensitivity to these factors than similarly equipped internal combustion engine (ICE) propelled vehicles [92-96]. While a number of studies have addressed these factors at the component level, complete systems investigations that include comparisons and implications are rare. The partial or complete use of grid-generated electricity by PHEV and EV architectures further complicates direct comparisons of energy consumption with liquid-fueled ICE or HEV vehicles. As a result, system-level energy sensitivity to driving cycle and ambient temperature is not completely understood for emerging vehicle architectures. Furthermore, while the literature includes a growing body of work to estimate the lifecycle emissions of alternative vehicles in consideration of upstream factors [97-99], "bottom-up" emission estimates that include iterative simulations of vehicle dynamics, propulsion and thermal energy demands through variations in driving cycle, ambient temperature and locality are novel and valuable.

2.4.1 Estimating battery and vehicle performance

It is significant that HEV and EV house battery modules that generate waste heat in proportion to their capacity. Battery thermal management is an active area of research, as typical energy storage capacities of commercially available compact cars increase from about 1.4 kWh to 16.5 kWh to 24.0 kWh, for HEV, PHEV and EV, respectively [100]. The roundtrip efficiency of a battery module reflects cumulative energy losses during charging and discharging cycles, and is therefore heavily dependent upon driving cycle. In addition, battery performance and life have been shown to be functions of operating temperature, which can be directly impacted by ambient conditions [101]. Heating, ventilating and air-conditioning (HVAC) requirements of both the cabin and battery module for a vehicle operating in an all-electric mode must naturally derive entirely from on-board batteries, further compounding thermal/electric system loads.

Due to the expense and specialized equipment needed to perform experiments in either a real-world or climate-controlled laboratory dynamometer setting, computational vehicle simulation is a viable low-cost means of comparing a variety of performance indices in major vehicle technologies. Numerous computational tools are available to simulate the performance of alternative vehicle architectures, such as ADVISOR, PSAT, and AUTONOMIE, which are part of collaborative U.S. Department of Energy (DOE) projects [102-104]. Some models employ a forward-facing approach yielding highly accurate but computationally-intensive simulation results [102]. Others adopt a high level backward-facing approach, where the velocity command trace is assumed to be met exactly in order to simplify powertrain control strategies employed by the vehicle simulations and to reduce computational time. Due to the comparative nature of the present study, the latter approach is appropriate and therefore used.

2.4.2 Assessing the impacts of driving cycle and ambient temperature in advanced vehicles

Standardized driving cycles are typically used as inputs to vehicle performance simulations because they are pre-defined by official regulations and facilitate equitable comparisons. Since 2008, the United States Environmental Protection Agency (EPA) has promulgated new regulations for fuel economy testing and labelling to better reflect real-world driving [14], including the addition of driving cycles performed at 35°C and -7°C to generalize performance under hot and cold weather conditions, respectively. Cabin heating and cooling loads have been shown to be generally linear with ambient temperature for conventional vehicles [93,105]. Thus, by increasing the number of driving cycles from two to five and introducing more empirically rigorous calculations, current fuel economy labels are a better indicator of real-world fuel economy for conventional vehicles [14]. Owing to rapid development as well as operational and design differences in HEV, PHEV, and EV, revisions to recommended test protocols J1711 and J1634 were issued in 2010 and 2012, respectively, by the Society of Automotive Engineers [106-107]. These protocols provide critical guidance on multiple drive cycle repetitions and means of ensuring accurate energy accounting between electrical energy and liquid fuel consumed during hybrid modes (known as "net energy change tolerances"), and are applied in the present work.

While the updated EPA and SAE protocols have dramatically improved testing, repeatability and consumer understanding, significant gaps and research opportunities remain. EPA labelling methodologies prescribe laboratory conditions modelled around aggregated U.S. domestic data, despite obvious regional variations. In 2002, the National Renewable Energy Lab (NREL) performed a state-level assessment of fuel consumption attributable to vehicle air-conditioning in the 50 states [95]. As a result of such assessments, several studies have compared selected vehicles of a given architecture and considered multiple driving cycles in temperature categories such as hot, temperate and cold. For example, Loiselle, et al. compared two HEV at 20°C and -18°C [93] and Hayes, et al. compared two EV at 35°C, 20°C and -11°C [108]. Argonne National Lab performed experiments in 2013 on several vehicle architectures at the prescribed -7°C, 23°C and 35°C temperatures using a chassis dynamometer in a full-vehicle environmental chamber [96].

While generalized hot/cold trends were revealed, the results fail to characterize potential non-linear responses in electrical requirements since only two representative temperatures were investigated. Along with internal resistances that vary with temperature, battery thermal management heating and cooling loads have a compounding effect on system energy consumption, suggesting that non-linear and adverse departures from traditional energy impacts are likely in PHEV and EV. For example, Kambly and Bradley [91] presented a comparison between conventional and electric vehicles which noted that EPA 5-cycle test methods overestimated the energy savings due to EV by 28% and resulted in inaccurate estimations of range, energy consumption and lifecycle emissions. This point was further demonstrated in a study by Yuksel and Michalek [97] in which range data from U.S. owners of a popular electric vehicle model were converted to electrical consumption values and plotted against outdoor temperature. The results implied that EV energy demand is non-linear and highly sensitive to outdoor temperature. The geographical location and behavior of users was aggregated, unfortunately limiting broad applicability of the study and suggesting the need for standardized and more comprehensive analytical approaches.

In order for hybrid and electric architectures to meet operational needs, batteries with high specific power, high specific energy density, larger capacities and higher current discharge rates are required [109-111]. The enabling electro-chemical mechanisms of modern batteries generate considerable heat under high load and transient conditions [112], including rapid acceleration (discharging), deceleration (charging), and start-stop operation (cyclic or alternating battery reactions) [113]. A first-order resistor-capacitor (RC) circuit offers a reasonable trade-off between fidelity and computational intensity for modeling interactions between drive cycle and battery response [114-116]. Increasingly large vehicle battery modules (i.e., > 3 kWh) operating in varying driving cycle and ambient temperature conditions call for a model that integrates thermal management, battery equivalent circuit, and vehicle propulsion sub-routines to evaluate energy consumption across a continuous temperature spectrum. Such a model would facilitate a comparison of the energy intensities of various vehicle architectures in different localities.

2.4.3 Methodologies for comparing vehicle energy consumption and emissions

When PHEVs operate in gasoline-only or "charge sustaining" (CS) mode, direct comparisons to conventional internal combustion engine propelled vehicles are straightforward, and are reported as fuel or energy consumption per distance travelled. However, vehicle operation in "all-electric" or "charge depleting" (CD) mode introduces substantial unknowns related to the native energy source employed for electric charging. In order to provide a baseline reference from the standpoint of the vehicle boundary itself, the concept of equivalent fuel economy has been introduced, expressed as "MPGe" and can be readily converted to energy consumption per unit distance travelled (20.9/MPGe ≈ kWh/km). However, MPGe can be a source of potential confusion [16-17] because it excludes consideration of energy sources upstream of the vehicle itself. MPGe is thus an unusable metric for making reasonable system-level, lifecycle energy, or emissions comparisons. In order to compare PHEV and EV energy consumption on a 'wells-to-wheels' or W2W basis, any losses from thermal generation of electricity, transmission and distribution, and charging must be considered. The U.S. Department of Energy (DOE) issued a petroleum-equivalent fuel economy calculation in 2002 as a basis for computing a simplified lifecycle energy consumption to facilitate comparison between ICE, HEV, PHEV and EV [79]. A primary contribution of the present study is to build on such lifecycle methodologies and extend them to the city level in the interest of investigating vehicle energy consumption as a function of locality. Relevant location-specific attributes include: typical diurnal and annualized weather history, sources and efficiencies of electrical power generation, efficiencies of grid transmission and distribution of electricity, and efficiencies of transporting and refining liquid fuels. Other parameters such as daily vehicle miles traveled, driving times and behavior, and vehicle charging are considered to be independent of location. It is assumed that all sources of energy have equal value in proportion to their intrinsic energy potential (i.e., a net energy basis). While this neglects potentially significant geopolitical and energy security considerations of energy demand and consumption, it is an appropriate scientific assumption for comparing thermodynamic efficiency and energy-derived emissions.

CHAPTER 3. FUEL ECONOMY AND VEHICLE ATTRIBUTE VALUATION TRENDS VIA HISTORICAL AND CONTEMPORARY HEDONIC PRICING ANALYSIS

This chapter investigates multi-decade trends in major passenger car attributes and selling prices using an objective function for utility comprised of three key characteristics: fuel consumption, zero to 60 mph acceleration time, and curb weight. Inflation-adjusted prices are demonstrated to have a relatively flat response in view of ever-increasing levels of consumer utility. Disaggregated contributions of individual vehicle attributes to vehicle price and estimates of the price elasticity of fuel consumption and acceleration performance with respect to vehicle price are presented. Both historical and contemporary data help quantify the impact of regulations upon these metrics fleet-wide. The chapter also explores the vehicle classification aspect of new regulations, suggesting that consumers of certain classifications are willing to pay more for improved acceleration than reduced fuel consumption. The results are compared to other selected research methods by way assessing the sensitivity of willingness to pay over time. The chapter concludes with a discussion of potential implications of the findings, noting that consumer choice and preferences may present challenges to footprint-based regulations. The material presented in this chapter has been submitted for publication in Transportation Research Part D: Transport and Environment [31].

3.1 Methodology

This section presents the selection criteria and definitions for the vehicle attributes considered in the study and introduces the primary data. Graphical trends are depicted that track technological progress in attributes between 1978 and 2014. As a means of more completely characterizing the disaggregated contribution and trade-offs among key attributes, vehicle price trends are introduced and investigated in view of technological time trends. Specific periods of interest and high-level insights are identified from the simultaneous comparison of trends in attributes and prices. The section concludes with a detailed overview of the modeling approach and formulae used to estimate two parameters of interest for each vehicle attribute in the selected periods. The first is the disaggregated contribution to vehicle price by each key attribute; and the second is the price elasticity of each key attribute with respect to overall vehicle price. This section establishes a protocol for quantifying and comparing these parameters among periods and among attributes, key findings and implications of which are reported in Section 3.2.

3.1.1 Vehicle attributes considered in the study

Since it is not the primary goal to characterize all measures of consumer utility or service, this study seeks to include a minimum number of objective, historically traceable and largely independent vehicle attributes that can sufficiently characterize consumer utility in view of market prices. A balance between simplicity and fidelity is achieved with the inclusion of three attributes plus total vehicle price. We include one measure of system efficiency (fuel consumption), one measure of vehicle performance (acceleration), and one measure of vehicle size and capacity (curb weight). Following are brief definitions and explanations of certain nuances related to the selected attributes.

Fuel consumption (FC) is selected because it provides an accurate representation of overall *system efficiency*. FC is preferred over fuel economy (FE) as a measure of consumer utility since it scales linearly with consumer-incurred costs per distance driven (notwithstanding fuel price variability). Because FE is familiar among consumers in the U.S., used in current regulations, and cited in prior studies, we derive FC from current EPA definitions for adjusted combined city/highway FE [14]. The units for FC are liters per 100 kilometers [L/100km] and it can be derived from FE [in mpg] according to the formula: FC = 235.21/FE. It should be noted here that FC scales inversely with utility, since reductions in fuel consumption result in utility benefits (such as reduced costs) for consumers.

Though several parameters could reasonably represent the *performance* aspect of utility (including power, torque, and ride), *zero to sixty miles per hour acceleration time* (ACCEL) is selected since it represents a composite performance metric, qualitatively similar to FC. Acceleration time incorporates the aspects of vehicle power, weight, aerodynamics as well as systems response, providing a more complete indication of performance than a single powertrain dynamometer rating performed at a given engine RPM (as is the case of rated power and torque). One caveat is that acceleration time, while objective, is a more difficult parameter to quantify and conventional correlations [117] have become outdated or inappropriate for characterizing today's vehicle technologies [13]. To remedy this, we employ recent regression-based models for ACCEL developed by MacKenzie and Heywood (2012) that reduce error and variability by drawing from a set of statistically significant and standardized independent test times [118]. We find the tool has usefulness for projections because it facilitates extrapolation of ACCEL into future periods (provided additional detail on up to eight vehicle characteristics is available). Like FC, ACCEL is an attribute that is inversely related to utility, since reductions in acceleration time afford consumers an increasing measure of performance.

Vehicle curb weight (CWT) appears to be, on the surface, one of the more rudimentary vehicle attributes. However, studies have shown links between vehicle weight and a host of other vehicle characteristics including *aesthetic value, comfort and ride, safety* ratings, and price [56,119-120]. Though a consumer is less likely to pay attention to CWT as compared with FC or ACCEL in a new vehicle purchase, it is a precise and objective vehicle attribute by which we can further represent many other more complicated or even subjective vehicle characteristics. Weight effectively becomes a proxy reflecting several dimensions of consumer utility. In this section, we mention CWT last, because it is perhaps the least independent and most nuanced of the three selected indicators. FC and ACCEL, as vehicle system parameters, share known yet model-specific correlations with CWT. However, FC and ACCEL also depend upon numerous additional factors, which serves to reduce potential collinearity with CWT. CWT has been used extensively as a suitable objective proxy for other parameters that are more difficult to quantify or track. While neither this study nor consumers are interested in curb weight, per se, it provides an excellent complement to FC and ACCEL to accurately characterize vehicle utility in view of price.

Additional parameters of critical importance to most buyers include safety and quality. However, due to the existence of minimum crashworthiness regulatory standards and standard factory warranties, such attributes are not believed to be as significant in differentiating relative utility for new vehicles. The same is true for the metric of interior volume in passenger cars according to EPA. Notwithstanding new definitions for classifying passenger cars, passenger interior volume has not varied more than about 4% over the past three decades (Table 3.1 and Figure 3.1). This observation has led the agency to suggest vehicle footprint may be a more appropriate indicator of vehicle size [13], and may warrant additional investigation as a blocking variable on future studies.

Clearly, FC, ACCEL and CWT are objective and well understood by OEMs, consumers and the research community. They have values that have been historically tracked and are either available in reputable databases or can be derived directly from such data. At a vehicle model and trim level, these attributes can be linked to data that corresponds with selling prices. Finally, they can of course be weighted in importance and/or combined to appropriately capture reasonable trends of aggregated utility. Thus, while other parameters could obviously be added, we argue that this list can be considered necessary and sufficient to approximate and compare historical and contemporary utility trends.

3.1.2 Vehicle price and attribute data

This study employs two comprehensive data sets in order to investigate attribute valuation from both historical and contemporary perspectives. The first set includes sales-weighted vehicle price and attribute history aggregated for the U.S. vehicle fleet. Nominal vehicle price information is derived from [121] and vehicle attribute data are derived from [13]. The second set is a trim-level disaggregated record of sales weighted price and attribute data for the 2014 model year. This data is derived predominantly from [122-124] with corroborating data from respective automaker specifications and MSRP information.[5]

We use two different versions of real vehicle prices in this study. To get the trend in real prices from the perspective of consumers, we use the general consumer price index (CPI) [80]. This index permits comparison of changes in vehicle prices with the general market basket of consumer purchases. The second real price series uses the new vehicle price index (CPI, new vehicles: cars [125]), and we use that when doing analysis of different vehicle attributes within the auto sector. These are referred to throughout the study as "Real Price_1" and "Real Price_2," respectively. As discussed, the three discrete system attributes of fuel consumption, acceleration time and curb weight have been selected because each introduces a complementary, yet largely independent aspect of utility, not explicitly captured by the others.

Tables 3.1 and 3.2 contain the historical and 2014 model year data for the two-fold analyses that follow.

[5] The historical record reports price data based upon the average expenditure per car, whereas the 2014 record reports price data based upon Manufacturer's Suggested Retail Prices (MSRPs). Actual transaction prices for 2014 were not available for this study. Though MSRPs would generally be slightly higher than average expenditures per car, they represent a reasonable proxy and are believed to have limited impact on the relative weightings or elasticities of the attributes. In Table 3.1, 2014 "average nominal price" was estimated by adding the difference of the average MSRP data for 2013 and 2014 to the actual 2013 average expenditures.

Table 3.1. Sales-weighted vehicle price and attribute history aggregated for new U.S. passenger cars, 1978-2014 [13,80,121,122,125].

Table 3.1 Definitions: Real Price_1 = Nominal price inflated by CPI (all items), Real Price_2 = Nominal price inflated by CPI (new cars), [6]FC = Fuel Consumption, ACCEL = 0 to 60 mph acceleration time, [6]CWT = Vehicle curb weight, VOL = Volume of vehicle passenger compartment, PWR = Rated engine power. All data represent sales-weighted averages for the given year. Estimated unit sales are shown for reference.

Year	**Nominal Price** (avg)	**Real Price_1** (avg) 2014$	**Real Price_2** (avg) 2014$	**Sales Units** (est) (000)	**FC** (avg) L/100km	**ACCEL** (avg) sec	**CWT** (avg) kg	**VOL** (avg) ft^3	**PWR** (avg) kW
Source(s)	[121-122]	[121-123, 80]	[121-125]	[13]	[13]	[13]	[13]	[13]	[13]
2014	26,320	26,320	26,320	8,000	8.43	8.3	1487	111	149.9
2013	25,487	25,900	25,407	9,377	8.52	8.5	1475	110	147.6
2012	25,593	26,389	25,644	8,648	8.71	8.6	1462	111	143.2
2011	25,474	26,810	25,874	6,934	8.88	8.6	1508	111	149.1
2010	24,903	27,036	26,052	6,969	9.15	8.8	1471	110	141.7
2009	23,156	25,552	24,475	6,244	9.41	8.9	1455	110	138.7
2008	23,442	25,776	25,013	8,243	9.84	8.9	1486	110	144.7
2007	23,892	27,279	25,406	9,001	9.92	8.9	1478	110	142.4
2006	23,634	27,753	25,031	8,744	10.23	8.8	1483	112	144.7
2005	23,017	27,900	24,589	8,839	10.18	9.0	1454	111	136.5
2004	22,076	27,666	23,813	8,176	10.27	9.0	1451	110	137.2
2003	21,646	27,850	23,217	8,496	10.23	9.1	1426	110	131.2
2002	21,249	27,962	22,360	8,904	10.32	9.4	1416	110	129.0
2001	21,474	28,705	22,331	9,148	10.41	9.4	1414	109	126.0
2000	21,041	28,927	21,783	9,742	10.45	9.5	1410	110	125.3
1999	20,710	29,429	21,440	8,865	10.36	10.1	1405	109	122.3
1998	20,364	29,576	20,910	8,425	10.23	10.2	1379	109	119.3
1997	19,236	28,373	19,615	8,695	10.14	10.0	1357	109	116.3

Table 3.1 is continued on the following page

[6] Some of the attributes appearing in Tables 3.1 and 3.2 including FC and CWT, are simple conversions from the EPA reported data. For example: Fuel Economy, FE (FC=235.21/FE) and Vehicle Inertia Weight, IWT (CWT=IWT-300 lbs)

Table 3.1. (cont.)

Year	**Nominal Price** (avg)	**Real Price_1** (avg) 2014$	**Real Price_2** (avg) 2014$	**Sales Units** (est) (000)	**FC** (avg) L/100km	**ACCEL** (avg) sec	**CWT** (avg) kg	**VOL** (avg) ft^3	**PWR** (avg) kW
Source(s)	[121-122]	[121-123, 80]	[121-125]	[13]	[13]	[13]	[13]	[13]	[13]
1996	18,777	28,331	19,182	8,177	10.18	10.1	1362	109	115.6
1995	17,959	27,897	18,663	9,616	10.10	9.8	1352	109	114.1
1994	17,903	28,598	19,020	8,747	10.23	9.9	1349	108	107.4
1993	16,871	27,640	18,536	8,929	10.23	10.1	1337	108	104.4
1992	16,336	27,565	18,385	8,350	10.27	10.8	1343	108	105.1
1991	15,475	26,898	17,839	8,748	10.10	11.3	1304	107	99.2
1990	15,042	27,245	17,963	8,875	10.10	11.4	1308	107	96.2
1989	14,371	27,437	17,411	10,126	9.97	12.5	1275	108	90.2
1988	13,932	27,880	17,223	10,845	9.76	13.3	1250	107	86.5
1987	13,386	27,896	16,875	10,826	9.88	13.3	1243	107	84.3
1986	12,652	27,328	16,524	11,074	9.92	13.2	1247	107	82.8
1985	11,838	26,045	16,128	10,879	10.23	13.9	1271	108	82.8
1984	11,375	25,918	15,992	10,730	10.50	14.5	1273	108	79.0
1983	10,606	25,209	15,343	8,035	10.64	14.8	1278	109	77.6
1982	9,890	24,262	14,674	7,832	10.60	16.6	1251	106	73.8
1981	8,910	23,205	13,730	8,734	10.99	15.6	1262	106	73.8
1980	7,574	21,760	12,384	9,444	11.76	15.5	1273	104	74.6
1979	6,847	22,327	12,090	10,810	13.68	14.5	1448	109	88.7
1978	6,379	23,162	12,158	11,191	13.92	13.7	1495	109	92.5

Table 3.2. Sampling of 2014 model year trim-level price and attribute data with illustrative statistics [118,122-124].

Table 3.2. Definitions: MSRP = Manufacturer's Suggested Retail Price, [7]FP = Vehicle footprint. Except for [8]ACCEL and FP, which are calculated, above data represent vehicle specifications for the given make, model and trim level. Estimated trim level unit sales are shown for reference.

Make	**2014 Model & Trim Level**	**Price MSRP**[5] 2014$	**Sales Units** (est)	**FC** L/100km	**ACCEL** sec	**CWT** kg	**FP** ft^2
…	…	…	…	…	…	…	…
Chevrolet	Cruze LT	19,640	121,699	7.42	9.4	1418	44.8
Chevrolet	Malibu LT	24,435	75,089	7.77	8.3	1560	46.5
Dodge	Charger SXT	30,290	28,562	9.65	6.4	1813	53.1
Ford	Fiesta S	15,425	35,406	6.93	9.8	1151	38.8
Ford	Focus SE	19,440	97,425	7.61	8.6	1319	44.0
Ford	Fusion SE 2L Turbo	27,550	80,060	8.66	7.0	1554	48.7
Honda	Fit	16,215	19,280	7.81	9.9	1132	39.9
Honda	Civic LX	18,980	55,392	7.34	9.4	1316	42.6
Honda	Civic SI	23,780	64,679	8.92	7.1	1362	43.5
Honda	Accord LX-S	24,415	52,608	8.16	7.9	1445	46.5
Honda	Accord EX-L V6	31,135	44,843	8.76	6.5	1612	47.5
Hyundai	Accent GLS	15,455	30,876	7.27	8.5	1129	41.7
Hyundai	Elantra Sport	23,510	45,890	8.16	7.4	1326	45.6
Kia	Soul+	18,995	86,086	8.72	8.8	1287	43.5
Lexus	ES 350	37,380	57,851	9.14	6.7	1610	48.0
Nissan	Sentra S Plus	14,600	39,168	7.47	10.0	1286	44.4
Toyota	Corolla LE Eco	19,510	66,072	6.72	9.5	1295	44.2
Toyota	Prius III	26,575	26,461	4.78	10.0	1380	44.2
Toyota	Corolla S	19,810	66,072	7.24	9.9	1290	44.6
Toyota	Camry SE	24,210	112,477	7.88	8.5	1470	46.9
VW	Jetta 1.8T SE	19,715	115,511	7.61	8.0	1370	43.9
…	…	…	…	…	…	…	…
…793 Additional trim-level models not shown…				…	…	…	…
N=814 Tot. Observations							
Weighted Mean		**27,841**		**8.16**	**8.2**	**1468.6**	**45.77**
Standard Deviation		**13,517**		**1.52**	**1.5**	**200.2**	**3.12**
Sum (Pass. cars sold)			**7,868,192**				

7 Vehicle footprint (in square feet) is calculated by multiplying the vehicle's average (front/rear) track width (in feet) by the vehicle's wheelbase (in feet), as discussed in CAFE 2012-2016 [15] and CAFE 2017 and later [27].

8 Acceleration times were determined using comprehensive vehicle specifications from Ward's [123] and using methods described in MacKenzie [118] as discussed in EPA [13].

3.1.3 Initial inspection of attribute trends, periods of interest, and correlations among contributing parameters

At this juncture, a quick overview of attribute trends and primary correlations among the selected attributes helps shed light on the approaches undertaken in this study. This is particularly relevant given the multi-decade time horizon considered in this study. Normalizing the performance of each individual vehicle attribute to a base year of 2014, Figure 3.1 illustrates key technological progress trends since 1978.

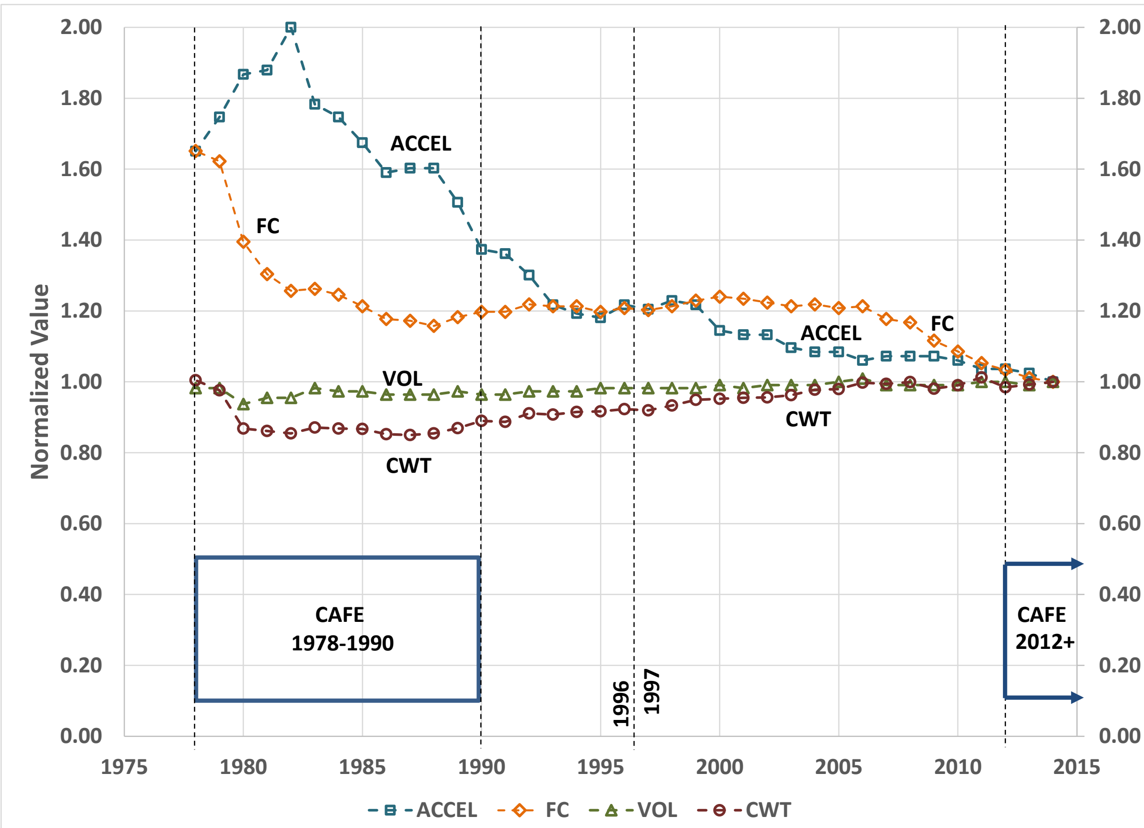

Figure 3.1. Technological progress trends in key vehicle attributes, 1978-2014. [Data source: 13].

Several points are worth noting to help substantiate the time-period analysis that follows. First, Figure 3.1 shows the dramatic reductions in fuel consumption associated with the advent and enforcement of initial CAFE regulations (1978-1990). Corresponding trade-offs in acceleration time and curb weight are similarly reflected during that period. CAFE standards remained unchanged between 1990 and 2011, as witnessed by the flat response of FC until renewed legislation was signaled in about 2007 [26]. It is of note that the relative lines of innovation for FC and ACCEL intersect between 1994 and 1999 (with a midpoint about 1996 or 1997).

A comprehensive review of all the relevant interactions among the selected parameters is beyond the scope of this paper. It is, however, of considerable interest that the correlations among the variables are predominantly driven by time period rather than by physical correlations. Three correlation matrices for various subsets of the historical data are shown in Tables 3.3, 3.4, and 3.5 for the periods of 1978-2014 (overall period), 1978-1996 (first half) and 1997-2014 (second half) respectively. All reported correlations during the periods are driven primarily by technological time trends, or more simply innovation. Clearly, the attributes of fuel consumption, acceleration time and vehicle weight have been improving together over time even though from a technical perspective, they sometimes are counter to each other. This was shown clearly in Figure 3.1, as well as in Figures 2.2 and 2.3.

Table 3.3. Historical correlations among the three vehicle attributes, 1978 - 2014.

	FC	*ACCEL*	*CWT*
FC	1		
ACCEL	0.574	1	
CWT	-0.110	-0.745	1

Table 3.4. Historical correlations among the three vehicle attributes, 1978 - 1996.

	FC	*ACCEL*	*CWT*
FC	1		
ACCEL	0.390	1	
CWT	0.733	-0.307	1

Table 3.5. Historical correlations among the three vehicle attributes, 1997 - 2014.

	FC	*ACCEL*	*CWT*
FC	1		
ACCEL	0.728	1	
CWT	-0.624	-0.910	1

The positive correlation between fuel consumption and acceleration that typifies the historical trends is at odds with the negative correlation expected, since reduced acceleration times incur fuel consumption increases. This is explained by technical progress made on both fronts simultaneously; the positive correlation is essentially picking up the positive time trend in both. The period between 1978 and 1996 largely overlaps with the implementation of original CAFE standards, whereas the latter period (from 1997 to 2014) is dominated by 15 years of unchanged CAFE standards, followed by just 3 years of increasing standards. The extent of the innovation trend is best understood by considering the correlations within a recent model year as in Table 3.6.

Table 3.6. Model year 2014 correlations among the three vehicle attributes.

	FC	*ACCEL*	*CWT*
FC	1		
ACCEL	-0.832	1	
CWT	0.644	-0.667	1

Thus, rather than forcing technological trade-offs over the long run, fuel consumption has been decreasing as cars have been getting heavier and quicker with respect to acceleration. Similarly, acceleration times have dropped as cars have gotten heavier, more functional, and more efficient in their use of fuel. In particular, acceleration times have improved 30% while average the fuel consumption has been reduced 40% between 1978 and 2014.

It is of note that within a given model year, correlations are more likely to emulate fundamental physics-based limits than long-run correlations. For instance, for model year 2014, the magnitude and sign of the FC-ACCEL correlation and the FC-CWT correlation are consistent with physics-based principles given that for a given vehicle design in time, fuel use increases with reduced acceleration time or with increased mass. The authors' vehicle simulations in MATLAB/Simulink confirm that fuel increase is roughly linear over typical ranges of acceleration performance and mass. These trends represent rather remarkable simultaneous technological progress in these dimensions.

3.1.4 Modeling approach

The first model used in this work describes an expression for utility as a function of disaggregated attributes.

$$Utility = fn(FC, ACCEL, CWT) \tag{3.1}$$

We define the generalized form of the utility objective function as follows:

$$U_i = FC_i^{-1} \cdot ACCEL_i^{-1} \cdot CWT_i \tag{3.2}$$

Eq. (3.2) can be applied to a given vehicle i or a sales-weighted average data set for a given year i. FC_i, $ACCEL_i$ and CWT_i represent respective attribute values for the given vehicle or year. Initially, our objective function for utility is defined as the product of the constituent utility parameters, in a first-order inverse relationship with respect to fuel consumption (FC_i has units of [L/100km]), in a first-order inverse relationship with respect to acceleration time ($ACCEL_i$ has units of sec), and in a first-order relationship to curb weight (CWT_i has units of kg). The units of U_i are: kg*[L/100km]$^{-1}$*sec-^{1}. We normalize these parameters to a 2014 baseline.

Our first simple analysis is to demonstrate the link between technological progress and vehicle prices. Figure 3.2 shows the time trend for nominal and real vehicle prices and for utility as defined above.

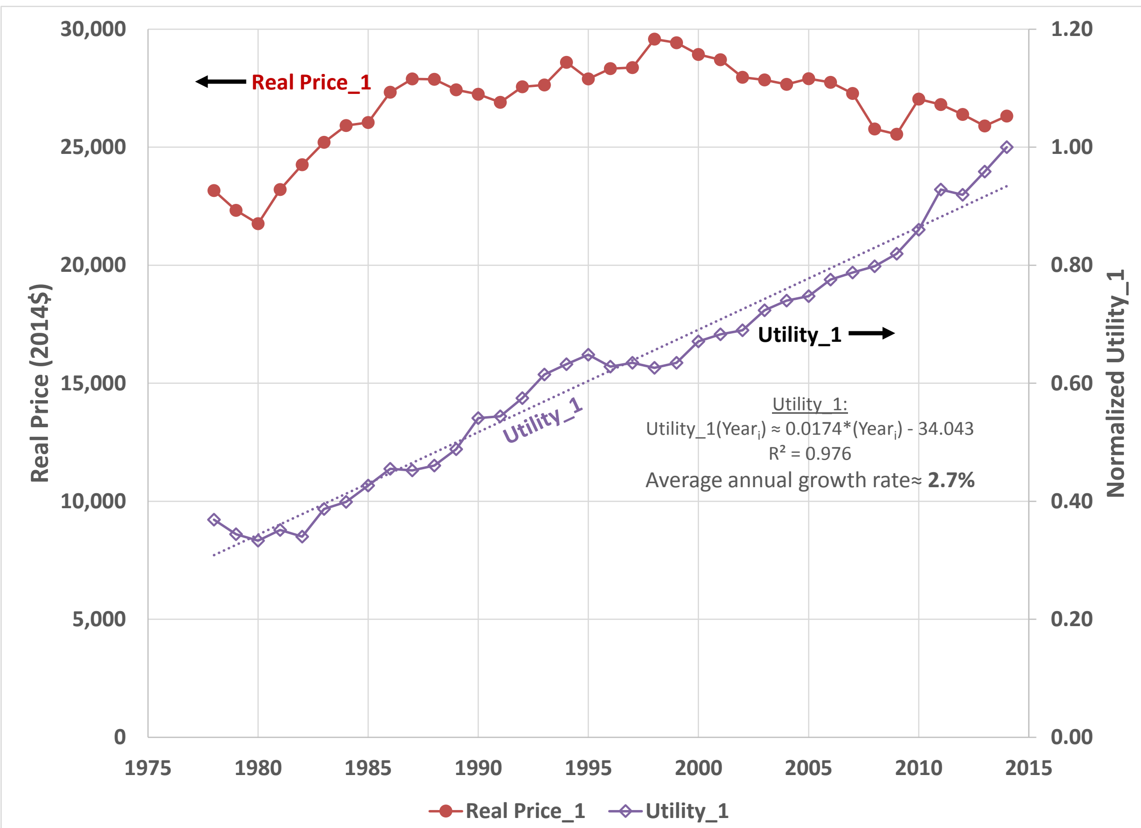

Figure 3.2. Passenger car price and utility trends, 1978-2014. [Data sources: 13,80,121].

In this figure we use the general price index (CPI- all items [125]) to convert nominal prices to real prices. Two important points emerge from this graph:

1) Real prices rose from 1978 through 1987, but the 2014 real price is about the same as that of 1985. In other words, substantial technical progress has been achieved over the past 30 years with no real price increase for consumers. Nominal vehicle prices increased at an average annual rate of 3.9% compared with 3.5% for the general CPI. All of the difference between the nominal vehicle price increase versus the general CPI was between 1978 and 1985.
2) Utility as defined above has increased at an average annual growth rate of 2.7%.

The next step in our analysis is to acknowledge that these characteristics do not contribute to utility with equal weighting, but to begin with an equal weighting assumption for the purposes of comparison to prior research that has made that assumption [5,126].

Hedonic pricing methods applied to automobile attributes were introduced by Griliches [127] and Rosen [128] and others [57,126]. Price is assumed to be an aggregated function of the attributes that comprise overall vehicle utility.

$$Price = fn(Utility) = fn(FC, ACCEL, CWT) \tag{3.3}$$

A hedonic pricing analysis is subsequently performed on the specified vehicle attributes so as to quantify the linkage between consumer utility and purchase prices. The desired output of the hedonic analysis is twofold: (1) to determine the approximate disaggregated contribution of each attribute to overall utility, where utility is represented by the bundled vehicle purchase price; and (2) establish the price elasticities for each attribute with respect to overall vehicle price. The most useful general model form is log-log, which provides a convenient basis by which to compare coefficients on the regressors.

$$\ln(P_i) = \beta_0 + \sum_{j=1}^{n} \beta_j \cdot \ln(X_{ij}) + \sum_{j=n+1}^{m} \beta_j \cdot Y_{ij} + \epsilon_i \tag{3.4}$$

In Eq. (3.4), P_i represents the purchase price for vehicle i, β_0 represents the intercept, and the regressor coefficients β_j represent elasticities of price with respect to a set of up to n continuous variables, X_{ij}, and a set of m-n dummy variables, Y_{ij}, for vehicle i. ε_i represents the residual error between the predicted and actual values. For purposes of simplicity, continuity and comparison, the majority of the analysis in this study assumes a three attribute model and neglects the contribution of additional variables, where Eq. (3.4) simplifies to:

$$\ln(P_i) = \beta_0 + \beta_1 \cdot \ln(FC_i) + \beta_2 \cdot \ln(ACCEL_i) + \beta_3 \cdot \ln(CWT_i) + \epsilon_i \tag{3.5}$$

In Eq. (3.5), FC_i, $ACCEL_i$, and CWT_i represent the fuel consumption, zero to 60 mph acceleration time and the curb weight for vehicle i, respectively.

For this estimation we use the new car price index [125]. The transformed log-log equation is useful in that these coefficients indicate the % change in vehicle price caused by a 1% change in the given attribute, holding all other independent variables constant (and providing changes are relatively small).

It should be noted here that Eq. (3.5) as shown assumes each data point has equal weight, i.e., it uses the Ordinary Least Squares (OLS) regression approach. However, given the emphasis of the CAFE policy on sales-weighting, it is preferable to apply a Weighted

Least Squares (WLS) to improve model accuracy as suggested by Kiso (2013) [129]. Therefore, where applicable and available, the statistical analysis of this study follows the WLS approach.

With price now replacing utility as our dependent variable, we explore the hypothesis that attributes do not contribute to price with equal weight, and further that weightings are not static in time. One reasonable way to disaggregate attribute contribution is to partition the sum of squares for each attribute using analysis of variance (ANOVA) methods. While the attributes chosen herein are representative system-level attributes, they are unfortunately not entirely orthogonal, meaning some confounding is inherent. Due to the limited number and utility-proxy nature of the regressor (attribute) variables selected, the estimated relative contributions are not intended to correspond directly to a given share of purchase price. Rather, it should be emphasized that this approach is intended to approximate notional attribute contributions to utility for broad, high-level comparisons purposes between major historical time periods.

In ANOVA, total variability is partitioned into its constituent parts, including variability associated with the model and any error unexplained by the model as shown below.

$$\mathrm{SS}_{Total} = SS_{Model} + SS_{Error} \tag{3.6}$$

$$\mathrm{SS}_{Model} = SS_{FC} + SS_{ACCEL} + SS_{CWT} \tag{3.7}$$

In Eqns. 3.6 and 3.7, SS_x indicates the sum of squares for component x. In a three attribute model where confounding may be present, it is useful to perform a sensitivity analysis on each of the individual attributes. This is done by performing ANOVA analyses using Statistical Analysis Software (SAS), on the model of Eq. (3.5) six different times:

one corresponding to each possible order of regressor variables. In other words, given F=FC, A=ACCEL, and C=CWT, Eq. (3.5) as presented suggests the regression algorithm proceeds in the order F-A-C. Thus all possible orders (FAC, FCA, AFC, ACF, CFA, CAF) are analyzed, total model variability (SS model) is partitioned among the three attributes, allowing for an estimate of the average contribution of each attrbute to the total model response. An example of this approach yielding an estimate of the average contribution allocable to F is therefore given as follows.

$$\chi_F = \frac{2 \cdot SS(F) + SS(F|A) + SS(F|A,C) + SS(F|C) + SS(F|C,A)}{6 \cdot SS_{Model}} \tag{3.8}$$

In Eq. (3.8), χ_F is the average portion of the model response explained by attribute F alone. SS(F) is the partition of the sum of squares due to F in iterations with regression order FAC and FCA, which are commonly referred to as the type I sum of squares for F. SS(F|A) and SS(F|C) are the partitions due to F resulting from iterations AFC and CFA respectively. SS(F|A,C) and SS(F|C,A) are the partitions due to F in iteration ACF and CAF, and are commonly referred to as the type III sum of squares for F. Since six iterations were performed, the total sum of squares paritioned to F are then divided by the model sum of squares multiplied by six. Providing the model explains a high level of the total response (i.e., the error is small and the R^2 is sufficiently high), χ_F gives an average indication of its contribution to the dependent variable. The approach qualitatively simulates a compound method based upon conventional type I and type III sum of squares analytical methods. In this manner, counfounding is effectively navigated to facilitate high-level comparisons. The average contributions attributable to A and C are determined in the same manner.

Trends in χ_F and β_1 with respect to various time periods and with respect to the comparative weightings and elasticities of other vehicle attributes convey useful information about eonomic trade-offs. Due to the substantially different nature of the technological and economic trade-offs, such infomation can provide complementary insight into current markets, future scenarios and expected price responses to attribute evolution.

3.2 Results

In this section, utility trends are investigated in view of real vehicle price data via disaggregation of constituent attributes. As noted, relevant historical time periods are considered, including one from 1978 to 1996 during which time increasing CAFE regulations were dominant. A second time period covers the years from 1997 to 2014, during most of which time, no changes to fuel economy standards were imposed. Model year 2014 is reviewed in greater resolution in the context of historical results. For each period, price elasticities and average contributions of key attributes are quantified and compared, providing linkages and insights to better characterize technological innovation and economic trade-offs as enabled by hedonic pricing models.

3.2.1 Hedonic modeling results: comparing historical and contemporary trends

The linkage between consumer utility, its constituent attributes, and prices is informed by performing a series of hedonic analyses as described in section 3.1.4. We estimate that price is an aggregated function of three selected attributes that comprise overall utility. We will test the theory that the comparative contributions of attributes are highly sensitive to prevailing levels of fuel economy regulation as a prelude to quantifying current-day economic trade-offs and valuations of attributes that impact energy use. Table 3.7

demonstrates the application of the primary hedonic model employed in this study given by Eq. (3.5) to various subsets of the raw data from Tables 3.1 and 3.2 as shown.

Table 3.7. Regression outputs of log-log hedonic model on historical data sets.

Time Period		**1978-1996**	**1997-2014**	**1978-2014**	**2014**
Data Set		Table 3.1	Table 3.1	Table 3.1	Table 3.2
Response Variable		ln(Real Price2)	ln(Real Price2)	ln(Real Price2)	ln(MSRP)
Hedonic Model		Eq. (3.5)	Eq. (3.5)	Eq. (3.5)	Eq. (3.5)
Estimator		WLS	WLS	WLS	WLS
Observations		19	18	37	814
R^2		0.992	0.963	0.943	0.722
Attribute	**Coeff.**	**Param. Est.** (Std. Error)	**Param. Est.** (Std. Error)	**Param. Est.** (Std. Error)	**Param. Est.** (Std. Error)
Intercept	β_0	**0.414**	**-3.526**	**9.965 *****	**0.592**
		(2.054)	(3.175)	(2.180)	(0.527)
ln(FC)	β_1	**-1.946 *****	**-0.076**	**-0.930 *****	**-0.262 *****
		(0.163)	(0.091)	(0.158)	(0.049)
ln(ACCEL)	β_2	**-0.050**	**-0.414 ***	**-0.647 *****	**-0.704 *****
		(0.073)	(0.220)	(0.114)	(0.051)
ln(CWT)	β_3	**1.951 *****	**2.019 *****	**0.499 ***	**1.590 *****
		(0.314)	(0.385)	(0.302)	(0.063)

Note: ***denotes significance to the 1% level; **to the 5% level; *to the 10% level.

These regression results link high level attributes to price over time. They should be interpreted as having both supply and demand components. In other words, they trace the supply-demand equilibrium points over time. Thus, they measures both consumer valuation on the demand side and manufacturers' cost components on the supply side. It is interesting to note that the parameter estimates for the price elasticities of the various components are strong functions of time, reflecting changes in technology and market response to regulations and other factors. There is implicit evidence that these attributes (and those for which they represent a proxy) are key in driving cost. They also appear to be important from the consumer perspective. Note how fuel consumption was dominant during the phase I CAFE period (Table 3.7, column 1, β_1=-1.946) and acceleration time was only a minor factor (β_2=-.050, with little statistical significance). This phenomenon reversed itself during the period 1997-2014 (Table 3.7, column 2), suggesting consumers and/or OEMs allocated higher value to performance (β_2=-0.414) than fuel consumption (β_1=-0.076, with little statistical significance). Through both periods, CWT has been dominant and statistically significant. When the entire 37 year period is analyzed overall (Table 3.7, Column 3), all three attributes are significant and suggest higher price elasticity for FC than either ACCEL or CWT.

With 814 unique trim levels and unit sales information, the 2014 model year data has greater richness and resolution. These results (Table 3.7, Column 4) suggest that fuel consumption has been de-emphasized with respect to the overall period, but not relative to the 1997-2014 period. This suggests that 2014 consumers continue to value fuel consumption, but may value acceleration performance even more. This time-phased view of innovation with respect to consumer response quantifies the extent to which periods of intense regulation influence economic trade-offs.

3.2.2 Estimation of attribute contributions to utility

Having now quantified the extent to which the instantaneous economic trade-offs among attributes have evolved over historical periods of time, it is of further interest to roughly estimate the share of utility allocable to each attribute during the selected periods. As explained in Section 3.1.4, the disaggregated attribute contribution is derived by partitioning the sums of squares using the ANOVA approach. Using SAS to analyze each regression order as discussed, model variability is partitioned into its constituent parts yielding an approximation of the average contribution of each attribute. A representative sum of squares analysis for the partition allocated to F for the period 1978-2014 is shown in the Table 3.8 below.

Table 3.8. Example partitioning of the sum of squares for F in six regression orders, 1978-2014.

ORDER	SS(F)	SS(F|A)	SS(F|C)	SS(F|C,A)	SS(F|A,C)	TOTAL SS_F	SS_Model	SS_Error	SS_Total
FAC	10267.3					**10267.3**	**16635.2**	**1004.8**	**17640.0**
FCA	10267.3					**10267.3**	**16635.2**	**1004.8**	**17640.0**
AFC		1277.1				**1277.1**	**16635.2**	**1004.8**	**17640.0**
ACF					1057.6	**1057.6**	**16635.2**	**1004.8**	**17640.0**
CFA			9209.6			**9209.6**	**16635.2**	**1004.8**	**17640.0**
CAF				1057.6		**1057.6**	**16635.2**	**1004.8**	**17640.0**
TOTALS	**20534.5**	**1277.1**	**9209.6**	**1057.6**	**1057.6**	***33136.4***	***99811.0***	**6028.7**	**105839.7**

(ΣSS_F)/(ΣSS_Model) = 0.332 = χ_F
(ΣSS_F)/(ΣSS_Total) = 0.313
(ΣSS_Model)/(ΣSS_Total) = 0.943 = R^2

In Table 3.8, the two regression iterations in which F appears first (FAC and FCA) yield the type I sum of squares, as if F were the only regressor. Two additional sums are then added for the regression iterations in which F appears second (AFC and CFA). Finally, the type III sum of squares are added for the two regression iterations in which F appears last (ACF and CAF). This grand sum is then divided by the total model sum of squares, suggesting the average contribution of F to the overall model of utility is, in this example, about 33%. While confounding is much more difficult, if not impossible, to permit disaggregation for attributes that are not orthogonal, this approach provides a basis for broad comparisons among attributes and over time.

Table 3.9 summarizes the estimated percentage contribution of the attributes for the given model to utility.

Table 3.9. Approximate attribute contribution share to total vehicle utility by time period.

Time Period	**FC** χ_F	**ACCEL** χ_A	**CWT** χ_C	**Model Total**	**Unexplained Total**
1978-1996	48.9	37.5	13.6	99.2	0.8
1997-2014	16.4	38.9	44.7	96.3	3.7
1978-2014	33.2	48.0	18.8	94.3	5.7
2014	11.2	34.0	54.8	72.2	27.8

A few high level implications of the comparative weighting study emerge. First, taken as notional indicators, estimated contributions of FC were comparatively high during CAFE 1978-1990, as expected. Second, the overall contribution of FC to utility revealed in 2014 is comparatively low. Third, contributions of ACCEL appear to have remained more consistent across the diverse time periods. Fourth, the contribution of CWT appears to have increased over time. This is likely explained in the early period by immediate substitution to achieve greater FC, and in the latter period due to the fact that it represents a proxy for an increasing number of now standard automobile features. Despite the obvious limitations of the three attribute model (R^2=0.722), the findings suggest contemporary responses to regulations may be structurally different than in historical periods.

3.2.3 Hedonic modeling results: investigating 2014 trends

The comparative elasticity and contribution analyses provide useful insights into the historical evolution of trade-offs and into the implications of future trade-offs. It is of interest to utilize similar methodologies to both improve model accuracy and to explore individual vehicle classifications. Model accuracy can be readily improved with the introduction of additional vehicle parameters. Noting that our continuous system attributes in the foregoing analysis account for more than 72% of the total response, we introduce dummy variables to represent drive type and trim prestige level. The 7-parameter model has the following form:

$$\ln(P_i) = \beta_0 + \beta_1 \cdot \ln(FC_i) + \beta_2 \cdot \ln(ACCEL_i) + \beta_3 \cdot \ln(CWT_i) + \beta_4 \cdot Y_{i,RWD} + \beta_5 \cdot Y_{i,AWD} + \beta_6 \cdot Y_{i,TRIMBASE} + \beta_7 \cdot Y_{i,TRIMPREM} + \epsilon_i \quad (3.9)$$

In Eq. (3.9), $Y_{i,RWD}$, $Y_{i,AWD}$, $Y_{i,TRIMBASE}$, and $Y_{i,TRIMPREM}$ represent dummy variables for the respective drive and trim features accordingly. For rear-wheel drive (RWD) and all-wheel drive (AWD), these dummy variables assume a value of 1 in Eq. (3.9) when they are present (or 0 when the default, Front Wheel Drive, is present). For trim prestige level, a base level (TRIMBASE) and a premium level (TRIMPREM) are introduced, and similarly assume a value of 1 when present (or 0 when Medium Trim is present). The improved model now explains about 78% of the overall response across all classes of 2014 cars, and helps reduce collinearity that may have been present with the 3-parameter model. This is shown in the “All Cars” column of Table 3.10.

Table 3.10. Regression results of the 7-parameter model on the 2014 data set.

Vehicle Category		All Cars	Sub-Compact	Compact	Midsize, Lower Half	Midsize, Upper Half	Full Size
Model Year		2014	2014	2014	2014	2014	2014
Footprint (FP) Min		26.8	26.8	42.1	44.8	47.0	49.1
Footprint (FP) Max		56.4	42.0	44.7	46.9	49.0	56.4
FP, Weighted Mean		45.8	39.7	43.7	45.9	47.8	51.7
Data Set		Table 3.2	Table 3.2	Table 3.2	Table 3.2	Table 3.2	Table 3.2
MSRP, Wtd. Mean		$27,841	$20,097	$21,931	$28,124	$30,368	$46,676
Sales Vol., Units		7,868,192	672,253	2,376,006	1,825,863	2,309,412	684,659
Sales Revenue, $B		219.1	13.5	52.1	51.4	70.1	32.0
Response Variable		ln(MSRP)	ln(MSRP)	ln(MSRP)	ln(MSRP)	ln(MSRP)	ln(MSRP)
Hedonic Model		Eq. (3.9)	Eq. (3.9)	Eq. (3.9)	Eq. (3.9)	Eq. (3.9)	Eq. (3.9)
Estimator		WLS	WLS	WLS	WLS	WLS	WLS
Observations		814	126	142	156	202	188
R^2		0.781	0.850	0.674	0.825	0.751	0.752
Attribute	**Coeff.**	**Param. Est.** (Std. Error)	**Param. Est.** (Std. Error)	**Param. Est.** (Std. Error)	**Param. Est.** (Std. Error)	**Param. Est.** (Std. Error)	**Param. Est.** (Std. Error)
Intercept	β_0	**1.626*** **	**5.679*** **	**-0.883**	**0.663**	**-4.036*** **	**-10.178*** **
		(0.478)	(1.630)	(1.462)	(1.270)	(1.189)	(2.373)
ln(FC)	β_1	**-0.306*** **	**-0.709*** **	**-0.301*** **	**-0.359*** **	**-0.034**	**-2.285*** **
		(0.044)	(0.130)	(0.070)	(0.102)	(0.061)	(0.204)
ln(ACCEL)	β_2	**-0.526*** **	**-0.937*** **	**-0.355*** **	**-0.745*** **	**-0.118** **	**-2.664*** **
		(0.048)	(0.138)	(0.102)	(0.099)	(0.058)	(0.190)
ln(CWT)	β_3	**1.403*** **	**1.080*** **	**1.699* **	**1.613*** **	**1.985*** **	**4.128*** **
		(0.058)	(0.199)	(0.178)	(0.164)	(0.161)	(0.316)
RWD	β_4	**0.227*** **	**0.604*** **	**0.403*** **	**0.238*** **	**0.291*** **	**-0.101* **
		(0.022)	(0.072)	(0.078)	(0.043)	(0.038)	(0.056)
AWD	β_5	**0.198*** **	**0.692*** **	**0.033**	**0.217*** **	**0.188*** **	**0.061**
		(0.026)	(0.141)	(0.051)	(0.051)	(0.040)	(0.060)
TRIMBASE	β_6	**-0.072*** **	**-0.096*** **	**-0.075*** **	**-0.062** **	**-0.075*** **	**0.083* **
		(0.015)	(0.028)	(0.024)	(0.027)	(0.022)	(0.043)
TRIMPREM	β_7	**0.113*** **	**0.116*** **	**0.083*** **	**0.075*** **	**0.097*** **	**0.071**
		(0.015)	(0.037)	(0.024)	(0.027)	(0.021)	(0.046)

Note: ***denotes significance to the 1% level; **to the 5% level; *to the 10% level.

We note that compared to the 3-attribute model, the improved model suggests the elasticity of FC is greater, while the elasticities of ACCEL and CWT are reduced. We also note that statistical significance has been greatly improved in the expanded model.

Given the footprint-based regulations defined in the 2012-2016 CAFE standards, an assessment of the relevant elasticities by vehicle class is novel and of considerable interest. Table 3.10 also sub-divides the regression results into five different vehicle groupings, using vehicle footprint as a blocking variable[9]. An indication of the relative sales units and revenue is also provided for each footprint range. It is of note that the price elasticity of FC with respect to vehicle price is lower than that of ACCEL in each vehicle classification. However, the spread between these elasticities is more pronounced for the midsize categories, presumably because consumers of these vehicles value acceleration and performance to a greater extent. Likewise, the elasticities imply that consumers of sub-compact and compact cars have a greater relative willingness to pay for reductions in fuel consumption. Additional hedonic modeling results by vehicle class for the 2013 model year are located in Appendix B.

3.2.4 Results of this study in context

By way of quickly corroborating estimated elasticity parameters suggested by our 2014 data, we compare implied values of fuel consumption reduction to others from the literature that employ different approaches. A benefit-cost study of fuel-saving vehicle technologies available in new 2014 compact and mid-size cars suggests that consumers who elected to invest in greater fuel economy spent an average of $1490 more than consumers who did not, in order to realize an estimated 17.3% improvement in fuel economy [32]. This converts to a 14.7% reduction in fuel consumption, and an implied

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[9] Due to the disproportionate quantity of sales (by unit volume and revenue) in the “midsize” classification, this study divides this group into two roughly equal-sized subsets. The midpoint of the vehicle footprint (FP) for the entire midsize class (46.9 ft^2) is used as the division criteria between “Midsize, Lower-Half” and “Midsize, Upper-Half.”

value of about \$101 per 1% reduction in fuel consumption (in 2014\$). This compares to an implied value of about \$85 per 1% reduction in fuel consumption (in 2014\$) predicted by this study. This \$85 estimate is computed by taking the elasticity of price with respect to FC ($\beta_1 \approx -0.306\%$, Table 3.10, column 1) for the 2014 model year, dividing by 100%, then multiplying by the mean vehicle MSRP for 2014 (\$27,841). Much of the discrepancy between to the two estimates can be explained by the fact that this study assesses the entire 2014 sales-weighted fleet of cars, whereas the higher estimate of the cited study considered the willingness to pay for fuel economy in only the best-selling compact and midsize cars.

Other estimates in the literature corroborate the results of this study, including one that used a vehicle miles traveled (VMT) approach to estimate that a 1% reduction in fuel consumption for 2001 model year vehicles was in the \$47 to \$60 range (\$2014) [129]. This lower estimate confirms the direction and magnitude by which time period and regulatory conditions impact the price elasticity of fuel consumption. That same study suggested that the total price attributable to fuel economy in model year 2001 was in the 5-10% range [129], suggesting the rough attribute contributions in recent periods estimated by this study are plausible and useful for qualitative comparisons.

The analyses presented are based upon an extensive set of data sources. Though aggregating historical data at a high level incurs risks of lost resolution with respect to a specific attribute or measure of utility, this is compensated for by the extended time period under review, the estimated 300,000,000 vehicles included in the data, and the qualitative and comparative approach taken in the historical trends analysis. The 2014 data set is shown to be invaluable for comparisons of current markets with historical trends, as well as for providing insight into the footprint and sales-weighting aspects that will play critical roles in the more highly regulated car markets of the near future. The quantitative technical, market and pricing datasets are deemed robust for the purposes of these analyses.

3.3 Summary of Key Findings

Objective vehicle attributes as representative indicators of consumer utility are shown to have merit in informing economic trade-off trends. Constant upward trends in disaggregated and aggregated measures of utility have resulted in dramatic increases in consumer value of the time period studied. Key points that emerge very strongly from this research include:

- Real weighted average prices for autos have remained roughly constant since 1985
- While real prices have not increased, the technological performance of car attributes has increased substantially over this time period. Initially assuming a simple equal weight index shows that performance has increased about 2.7% per year while real prices remained relatively constant.
- The correlation and regression analysis demonstrates that technical progress has been achieved on several technical dimensions simultaneously; e.g., quicker cars with greater fuel economy.
- Hedonic pricing methods demonstrate that historical real vehicle prices represent strong indicators of consumer utility defined by primary disaggregated attributes. In particular, implied valuations of reductions in fuel consumption are rebounding after a period of unchanged regulations that ended in 2011. Fleet-wide however, consumers appear willing to pay up to 50% more for acceleration performance than fuel consumption reductions.

- Increasing the accuracy of hedonic models with additional predictor attributes and sub-dividing the analyses by vehicle classification provide insight into future valuation trends. Consumers of sub-compacts are substantially more willing to pay for fuel economy, and consumers of certain mid-size cars appear to neglect the value of fuel economy while highly valuing acceleration.
- These findings imply that vehicle attributes do not contribute equally to consumer utility, nor are their price elasticities with respect to vehicle price equal. Both weightings and elasticities evolve in response to regulatory constraints and consumer preferences by vehicle classification.
- When we estimate the contribution of different attributes in driving equilibrium prices, we find fuel consumption had a significant impact, perhaps as high as 40%, during initial phases of U.S. fuel economy regulations (1978-1997), but the current share of price allocable to fuel consumption is estimated to be much lower, in the 10-12% range.
- The results suggest relative contributions of attributes to utility and the willingness to pay for vehicle attributes can be complementary to technological tools for estimating the trade-offs required in future (CAFE) compliance scenarios.
- Given that fuel economy standards are sales weighted, and that consumers appear now to place lower value on fuel economy, this suggests it may be more difficult and costly to achieve future fuel economy standards than it has been in the past.

CHAPTER 4. A BENEFIT-COST ASSESSMENT OF NEW VEHICLE TECHNOLOGIES AND FUEL ECONOMY IN THE U.S. MARKET

As revealed by the literature in Chapter 2 and the temporal trends in Chapter 3, original equipment manufacturers (OEMs) and consumers have generally been successful in migrating toward cleaner vehicle options with little sacrifice in cost, performance or overall utility. Projections regarding the challenges and impacts associated with compliance with mid- and long-term fuel economy targets in the U.S., however, incur much greater uncertainty. The share of existing new vehicles that is expected to comply with future regulations, for example, falls below 10% by 2020. Adding to the uncertainty are volatile fuel, energy and commodity prices, as well as consumer acceptance of novel fuel saving vehicle technologies.

This chapter employs a benefit-cost approach to assess advanced technologies that result in reduced fuel consumption and emissions. This study looks at the empirical record, drawing from vehicle and technology specifications, published selling prices, and established conventions for financial decision-making by consumers and the economy as a whole. To ensure consistency, it uses accepted terms, definitions and concepts while drawing from many of the same literature sources that were used to formalize the standards. The goal of this chapter is to ascertain how closely costs, fuel economy improvements and the recently promulgated regulatory standards align, as well as to quantify the extent to which novel fuel saving technologies are financially attractive to consumers and how their value proposition may evolve in the future. While the focus of the present study is on mass-production technologies available in 2014 Model Year compact and midsize passenger cars, the methodologies are broadly applicable. Such an assessment may prove valuable to a wide range of stakeholders, including researchers working at the intersection of transportation and energy, economics and policy as well as consumers and OEMs. The material presented in this chapter was published in Applied Energy (157 (2015) 940-952) [32].

4.1 Resources and Approach

4.1.1 Vehicle selection and data sets

In order to appropriately reflect revealed consumer preferences, many of the best selling cars in the U.S. market for recent years were included in the analysis. A database populated with vehicle sales by model and engine type, specifications, standard options, other options influencing fuel economy, and all associated costs was developed. For the vehicle selling prices, we use Manufacturer's Suggested Retail Prices (MSRPs) [130]. Table 4.1 indicates the vehicle makes and models that are included in the analysis, along with a few market indicators.

The grouping of vehicles in Table 4.1 accounts for nearly 4 million units, or about 55% of new sales (by volume) in the passenger market and 28% of new sales in the entire light duty vehicle fleet (light trucks and SUVs account for nearly 50%). While the top 14 best-selling passenger cars account for more than half of the sales (by unit volume), some 200 additional models account for the remaining portion [131].

Table 4.1. Compact and Midsize 2014 MY vehicles included in the analysis [122,130,132].[10,11]

Approx. Rank by sales	**Vehicle Make**	**Vehicle Model**	**Sales** 1000s of units	**MSRP Base Model** in 2014$	**Fuel Economy**		**EPA Class**
					Base Model mpg	**High mpg Model**[12] mpg	
1	Toyota	Camry	450	22,425	28	40	Mid-size
2	Honda	Accord	375	21,955	28	57	Mid-size
3	Nissan	Altima	350	22,300	31	31	Mid-size
4	Toyota	Corolla	350	16,800	31	34	Compact
5	Honda	Civic	335	18,390	31	45	Compact
6	Ford	Fusion	325	22,400	26	51	Mid-size
7	Chevrolet	Cruze	285	18,345	29	33	Compact
8	Ford	Focus	235	16,810	30	31	Compact
9	Hyundai	Elantra	230	17,250	31	32	Compact
10	Hyundai	Sonata	220	21,450	28	38	Large/Mid
11	Toyota	Prius	220	24,200	50	58	Mid-size
12	Chevrolet	Malibu	200	23,165	29	29	Mid-size
13	Nissan	Sentra	190	15,990	30	34	Mid-size
14	VW	Jetta	170	16,895	28	45	Compact
-	Chevrolet	Volt[13]	23	26,670	63	63	Compact

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[10] Unless otherwise specified dollar amounts are in 2014 dollars.

[11] Fully electric vehicles (or EV's) have not been included in this study. While there are at least 2 EV models in the subject classes, it is complicated to account for the loss of utility through reduced range, as well as to make a fair accounting for the equivalent energy efficiency (see Appendix A). It may also be that due to low volume production, MSRPs are less likely to reflect true costs. PHEV's share some of the same concerns, but have little or no range reduction, and, with qualification, have costs and weighted equivalent fuel economy ratings that can be compared to the other conventional ICE-only and hybrid vehicles in the study. PHEVs have therefore been included accordingly.

[12] The "High mpg Model" listed corresponds to the vehicle sharing the same chassis as the given base model with the highest EPA combined mpg rating [132].

[13] The Volt is not among the top-selling passenger cars and lacks an internal-combustion-only version. However, it is included in this analysis because it offers novel fuel-saving technology. Though it is officially classified in a category of its own as an extended-range electric vehicle, it is simply referred to as a PHEV in this analysis. Also, its base MSRP reflects a $7500 discount offered via Federal subsidy because it is a qualifying vehicle [82].

For the purpose of estimating fuel economy improvements, officially reported EPA combined city/highway miles per gallon ratings are used [132]. This point is important, because real world fuel economy, often termed "adjusted fuel economy," varies considerably and is generally lower than official EPA ratings [68,133]. Though the use of official ratings may give a slightly conservative result (i.e., overstating the benefits attributable to fuel savings), the analysis remains valid because it is most concerned with relative fuel economy improvements over base technologies. Furthermore, Federal CAFE standards employ an EPA rating basis, facilitating comparisons with other studies and official regulations.

4.1.2 Approach methodology

In this study, costs and fuel economy impacts are compared in two distinct ways. In the first approach, technology changes are compared against a specific base model of the same manufacturer, with the same chassis. This is referred to here as a "model-specific" approach to benefit-cost analysis. In the second approach, a sales-weighted average vehicle is developed for each vehicle class (compact and midsize). Then, by tracking the relative differences as compared to the model-specific base case, it can be determined how a technology compares to a reference vehicle that is representative of consumer preference by class.

Regarding the model-specific approach, the analysis of new technologies against their respective baseline models is insightful because it demonstrates the incremental impact in cost and fuel economy directly associated with a given technology change. The process for extracting this information is not transparent, however, and great attention to detail has therefore been paid in this study to the other variables and attributes of the vehicle model that are unrelated to the fuel economy technology itself (e.g., larger alloy wheels, leather seats, moon roof, navigation, etc.). Thus what is needed is an approach that extracts solely the relevant portion of the price increase that should be allocated specifically to changes in fuel economy. The net price impacts associated with any extraneous attributes included in the inflated MSRP can then be subtracted to establish a net price difference. As discussed, conventional terminology is used for this difference, known as the "incremental retail price equivalent" or IRPE associated exclusively with a given vehicle fuel efficiency technology. This provides the means to populate a chart comparing incremental price changes and fuel economy improvements. Prices are in 2014 dollars, and fuel economy improvements are reported as either absolute Δ mpg (with units of mpg), or as Δ % change (reported in % difference in fuel economy) against a model-specific baseline.

Some vehicle models include upsizing of engine displacement, or turbo-charging at constant displacement, both of which result in increased power, but diminished fuel economy. Others include Compressed Natural Gas (CNG) fuel-capable engine technologies. However, a conscious decision has been made to intentionally leave these technologies out, in order to develop a curve that focuses specifically on technologies that contribute to fuel economy improvements. That said, there is a notable market demand for increased engine power, and even alternative fuel technologies. While the focus of this paper is on fuel economy, certain studies indicate that consumers value an increase in power more than an increase in fuel economy [63]. Certainly the interrelationship between power and fuel economy has unique implications for consumers, OEMs and compliance with future regulations [6].

The model-specific approach is a necessary first step to begin quantifying the revealed market correlation between end-user prices and fuel economy. However, this model-specific aspect which brings clarity to a true “differential cost vs. differential mpg” comparison suffers from the inherent limitation that such findings may not be categorically applied to a broad class of vehicles. In other words, comparing the cost and fuel economy associated with a given upgrade on a given chassis is one thing, but comparing several different models from different OEMs with different standard specifications and features to one another may introduce significant uncertainties in incremental costs and in allocations of utility (such as fuel economy, passenger volume, and power). In addition, a few advanced vehicles have been uniquely designed on exclusive platforms to specifically introduce fuel saving innovations, such as the Toyota Prius and the Chevrolet Volt. A challenge in determining the incremental costs and impacts associated with such vehicles from the model-specific approach is that a “baseline, standard, internal combustion engine (ICE) vehicle only” version is non-existent.

To navigate both of these concerns with the model-specific approach, a “classification-average” approach is undertaken in which sales-weighted average criteria for vehicles in the compact and midsize car classifications are established. This is accomplished via current-day investigation into the respective market segments for the selected advanced fuel-efficiency technology vehicles. With just a few minor exceptions (such as the unique hybrid platforms), OEMs of the selected top-selling models generally offer several conventional models, often with multiple engine choices, and one or more models that include improved efficiency technologies available at some premium price.

Even so, the classification-average approach does not fully isolate the cost-fuel economy correlation either, because it remains possible and even likely that aspects of the vehicle's utility may differ (such as power and passenger compartment volume) from the baseline. For this reason, most of the analysis follows the model-specific approach, whereas the sales-weighted average results are offered merely as a check against this preferred method. Just two exceptions are made to permit the inclusion of data for the Prius and Volt. For these, the sales-weighted average vehicle method is initially employed to establish a baseline, then comparative data is transformed and included into the model-specific analysis[14]. This is done to capture the effect of such high-profile, commercially available advanced vehicle technologies. PHEVs introduce the need to account for multiple energy sources, and the present study follows EPA guidance to determine relative shares of electricity and gasoline, which varies by OEM model[15].

4.1.3 Initial results from the model-specific analysis

The model-specific approach isolates the true incremental price of a new technology specifically allocable to fuel economy, and is performed on a model-by-model basis. By way of example, Table 4.2 describes the basic process for separating the

[14] The Toyota Prius is officially classified by EPA as a mid-size vehicle owing to its passenger (93.7) plus cargo (21.6) volume of (115.3); EPA defines: midsize 110-110, compact 100-109. However, the Prius's power (134 hp) is closer to the average compact (144 hp) than the average midsize (191 hp). Its footprint is 44.22 sq ft, aligning more with compact cars (43-45) than with midsize cars (45-49). Thus in terms of power, footprint and other aspects of utility, the Prius is more similar to a compact car than a midsize. It has therefore been so considered in this analysis, to enable an estimation of its incremental price equivalent and fuel economy % improvement. For the purposes of this analysis the Prius (at MSRP of $24,200 and 50 mpg) is compared against an average compact vehicle (MSRP=$19,746 and 33.2 mpg).

[15] The EPA estimates the share of all-electric driven miles as compared with gasoline driven miles for PHEVs. These estimated shares are model specific and based upon "the vehicle's design and average driving habits." The assumed shares (elec/gasoline) by vehicle are: Fusion Energi (45/55); Volt (66/34); Prius (29/71). The EPA rated all-electric ranges of these vehicles are: Fusion (20); Volt (38); Prius (11). This study uses the EPA assumptions accordingly [132]. See also SAE J1711 [106].

constituent cost and fuel economy improvement data from an actual model, in this case a hybrid, drawn from the data set. Price variances are accounted for between the new technology model and a baseline vehicle with which it shares an identical chassis.

Table 4.2. Example of methodology used to determine the model-specific IRPE and % fuel economy improvement. Data sources [130,132].

Description	Actual MSRP ($)	IRPE for technology alone, model specific case ($)	EPA combined Fuel econ. (mpg)	Fuel econ. change (Δ mpg)	Fuel econ. percent change (Δ%)
Baseline Vehicle 1	18,390		31	-	-
Unrelated Options	2,550				
Hybrid version Vehicle 1	24,635	**3,695**	45	+14	**+45.2**

This process is continued for each fuel economy technology grouping offered with each model. By using the manufacturer's suggested retail price (MSRP), it is assumed that technology costs are directly correlated to suggested retail prices. It is reasonable that MSRPs would more closely reflect true costs than heavily discounted prices, for example via year-end or dealer incentives; however, some degree of cost-price uncertainty remains.

That said, from a consumer perspective, OEM technology costs are less important than market-based prices, which reflect what the consumer actually pays for a given technology. Collecting incremental price data from multiple OEMs, as is done here, helps reduce potential anomalies. Groupings by technology type are of interest because they provide a means of comparison between different OEMs and with other studies. This allows for decision-makers to assign an order of magnitude to major technology bins as well as assess technology penetration in view of near- and long-term requirements. Table

4.1 shows the relative position of major technology categories on a cost vs. fuel economy improvement graph for selected compact cars.

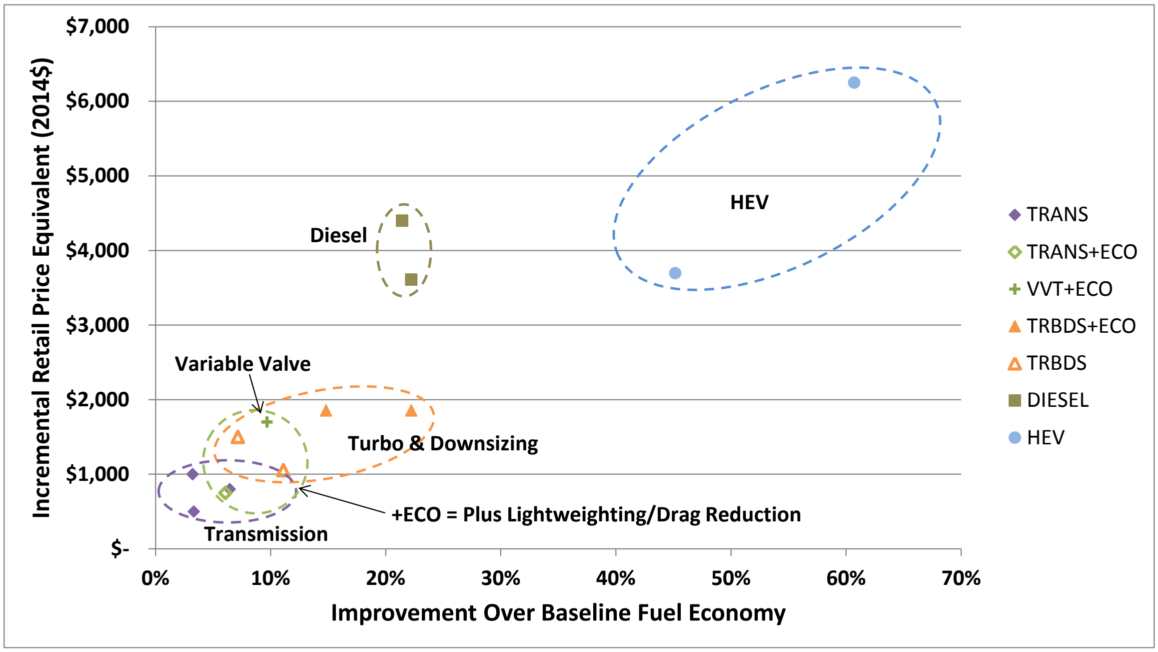

Figure 4.1. Cost of improved efficiency from 2014MY vehicle technologies, compact class, model-specific basis.

The purpose of this figure is to illustrate where the benefits and costs of fuel-saving technologies fall on a spectrum, and that they can roughly be grouped by technology category and relative impact level. A few of the technology categories overlap or are bundled, as shown by data points that include advanced transmissions with 5 or 6 speeds with features marketed in “ECO” packages. These generally include modest weight savings, for example provided by replacing steel wheels with aluminum alloys, or removing a spare tire in exchange for a tire patch kit. Some of the ECO technologies include low rolling-resistance tires, or aerodynamic features such as underbody treatments or spoilers to reduce drag. Generally, transmission technologies and ECO options have costs below $1000 and improvements on the order of 3 to 10%. In the case of most turbochargers in the compact and midsize classes, engines are downsized first, and then boosted to recover the power, frequently at a lower fuel consumption level. Turbocharging and downsizing often accompany gasoline direct injection, and therefore often include the impact of all three changes simultaneously. There is variation in different OEM approaches to turbocharging and downsizing, because power is dependent on engine design, which is in turn linked to fuel economy. In most cases, OEMs elect to match or exceed the power level of the normally aspirated version, which does not always result in the same fuel savings. This is a complicated marketing trade off, but one with significant implications on future trends.

The cost of a given improvement in fuel economy over time has been estimated in the literature [45,134]. Though such estimates cannot be generalized, it is of note that the ranges typical of technologies considered in the authors' study here are consistent with those of other studies. For the compact and mid-size classifications, current technologies in the 0-15% improvement range cost between \$50 and \$100 per percent improvement in fuel economy. For larger increases, the range can be broader, extending upwards to \$200. However, depending on the type of technology used, hybrids appear to come in below \$100. It should be noted that at a level of 50 mpg, a 1% increase represents lower volumetric fuel savings (0.000198 gal/mile) than a 1% fuel economy increase on a baseline of 30 mpg (0.00033 gal/mile). For this reason, many researchers prefer to use fuel consumption in lieu of fuel economy when considering broad ranges of improvement, and caution is advised in the use of such rule of thumb indicators. Figure 4.1 exhibits an interesting bifurcation: there are many relatively low cost technologies that deliver modest gains and another grouping of high cost technologies delivering substantial increases. Though this data set is not comprehensive, the valley between is of note.

4.2 Benefit-Cost Assessments

In order to generate a baseline benefit-cost analysis, it is more compelling to use the model-specific data since the goal is to estimate the investment and fuel savings on *actual vehicles*. In simplified terms, the model specific approach considers the IRPE as the initial outlay of cost, and the % fuel economy increase as an incremental time-phased benefit (i.e., fuel savings). Table 4.3 defines the assumed or given values, which along with the existing IRPE and % fuel economy improvement data can establish a baseline benefit-cost curve.

The impact of the most significant parameters is assessed by virtue of the sensitivity analysis. The residual (or salvage) value is an important aspect of this study, since it is well known that more advanced technologies such as diesels and hybrids retain their value more strongly than vehicles operated exclusively by an internal combustion engine. The residual values indicated in Table 4.3 represent a best fit exponential function of average residuals by technology type for the subject classes. Since time value of money has not yet been considered, all references to IRPE thus far imply the entire incremental retail price equivalent (i.e., the full price paid for a given technology at the time of purchase).

Table 4.3. Parameters used in the benefit-cost analysis, their baseline values and bases.

Parameter	**Baseline Value**	**Units**	**Source or Basis**[16]
Gasoline Price (initial)[17]	3.50	$/gal	[135]
Diesel Price (initial)	3.87	$/gal	[135]
Annual Mileage[18]	12,000	miles/yr	[136] [137]
Vehicle Service Life[19]	7	years	[138] & author
Residual (Salvage)[20] Value-Default	21.0	%	[139] & author
Residual (Salvage) Value-Hybrid	26.0	%	[139] & author
Residual (Salvage) Value-Diesel	23.0	%	[139] & author
Interest rate (or discount rate)	7.0	%	[15] [27] & author
Inflation rate	2.0	%	[140]
Real interest rate	4.9	%	calculation
Real gas price increase (annual)	1.5	%	[141]
Nominal gasoline price increase (annual)	3.5	%	calculation

Upon analyzing benefit cost results and for all net present value calculations, attention is now paid to the residual value of the technology assessed, such that a net present value (or NPV) of its salvage value can be deducted from the initial investment, yielding a "net IRPE." For advanced technologies which incur considerable capital cost premiums, residual value may have a significant impact on the final benefit cost result. In this study,

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[16] When "author" appears in the "source or basis" column next to a given reference citation, that indicates the authors relied upon multiple sources, or applied reasonable judgment to cited norms in selecting the baseline values.

[17] The initial price of U.S. Regular gasoline for the period July 14 through August 4, 2014 is taken to be $3.50 per gallon. The initial price of U.S. on-highway Diesel fuel prices for the same period is taken to be $3.87 per gallon. Per EIA, prices include all taxes [135].

[18] The 12,000 mile annual estimate of vehicle miles traveled is determined by averaging self-reported actual annual mileage for US household vehicles with odometer readings [136-137].

[19] [138] indicates ownership life of new vehicles was about 6 years in 2011 and is combined with authors' projection of trends to 2014, yielding an average ownership life of new vehicles of about 7 years.

[20] [139] provides residual values by selected technology classes at 5 years from purchase. This was then combined with authors' (exponentially decaying) curve-fitting analysis to project residuals at the end of the 7th year of vehicle ownership.

a seven-year service life is assumed based upon ownership trends for new vehicles in the U.S. market [138]. That said, since a salvage value is computed at the end of the terminal year, the given service life assumption used in this study has much less effect on the net present value results than annual vehicle miles traveled. In other words, it is vehicle usage, not calendar life that has the greater impact. The baseline assumption for annual usage is 12,000 miles per year, based average new vehicle mileage data for U.S. households drawn from DOT's National Personal Transportation Survey [136]. Using the model specific data, baseline benefits derived from fuel savings over time, and net IRPE costs for the vehicle technologies have been generated. Figure 4.2 illustrates the benefit-cost results by technology grouping for the baseline case.

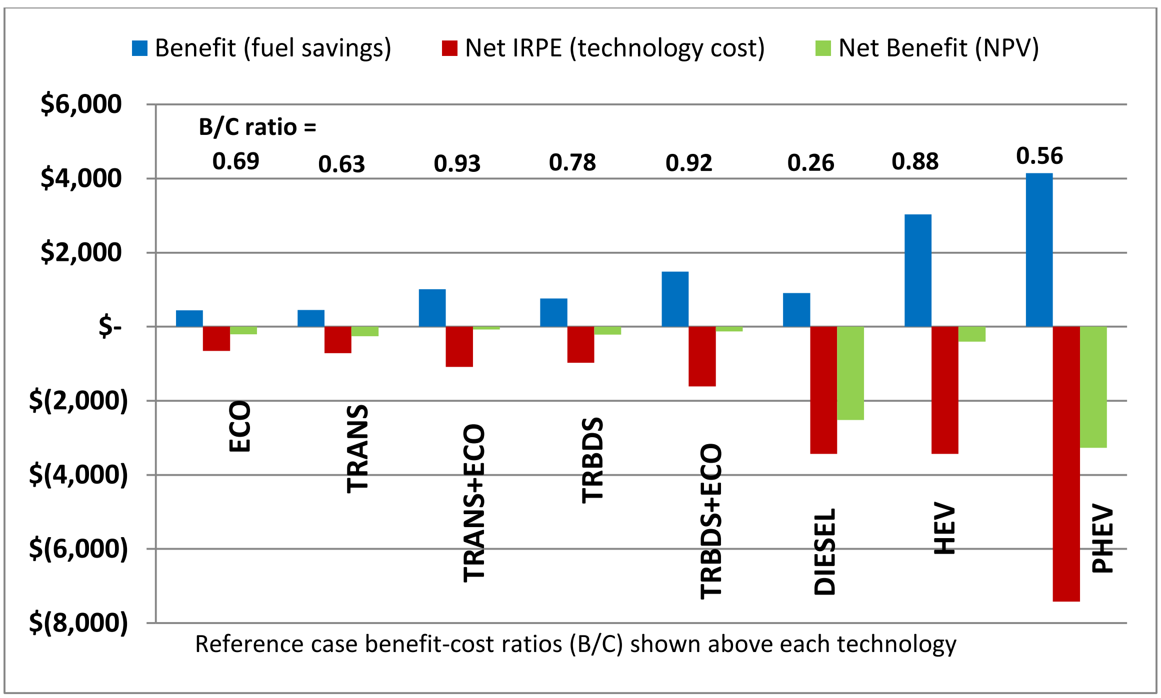

Figure 4.2. Results of baseline benefit-cost assessment by technology category.

By definition, a "Benefit/Cost (B/C) ratio" is the quotient of the net present value of the benefits (or fuel savings) divided by the net incremental retail price equivalent (or net investment costs) of the technology; thus a ratio of unity means that benefits and costs are equal. Benefit-cost ratios for each technology category have been averaged and reported in Figure 4.2 above each respective grouping. For the baseline condition, an un-weighted average benefit-cost ratio can be obtained by considering each individual observation in the analysis as equal weight. Though perhaps slightly more biased toward what is offered than toward what is actually purchased, this “notional” average ratio of all constituent technologies assessed is 0.73 (R^2 = 0.88). This means that under the assumed conditions, these technologies do not, on average, yield economic returns to consumers that buy them instead of base model technologies.

Despite these relatively low values, the figure illustrates that substantial fuel savings can be generated at reasonably affordable costs, especially for specific technology groupings such as transmission upgrades, downsized turbos and hybrids. Payback periods and benefit cost ratios obviously have a greater financial impact when a consumer invests in more expensive technologies. Thus, a low B/C ratio may not result in meaningful cash losses by a consumer adopting weight savings, drag reduction, or upgraded transmission technologies; but it would be more imperative to rational consumers that B/C ratios approach or exceed 1.0 for higher cost technologies, such as diesels, hybrids, and PHEVs. Average B/C ratios below one are not meant to imply that specific technologies on specific models do not exceed a breakeven condition (as several do), but rather that consumers of these selected technologies as a whole under the given assumptions do not generally appear to breakeven.

Figure 4.3 displays all of the discrete technology packages on a common plot. For reference, a benefit cost curve equating to a breakeven condition (B/C = 1.0) is shown.

This breakeven line was generated by requiring the net IRPE costs to be equal to the benefits of a given model under given assumptions. In other words, we work backward to determine what the costs *have to be* in order to justify their payback in fuel savings over time. The resultant virtual costs are then plotted against the corresponding fuel economy improvements, and linearly regressed to characterize the breakeven condition.

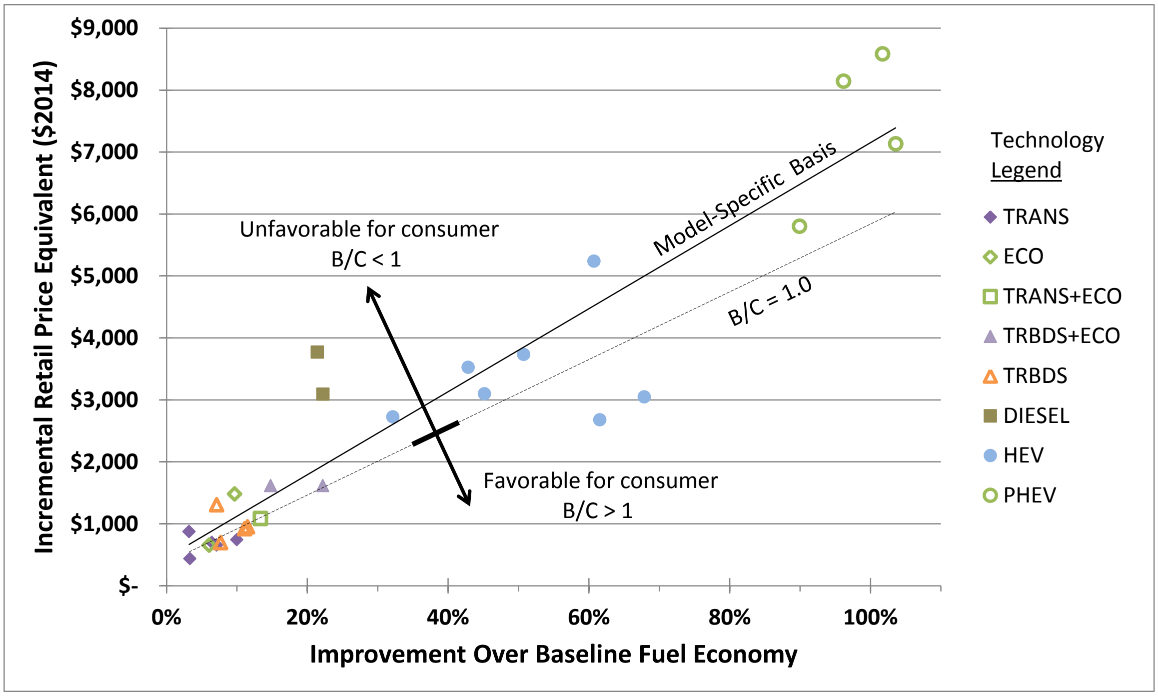

Figure 4.3. Discretized data points representing compact and midsize car technologies from model-specific basis and best fit regression shown relative to the breakeven line.

As shown in Figure 4.3, approximately six of the 28 discrete technologies in the study yielded benefit-cost ratios greater than one in the baseline case. Three of these have turbos with downsizing, two are hybrids, and one has a continuously variable transmission. These points appear on the plot below and to the right of the breakeven line in the region that yields a favorable benefit cost ratio for the consumer. Two additional points are extremely close to breakeven (such that the line appears to intersect them), have benefit-cost ratios of 0.94 and 0.93, and include CVT and CVT+ECO, respectively. Conversely, points that are above and to the left will yield an unfavorable result for the consumer under the assumed conditions. A linear regression is performed to characterize the relationship between cost (net IRPE) and fuel economy improvement according to the model specific basis. The relationship is of first order, has an R^2 of 0.88, and can be estimated by the following formula where $IPRE_1$ represents the net incremental retail price equivalent in dollars compared to the model-specific baseline, MPG_X and MPG_{MS} represent the fuel economy of the improved model (X) and the model-specific (MS) baseline respectively, and the argument in parentheses is the percent change in fuel economy relative to the model-specific (MS) baseline.

$$IRPE_1 \approx 67 \cdot \left(\frac{MPG_X - MPG_{MS}}{MPG_{MS}} * 100 \right) + 451 \tag{4.1}$$

Performing a regression on the aggregated set of technologies has clear limitations, but helps to indicate relative cost effectiveness for both discrete technologies and families of technologies. It serves to demonstrate, for example, that passenger cars with diesel engines and certain plug-in hybrids deviate significantly from the mean expected trends. It also shows that the initially small gap between the unweighted average trendline and the breakeven line grows larger as a function of fuel economy improvement. The non-zero intercept is of note, and is possibly a function of the model specific approach, where extraneous costs (due to the inclusion of more options as ‘standard’) are inadvertently linked to “premium” fuel saving technology attributes. When technologies with lower fuel economy improvements (<20%) are evaluated as a separate group, the regression slope decreases with respect to the larger data set and roughly predicts that a \$500 to \$600 incremental cost will buy a 10% increase in fuel economy (from 5% to 15%). However, the non-zero intercept implies some minimum static threshold of cost (up to $450) may be required on actual vehicles to realize this rate of gain.

Downsized turbos provide from 7 to 22% fuel economy improvements for costs ranging from $700 to $1600. This seems to offer consumers considerably more value than diesels which increase fuel economy by about 22% at costs between $3000 and $4000. Hybrids can deliver about twice this fuel economy improvement (from 35 to 63%) for costs between $2700 and $5200.

4.3 Sensitivity Analysis

Uncertainty is inherent in many variables relevant to this analysis, including technology specifications, market pricing, driving modes and behavior, and exogenous macro-economic factors. However, an appropriate sensitivity analysis quantifies the extent to which critical factors influence the results. Included in the sensitivity analysis are discount rate, annual mileage, and fuel price. Table 4.4 demonstrates the ranges of variables considered, as well as the baseline reference assumptions for each factor.

The literature provides good guidance on parameter values typically used for similar analyses (Table 4.3), and relevant sources from which the established baseline values and low and high limits are cited (Table 4.4). This study does not fully consider the impact of differing driving habits or driving modes (such as city vs. highway). Clearly these factors would affect the value proposition, but are highly variable, and would affect "fuel efficient" and "standard" technologies similarly, and are therefore not deemed to be differentiating in this analysis.

Table 4.4. Minimum, baseline, and maximum parameter values used for the sensitivity analysis.[21]

Variable	**Nominal Discount Rate**	**Annual Miles Driven**	**Fuel Price Rate of Change**[22]
Units	%	miles	Rates of change over 7 years
[Source]	[15] [27] [142] & auth	[136] [137] & author	[141] [142] & author[23]
Low limit	3	9,000	Decreases at 3% per year
Baseline value	7	12,000	Increases at 1.5% per year
High limit	10	15,000	Increases at 7% per year

Recall that under the baseline conditions, the un-weighted average benefit-cost ratio of all unique models and constituent technologies assessed is about 0.73 with an $R^2 \approx 0.88$. As described in the preceding section, consumers will realize a net economic benefit for anything below or to the right of the breakeven line (B/C=1.0 in Figure 4.3), and conversely will incur a net economic cost for anything above or to its left. Instead of exploring which specific technologies on this plot have a favorable benefit-cost ratio (which is in itself of interest), this sensitivity analysis is rather aimed at establishing a sense for the likelihood that a consumer will experience a positive net economic benefit from a given technology.

All three sensitivity variables seem to have a similar impact on the results within the stipulated ranges, with annual miles driven being narrowly more significant than fuel

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[21] For simplicity and to clarify the independent impacts of the sensitivity variables, only one parameter is set to its low (or high) limit at a time, while the other two are held at their baseline values.

[22] For initial fuel prices of fuel, please see Table 4.3 or source [135]. For fuel price rates of change, annual rates of increase (or decrease) are inferred based upon EIA long-term oil price forecast in 7 years: high case ($165/bbl), reference case ($110/bbl), low case ($75/bbl) [141-142].

[23] Again, when "author" appears along with a given reference citation, that indicates the authors considered multiple sources and applied reasonable judgment in selecting appropriate ranges for the values of sensitivity parameters

price and discount rate. However, if all breakeven benefit-cost ratios are averaged among all technologies, an average B/C of unity is not achieved by any one of the individual sensitivity variables alone, even when calculated at the given limits. In other words, no sensitivity parameter by itself taken to its limit results in a breakeven condition for all technologies. Table 4.5 illustrates the response of the benefit cost ratio to the sensitivity variables when the others are held at baseline values.

Table 4.5. Impacts of the sensitivity variables on benefit cost ratio.

	Discount Rate		**Annual Miles Driven**		**Fuel Price Rate of Change**	
	low limit	high limit	low limit	high Limit	low limit	high Limit
	3%	10%	9,000 mi	15,000 mi	-3%/yr	+7%/yr
B/C value	0.896	0.639	0.548	0.914	0.616	0.901

Note: These results assume only one variable is changed (i.e., the heading of the given column) and the other two sensitivity parameters are held at the baseline values (which are: discount rate=7.0%, mileage=12,000, fuel increase = +1.5%).

These observations may be interpreted to mean that economic or personal vehicle use conditions will have to vary *substantially* and *in more than one major* aspect from the assumed baseline for the consumer to realize any net economic savings from the investment in these technologies. To help quantify this, three additional scenarios were performed where sensitivity parameters were allowed to exceed the stipulated min/max criteria in Table 4.4. When the discount rate falls to 1.1% (a somewhat impractical rate, but meant for illustrative purposes), and the other two parameters are at their baseline values, a B/C of 1.0 is attained. When the annual mileage is 16,400 (a very likely possibility for some consumers), and the other two parameters are at their baseline values, again a B/C of 1.0 is reached. When fuel prices increase at a rate of 9.7% per year (or equivalently, the nominal price of fuel averages about $5.60/gallon over 7 years), and the other two parameters are held at their baseline values, a B/C of 1.0 is reached.

For context, when all parameters from Table 4.4 are set at their "best case" limits for maximum consumer benefit (i.e., discount rate at 3%, mileage at 15,000 mi/yr, and fuel at +7%/yr), the result is a compelling B/C = 1.39. A combined scenario such as this is extremely unlikely. Conversely, a minimum B/C taken at the opposite limits would approach a highly unfavorable ratio of 0.40. This simplified techno-economic analysis considers only the direct savings in fuel and the incremental capital outlay less residual for the technology upgrade. No consideration is given to either individual or societal follow-on impacts of reduced fuel consumption such as reduced fueling time, increased vehicle miles traveled, social cost of carbon, health effects, or energy security implications. However, second order effects have been shown to be about one order of magnitude lower than the direct, first-order effects of incremental investment and fuel savings [15,27].

Figure 4.4 depicts the breakeven conditions graphically. Note that many of the individual technologies are below the breakeven lines for both the high mileage and high fuel price conditions. This is particularly true for the points nearer to the origin, where fuel economy improvements between 5 and 15% have comparatively low investments and compelling cost tradeoffs. It is not surprising that many taxis and fleets in large urban centers, where both fuel and annual miles driven are much higher than average, have been quick to convert vehicles to include downsized turbos, reduced weight options, and hybrids. This figure helps to illustrate why the economic basis for such early adoption is compelling since many key technologies are below the high mileage breakeven line and therefore have B/C ratios greater than 1.0.

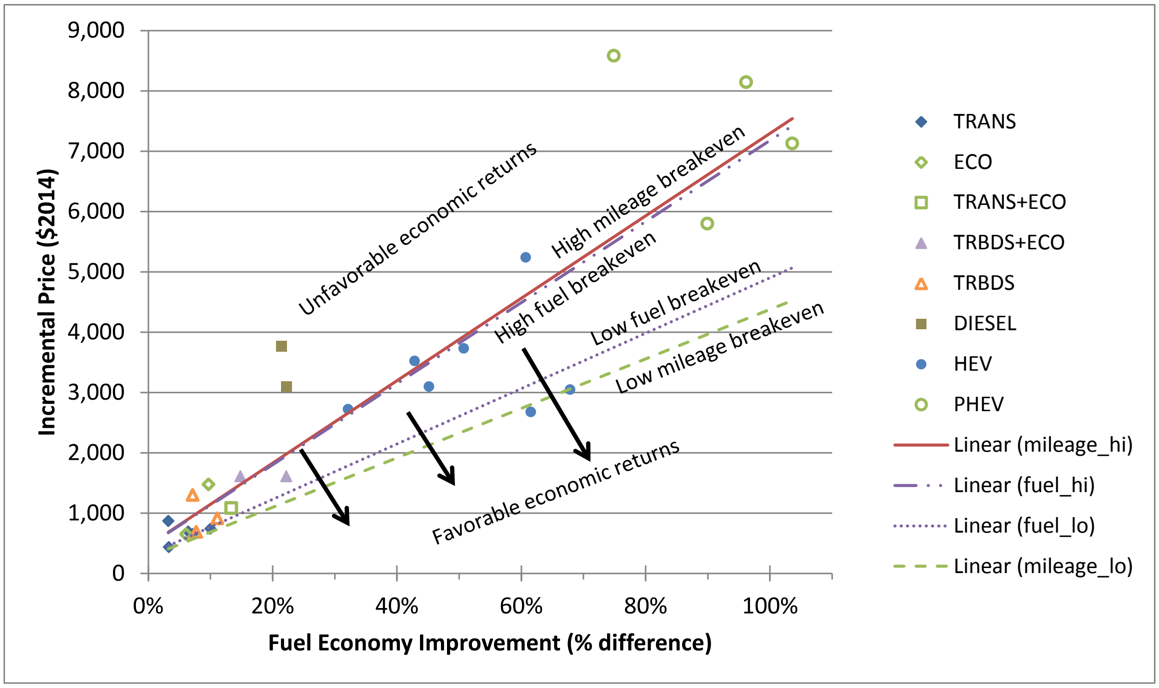

Figure 4.4. Graphical implications of the sensitivity analysis.

Note: "High mileage breakeven" means mileage=15,000 miles per year, discount rate and fuel price at baseline values. "High fuel breakeven" means fuel price ≈ nom $5.60 avg over 7 years, discount rate and mileage at baseline values. "Low mileage breakeven" means mileage =9,000 miles per year, discount rate and fuel price at baseline values. "Low fuel breakeven" means fuel price ≈ nom $3.20/gal over 7 years discount rate and mileage at baseline values.

It should be noted that even though the low discount rate scenario is not shown in Figure 4.4, its breakeven line is just slightly below the high fuel breakeven line, meaning that providing other sensitivity parameters are held at their baseline values, a discount rate at 3% has a similar impact on the results as a nominal fuel price of $5.60, as well as an annual mileage in the range of 15,000. It is also of note that transmission upgrades, turbos with downsizing and hybrids are the technologies most significantly impacted by the sensitivity variables. In the high mileage scenario, for example, 3 CVTs, 3 turbos with downsizing and 4 hybrids have B/C ratios of greater than unity.

4.4 Implications of Sales-Weighting

Though complicated due to OEM options-bundling, the model-specific approach, when IRPE values can be appropriately filtered from the base model, has merit. However, as a final check, it is of interest to consider the average vehicle in a class, by way of understanding whether a new technology is good overall, and not just with regard to its base chassis.

This approach begins with the model-specific IRPE. To this is added (or subtracted) any pricing difference between the MSRP of the base model for the given technology and the MSRP for the sales-weighted average vehicle in that class. This becomes the sales-weighted average IRPE. Likewise, the fuel economy improvement becomes the percentage difference between the fuel economy of the given technology and the sales-weighted average fuel economy in that class (not the model-specific fuel economy). Together the sales-weighted average IRPE and fuel economy improvements are used to characterize the relationship between benefits and costs of new technologies as compared to average vehicles in the appropriate class.

Despite certain obvious differences in MSRP, power and interior volume, the compact and midsize classifications are consistent in their qualitative trends. The average-vehicle basis permits the inclusion of additional Plug-in hybrid electric vehicles (PHEV) and hybrid vehicles for analysis in the model-specific analysis. A linear regression performed on all technologies using the sales-weighted average vehicle approach across both classes fits the data reasonably well (R^2 = 0.80) and yields Eq. (4.2). Here, $IPRE_2$

represents the net incremental retail price equivalent compared to the sales-weighted average vehicle baseline, MPG_X and MPG_{AV} represent the fuel economy of the improved model (X) and the average vehicle (AV) baseline respectively, and the argument in parentheses is the percent change in fuel economy relative to the average vehicle baseline.

$$IRPE_2 \approx 68 \cdot \left(\frac{MPG_X - MPG_{AV}}{MPG_{AV}} * 100\right) + 142 \tag{4.2}$$

This relationship essentially only differs from the model-specific case in y-intercept and in certain characteristics near the origin. Weighted class average selling prices are typically between the base MSRP of a given model and the MSRP associated with a fuel economy technology, explaining the price reduction of new technologies relative to an average vehicle basis. This modestly shifts the cost curve downward while keep the slope relatively constant. Serving primarily to corroborate the preferred (model-specific) approach, the sales-weighted average analysis is theoretical, since a consumer cannot actually purchase technologies according to this relationship. However, it may be a useful tool in isolating costs attributable to specific technological changes relative to average vehicle-derived market conditions.

4.5 Implications of Revealed Consumer Preference for Fuel Saving Technologies

Owing to the multiple interactions between consumers, OEMs, and the regulatory standard, it seems prudent to assess new fuel saving technologies in light of market conditions and the current phase of the regulatory cycle. Figure 4.5 depicts a sales-weighted bubble chart of the key technologies assessed in this study. Base models are not included, as they comprise more than half of the sales volume, and would further crowd the origin. From this figure, it can be concluded that benefit-cost ratio is not a litmus test for technology acceptability and market penetration. The fact that many high volume technologies have benefit-cost ratios of less than 1.0 (meaning they are above the B/C=1 line in Figure 4.5) implies that consumers purchase fuel efficiency in spite of the fact that it may not immediately, if ever, return on its investment.

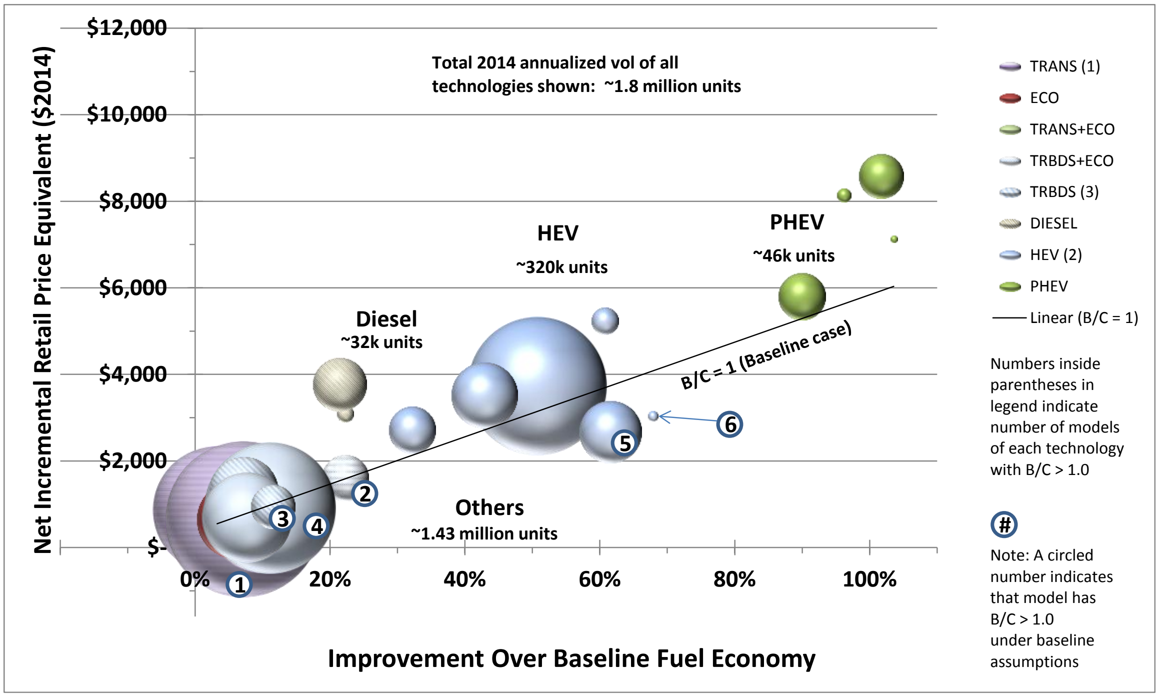

Figure 4.5. Costs, fuel economy improvements and sales weighting of key vehicle technologies.

Figure 4.5 Legend: Technologies are grouped by categories which share similar shading, and bubble size corresponds to relative sales unit volume for the models employing the subject technologies of Table 2.1 in the 2014 MY vehicles summarized in Table 4.1. Models with B/C > 1.0 under baseline assumptions are indicated by a circled number.

An aggregate sales-weighting performed on the entire set of fuel saving technologies reveals that the average consumer paid $1490 for an estimated $1070 savings in fuel, which represented an estimated 17.3% fuel economy improvement as compared to consumers that did not buy fuel saving technologies. As a result, the effective, sales-weighted average benefit-cost ratio for consumers is computed to be 0.72, very close to the un-weighted estimate of 0.73 reported in Section 4.2.

Several key insights emerge from this analysis of the MY 2014 trends. Based upon recent progress toward improved fuel economy, OEMs are likely to consider several options for compliance. Some are technological, while others are related to business and marketing. OEMs have squeezed additional mpg from existing models via a diversity of measures including refreshed designs, engine tuning, weight trim, aerodynamic tweaks, and friction reduction, among others. Fuel economy gains from such actions have limitations, but are low cost. Advanced transmissions, more aggressive "ECO" countermeasures such as more significant reductions in weight, drag and rolling resistance, and valve actuation technologies are the next set of likely improvements. These have already contributed significantly to the estimated 10% gains in new passenger car fuel economy since 2011. These too will eventually run their course, and be more or less fully integrated into the new vehicle fleet. This is the nature and intent of a continuously improving regulatory standard. That sets the stage for a sustained transition to downsized turbos and diesels, which may ultimately be incorporated into hybrids. The foregoing data indicate that turbos with downsizing deliver nearly twice the value today than diesel engines for small passenger cars. That notwithstanding, diesels may perform better in high mileage cases, or in vehicle applications where the EPA combined fuel economy rating may not be a preferable metric for quantifying the real-world benefits.

Based upon current sales volumes, it is likely that OEMs have adjusted pricing to incentivize purchase of higher efficiency vehicles. This is actually an accounting approach, as there is an implicit cost associated with failure to comply (i.e., a $ fine per mpg below regulatory standard). Even if costs are equal, most OEMs would rather sell volume at reduced or amended pricing than run the risk of paying a fine.

Hybrids are among the most capitally intensive new technologies, but also among the most promising in terms of sizeable leaps in fuel economy. As productivity and learning continue, costs will come down; and benefit-cost propositions will rise for consumers, accelerating their adoption. It is less clear whether PHEVs can be viable in the near term, given the massive subsidization and fuel economy "equivalent" ratings that have been needed thus far to facilitate their early commercial introductions.

Finally, in view of Figure 4.5, consider that each 10% increment can be roughly equated to two years' time (using a 5% yr/yr increase in fuel economy as called for by CAFE 2017-2025). This means that to sustain compliance though 2020, costs will rise to support the aggressive rate of technological improvement.

4.6 Summary of Key Findings

Eight significant conclusions can be drawn from this research:

- The continued commercialization of fuel efficiency technologies have enabled automakers to comply with CAFE standards, increasing the fuel economy of the passenger car fleet by about 10% since 2011. Vehicle models sold with specific fuel-saving technologies account for approximately 45% of total sales (by unit volume) considered in the present study for the 2014 model year. Key factors underpinning recent improvements include reductions in weight, friction, and drag; advancements in internal combustion efficiency, engine downsizing; transmission upgrades; and the growth of hybrids.

- Data from 2014 Model-Year compact and midsize vehicles provide insight into advanced fuel saving technologies, and their associated costs and benefits. Benefit-cost analysis performed on best-selling models in these classifications reveals a sales-weighted average benefit-cost ratio of 0.72, and as such, consumers thus far are not incentivized to purchase higher fuel economy. Furthermore, under baseline conditions, benefit-cost ratios are above a breakeven value of 1.0 for just 6 of 28 models employing improved fuel economy technologies.
- Aggregated benefits and costs for new fuel saving technologies based upon sales-weighted data indicate that the "average" consumer that elected to invest in greater fuel economy spent $1490 to realize a 17.3% improvement in fuel economy, equating to estimated savings of $1070. Thus savings were, on average, insufficient to cover technology costs in the baseline scenario.
- A sensitivity analysis performed on critical parameters reveals that annual miles driven and fuel price are the two most significant parameters influencing a consumer's benefit-cost results. A majority of new technologies become economically attractive to consumers (meaning benefit-cost ratios are greater than 1.0 for the given investment and ownership scenarios) only when annual miles travelled exceed 16,400, or when average fuel prices exceed $5.60/gallon. For the high mileage scenario, the technologies with the best overall value proposition are turbos with downsizing and regular hybrids (HEV).
- In the near term, fuel economy improvements between 5 and 15% over base models, will continue to be met by increasing transmission speeds from 4 to 5 and 6, and deepening the market penetration of advanced internal combustion technologies

including: variable valve architectures, gasoline direct injection, and turbocharging with downsizing. Improvements between 20 and 70% can be achieved by diesels and hybrids. The relationship between costs and fuel economy improvements from these families of technologies can be represented by a linear relationship characterized by a reasonably good fit (R^2=0.88).

- Other vehicle attributes that are related to fuel economy, such as power and torque, have largely been unaccounted for in this study. This is reasonable when vehicles of like size and classification are compared. The exclusion of such parameters has the tendency to overstate the isolated value of fuel economy since reductions in power or other potential loss of utility are not considered.
- Based upon the selected 2014MY vehicles, fuel economy technologies fall into two distinct bins of cost and relative efficiency that are separated by a relatively sizeable gap. Costs up to $2000 will buy fuel economy improvements up to 20%. Costs between $3500 and $10000 are needed to reach improvements that exceed 50%. The large costs associated with large fuel economy gains present consumers with capital constraints, economic viability issues, and slow their market penetration.
- Regarding alignment of future trends with CAFE predictions by NHTSA or EPA, few advanced technologies in the 2014 MY assessment can demonstrate economic viability at higher fuel economy levels. While technologies having the required efficiency levels are now (and will continue to become) available, current market data indicate that they will be more expensive than predicted by EPA/NHTSA. Even the relatively easy, evolutionary fuel economy gains are often not financially compelling for consumers. This implies OEMs may need to adjust sales with

creative pricing strategies, or cross-subsidization. The reality is that the higher fuel economy levels currently envisioned in CAFE are not expected to be economically viable for consumers at currently projected fuel prices.

CHAPTER 5. HYBRID, PLUG-IN HYBRID AND ELECTRIC VEHICLE ENERGY CONSUMPTION SENSITIVITY TO DRIVING CYCLE, AMBIENT TEMPERATURE AND LOCALITY

This chapter presents a comparative investigation of vehicle energy consumption for various vehicle architectures, driving cycles and ambient temperature conditions. Objective methodologies and quantitative metrics are developed for comparison among unlike energy sources, and disparate power and thermal management strategies available in today's hybrid and electric vehicles (EV). The three-step modeling approach includes a thermodynamic model of heating and cooling demands, a vehicle propulsion model of tractive power and battery attributes, and a dynamic vehicle modeling simulation of vehicle efficiency under a range of operating conditions. Locality-specific energy consumption values from a system perspective are then computed based upon relevant characteristics of large U.S. cities such as electricity generation, petroleum refining, and typical weather.

The chapter seeks to quantify the extent to which vehicle energy requirements are lower for hybrid and EV when operated under moderate driving cycles and temperatures, as well as to investigate the hypothesis that their energy use is substantially more sensitive to driving cycles and extreme hot or cold temperatures. This study quantifies the strong sensitivity to locality on energy and emissions for advanced vehicles, and highlights implications of their deployment. A portion of the material presented in this chapter was published in the proceedings of the 3rd Sustainable Thermal Energy Management

International Conference (SUSTEM 2015) [143]. The material presented in this chapter has been submitted for publication in Applied Energy [33].

5.1 Vehicles, Driving Cycles and Temperature Ranges Considered in the Study

The three primary independent inputs for this study are: vehicle architecture, driving cycle and outdoor temperature. A primary objective in considering multiple independent inputs to the simulation is to characterize the complicated interactions that occur among these inputs. A set of representative, commercially available, 2014 model-year vehicle architectures in the compact classification are chosen for this technology comparison. Key specifications appear in Table 5.1.

The five distinct driving cycles that comprise the EPA test and labelling protocol are well documented and widely used for comparative analyses [144]. The three 23°C (75°F) tests include a derivative of the Urban Dynamometer Driving Schedule (UDDS) known as the Federal Test Protocol (FTP), the high-acceleration aggressive driving schedule identified as the Supplemental FTP (US06), and the Highway Fuel Economy Driving Schedule (HWFET). The 35°C drive cycle is the Air Conditioning Supplemental FTP driving schedule referred to as SC03. The -7°C cold weather test schedule repeats the original FTP at the reduced temperature.

This study simulates vehicle performance when exposed to a continuous range of outdoor temperatures typical of seasonal variations in North America. The range selected is -16°C (3°F) to 42°C (108°F).

Table 5.1. Vehicle architectures used in the study and representative attributes.[24]

Vehicle Type:	**ICE-SI**[25]	**ICE-CI**[26]	**HEV-PS**[27]	**PHEV-40**[28]	**EV-PAC**[29]
Source:	[100[a,b,c]]	[100[d]]	[100[a]]	[100[e]]	[100[f]]
Vehicle Attribute					
Vehicle mass[30] [kg]	1438	1595	1519	1857	1610
Drag coefficient	0.29	0.30	0.25	0.29	0.28
Frontal area [m^2]	2.12	2.10	2.17	2.16	2.31
Engine power[31] [kW]	108	104	73	63	-
Electric motor power[31] [kW]	-	-	60	111	80
Total vehicle power[31] [kW]	108	104	100	111	80
Battery mass[32] [kg]	-	-	45	198	294
Battery capacity[32] [kWh]	-	-	1.3	16.5	24.0
Fuel economy[33] [US[34]mpg]	31.4	34.0	50.0	37.0	-
Fuel consumption[33] [L/100km]	7.5	6.9	4.7	6.4	-
Elec. consumption[35] [Wh/km]	-	-	-	214	184
Equiv. fuel econ.[35] [mpge]	-	-	-	98	114
All electric range [km(mi)]	-	-	-	64(40)	134(84)

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[24] Vehicle specifications such as engine maps and motor performance, battery cell parameters, physical or operational characteristics have been obtained from either OEM fact sheets or the literature [100a-f].

[25] The key specifications for three top-selling models (Toyota Corolla, Honda Civic, Ford Focus) were averaged to represent a baseline compact non-aspirated ICE-SI where SI=Spark Ignition.

[26] Volkswagen Jetta Value Diesel (ICE-CI) where CI=Compression Ignition.

[27] Toyota Prius (HEV-PS) where PS=Power Split.

[28] Chevrolet Volt (PHEV-40) where 40 represents the all-electric range in miles.

[29] Nissan Leaf (EV-PAC) where PAC=Passively Air Cooled.

[30] Vehicle mass reflects “vehicle inertia weight” which is equal to curb weight plus 136 kg per EPA rule.

[31] Engine and motor power represent maximum rated values reported by OEMs at vehicle-specific engine/motor speeds. Total vehicle power applies to HEV and PHEV, and reflects the maximum net combined propulsion of engine and motor.

[32] Battery mass and capacity represent complete battery modules.

[33] Fuel economy, consumption and range values reflect 5-cycle EPA combined ratings [14].

[34] This study uses U.S.gallons (not imperial) in all fuel economy MPG references.

[35] Electricity consumption is on a vehicle, not system basis, and is derived by dividing the energy content of a gallon of gasoline (33.7 kWh) by the EPA-reported equivalent fuel economy in MPGe. (Appendix A)

5.2 Vehicle Modeling Methodology and Analytical Basis

The present study introduces an iterative modeling approach depicted graphically in Figure 5.1.

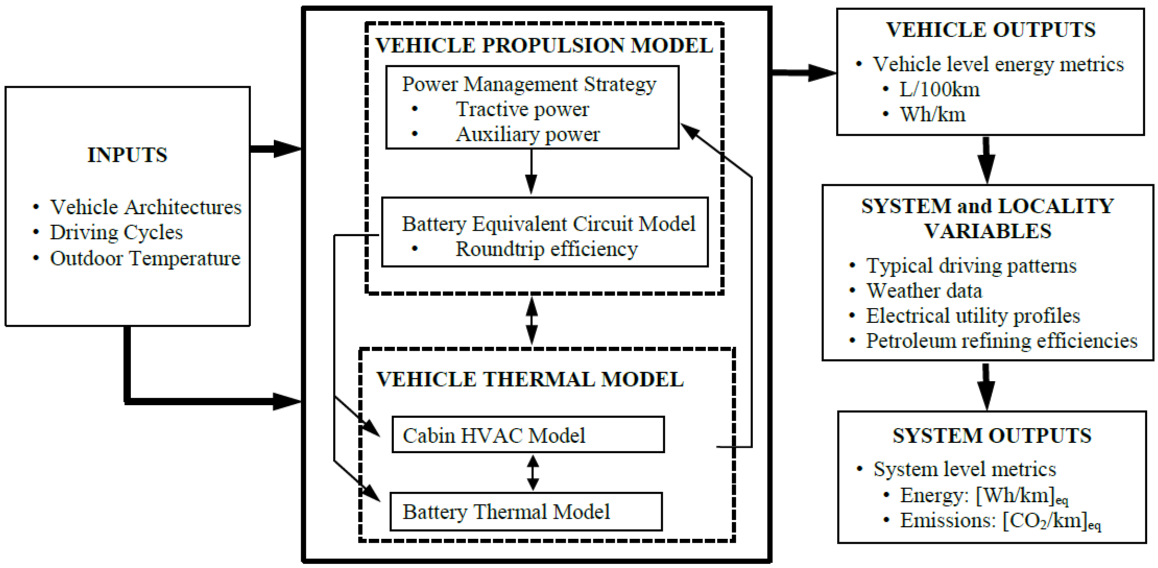

Figure 5.1. Iterative vehicle energy consumption modeling approach.

Energy consumption metrics are computed on a vehicle architecture basis as a function of temperature and driving cycle using the nested propulsion and thermal models as shown. Once the relationship between vehicle energy and temperature is determined, driving pattern and locality parameters are introduced to determine system-level equivalent energy and emission metrics. This investigation uses a backward-facing model which means that driving cycle velocities at every time *t* dictate vehicle power requirements at the wheel that are in turn met in real time by the propulsion system. This approach facilitates accurate and readily computable comparisons among vehicle architectures. The integrated model is created and executed in MATLAB/Simulink.

5.2.1 Power management strategy

Power management and traction battery subroutines comprise the vehicle propulsion model. The baseline power management follows that of a power-split or series-parallel HEV, because it embodies all constituent operational modes: gasoline-only, hybrid (CS) mode, and all electric (CD) modes. The governing formulae for the various tractive forces (F_{tr}) on the vehicle are:

$$F_{tr} = F_{rr} + F_{aero} + F_{hill} + F_{accel} \tag{5.1}$$

$$F_{tr} = m_{veh} g \cdot (C_{rr,0} + C_{rr,1} \cdot v_{veh}) + 0.5\rho_{air} C_D A_F v_{veh}^2 + m_{veh} g \cdot \sin\theta_{grade} + m_{veh} \cdot a_{veh} \tag{5.2}$$

F_{rr}, F_{aero}, F_{hill} and F_{accel} are the forces due to rolling resistance, aerodynamic drag, hill climb and acceleration, respectively. The mass, velocity and acceleration of the vehicle are m_{veh}, v_{veh}, and a_{veh}, respectively. $C_{rr,0}$ is the constant portion of the coefficient of rolling resistance and $C_{rr,1}$ is the first-order speed-dependent portion of the coefficient of rolling resistance. From [145], we assign values to these variables of 0.01 and 0.000225, respectively. The air density, vehicle drag coefficient, frontal area, and acceleration due to gravity are denoted as ρ_{air}, C_D, A_F and g, respectively. Hill grade, θ_{grade}, is assumed to be zero in our study, since a level ground assumption is reasonable for comparison purposes and the driving schedules employed do not include hill climb. An expression for tractive power (P_{tr}) in terms of tractive force and vehicle speed is:

$$P_{tr} = \int F_{tr} \cdot v_{veh} dt \tag{5.3}$$

The tractive power requirements are met by the baseline HEV according to several basic tenets of control strategy: (1) the engine is off when P_{tr} is below a predefined minimum threshold (10 kW default value) to conserve fuel and utilize the electric machine in either motoring or generating ("regenerative braking") mode; (2) the engine is also off when its speed is below a minimum (about 1000 RPM) as determined by vehicle driveline gear ratio; (3) when P_{tr} exceeds the maximum rated power of the engine, the electric machine provides the required difference (P_{tr}-$P_{eng,max}$); (4) whenever the engine is engaged, it operates on the optimum Brake Specific Fuel Consumption (BSFC) line for the calculated power at the given speed enabled by a Continuously Variable Transmission (CVT); and (5) the battery state of charge (SOC) is maintained at about 0.5 during charge sustaining operation, and the engine is decoupled from vehicle speed such that it operates on the optimal brake specific fuel consumption (BSFC) line. Net transmission efficiency factors based upon typical values of discrete speed and CVT transmission drivelines are applied to each vehicle architecture according to its design.

These simplified control strategies are sufficient for the purpose of the comparison in the present study. Straightforward modifications are made for gasoline-only operation, wherein the engine is the exclusive means of meeting P_{tr} requirements, and the engine is not capable of turning itself off at low power requirements, low speeds, or under idling conditions. Modifications are similarly made to adapt to charge-depleting mode, wherein the battery module and electric machine are the exclusive means for meeting the vehicle's tractive power requirements. In the case of the PHEV in CS mode, the engine operates at its most efficient point and is used exclusively to charge the batteries. In addition to tractive power requirements, the vehicle must satisfy the demand for auxiliary loads, denoted by P_{aux}, imposed upon the system, such as HVAC and accessory needs as defined by: $P_{total}=P_{tr}+P_{aux}$. For HEV and PHEV, the auxiliary power required to meet vehicle needs includes two components: one to satisfy cabin HVAC demands and a second to meet battery thermal management demands as follows: $P_{aux}=P_{aux,cabin}+P_{aux,batt}$. For the EV-PAC (Passive Air Cooled), passive convection battery thermal management does not incur auxiliary energy demands. While the PAC design has obvious energy benefits, concerns are warranted over reduced lifespan and performance.

5.2.2 Battery equivalent circuit (BEC) model

Battery operation and by extension, HVAC requirements, are strong functions of driving cycle and ambient temperature; an initial value for roundtrip battery efficiency must therefore first be determined before heating and cooling loads can be resolved. Here, an iterative modeling approach is proposed where an equivalent circuit determines the cumulative I^2R power losses that contribute to battery heating. A first-order RC model has proven successful at characterizing the charge-discharge response of vehicular lithium ion batteries, and is depicted by the equivalent circuit in Figure 5.2.

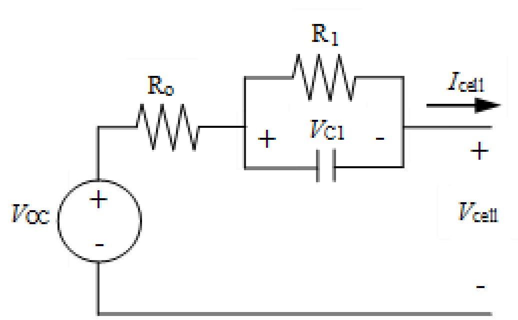

Figure 5.2. Battery Equivalent Circuit Model.

The voltage balance across the cell and the current through the R_1C_1 pair are:

$$V_{cell} = V_{OC} + I_{R_1} R_0 + V_{C_1} \tag{5.4}$$

$$I_{R_1C_1} = I_{R_1} + I_{C_1} = \frac{d}{dt}\left(C_1 V_{C_1}\right) + \frac{V_{C_1}}{R_1} \tag{5.5}$$

In Eq. (5.4), V_{cell} is the unknown cell voltage and V_{OC} is the open circuit voltage. Noting that $I_{R0} = I_{R1C1} = I_{cell}$ and substituting Eq. (5.5) into Eq. (5.4) yields a differential equation that can be solved to determine V_{cell} at any current, using a user-defined correlation for $V_{OC}(SOC)$ and approximate values of R_0, R_1 and C_1 as functions of temperature as defined by Huria [116]. For baseline operation at 23°C, the parameters are $R_0 = 0.0085\ \Omega$, $R_1 = 0.002\ \Omega$ and $C_1 = 25{,}000$ F. The modeling approaches used for HEV and PHEV/EV are differentiated due to the location and size of the respective battery modules[36].

The coulomb counting method is used to determine battery SOC as a function of the initial SOC, SOC_{init}, the fully charged battery cell capacity Q_{BC}, cell current I_{cell}, and time t.

$$SOC(t) = SOC_{init} + \frac{1}{Q_{BC}} \int_0^t I_{cell}\, dt \tag{5.6}$$

Given the defined indexing of SOC from zero to unity, Eq. (5.6) is valid for both a single cell and the full battery module. Battery roundtrip efficiency can now be determined with the introduction of additional variables. The power consumed or supplied by the electric machine is defined to be $P_{em}(t)$, and terms to capture the on-board charging and

[36] For HEV, following transient start-up conditions, the battery temperature is assumed to be maintained near (±10°C) the controlled cabin environment of 23°C, implying that the resistances and capacitances should be relatively temperature-independent during vehicle operation. For the PHEV and EV, the batteries range from 4 to 7 times larger in mass and are enclosed in underbody/mid carriage compartments that are more exposed to the external environment. Thus during PHEV/EV operation in charge-depleting mode, battery resistances, which are strong functions of operating temperature, are estimated using empirical correlations for individual cell resistances at 5°C, 20°C, and 40°C from Huria [116] and correlations for module resistances at -7°, 22°C and 35°C from Lohse-Busch [96]. The empirically-derived relationships are then used to more accurately estimate vehicle energy consumption across the temperature spectrum for vehicles operating in CD mode. While the decrease in battery module resistance from 23°C and 42°C is minimal (<15%), the increase between 22°C and -7°C is significant (on the order of 200% for these particular vehicles).

discharging efficiencies are defined as η_{ch} and η_{dch}. Current through a given cell during charging and discharging modes and cell power loss at time *t* are:

$$I_{celll,ch}(t) = \left(P_{em}(t) \cdot \eta_{ch}\right) / v_{cell}(SOC,t) \tag{5.7}$$

$$I_{cell,dch}(t) = \left(P_{em}(t) / \eta_{dch}\right) / v_{cell}(SOC,t) \tag{5.8}$$

$$P_{cell,loss}(t) = \left| I_{cell}(t) \cdot V_{OC}(SOC) - P_{em}(t) \right| \tag{5.9}$$

Note that $P_{em}>I_{cell}*v_{cell}$ during charging as per Eq. (5.7), and $P_{em}<I_{cell}*v_{cell}$ during discharging as per Eq. (5.8) to reflect the resistive dissipation according to current direction. Battery roundtrip efficiency $\eta_{b,rt}$ and total energy loss in the battery module $E_{batt,loss}$ [Wh] are found as follows, where N_t represents the total number of cells in the battery module.

$$\eta_{b,rt} = 1 - \left(\int_0^t P_{cell,loss}(t)dt \Big/ \int_0^t \left| P_{em}(t) \right| dt \right) \tag{5.10}$$

$$E_{batt,loss} = \left(N_t / 3600\right) \cdot \int_0^t P_{cell,loss}(t)dt \tag{5.11}$$

This cumulative loss is time-averaged over the given driving cycle, yielding a battery heat generation rate, $Q_{b,cycle}$ in W, where Δt is the total drive cycle duration in hours. This heat rejection term becomes a first-iteration heat addition term in the cabin and battery thermal model.

$$\overline{\dot{Q}}_{b,cycle} = E_{batt,loss} / \Delta t \tag{5.12}$$

5.2.3 Cabin HVAC model and battery thermal management (BTM) model

Primary sources of cabin HVAC loads include solar insolation through glass, heat conduction to/from the exterior surfaces, convection at exterior surfaces, flow leakage, fresh air intake, and heat from passengers and electronics, for which a variety of modeling tools have been developed. Due to substantial variation in these factors and the predominantly comparative nature of this study, expressions for simplified baseline cabin HVAC demand as a function of outdoor temperature are derived based upon studies in the literature, and corroborated with published component design specifications [92,96,105]:

$$\dot{Q}_{AC,Cabin} = 0.221 \cdot T_{outdoor} - 3.814 \qquad \{T_{outdoor} \geq 24°\text{C}\} \tag{5.13}$$

$$\dot{Q}_{Heating,Cabin} = -0.150 \cdot T_{outdoor} + 3.00 \quad \{T_{outdoor} \leq 20°\text{C}\} \tag{5.14}$$

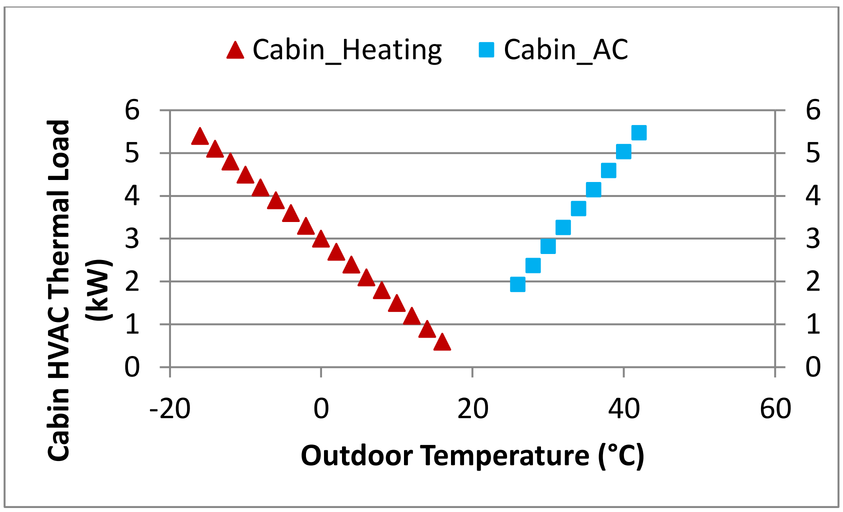

Figure 5.3. Empirical correlations for cabin heating and cooling loads.

The cabin air-conditioning demand is given by Eq. (5.13) when the outdoor temperature is greater than or equal to 24°C, while the cabin heating demand is given by Eq. (5.14) when the outdoor temperature is less than or equal to 20°C. These linear responses are depicted in Figure 5.3. It is assumed that the selected vehicle architectures will use a conventional vapor compression air conditioning cycle of equal performance using R134a with either a clutch-driven or electric compressor. For ICE, HEV and PHEV in CS mode, it is assumed that cabin heating requirements will be satisfied by the conversion of waste heat from the engine. For PHEV and EV in CD mode, it is further assumed that initial heating requirements will be met via a heat pump cycle with similar thermal performance as the air conditioner, since it will utilize the same machinery and be activated by reversing valves. For temperatures between -6°C and -16°C, it is assumed that EV will supplement heating requirements using an electrical resistance heater with a maximum capacity of 2 kW and a COP of unity. A parametric model was created in Engineering Equation Solver (EES) [146] to facilitate simulations of the baseline system with varying thermal inputs coming from the vehicle propulsion and battery equivalent circuit subroutines. Values assumed for the EES model include: superheating of 8.3°C, subcooling of 2.7°C, maintained cabin air temperature of 23°C, compressor isentropic efficiency of 70%, recirculation (if no battery cooling) of 100%, blower fan power of 100 to 250 W, and exterior condenser fan power of 0 to 200 W (depending upon average vehicle speed).

Air-cooled battery thermal management (BTM) systems are assumed for hybrid vehicles having modest battery capacities (< 3 kWh). The HEV of this study maintains battery temperatures via cabin air that is ducted around the battery housing with an adjustable speed auxiliary fan. The PHEV investigated here requires active battery cooling that can be achieved via liquid-cooling heat exchange with an auxiliary liquid-liquid heat exchanger connected in series with the baseline vapor refrigeration system. The EV investigated uses a passive air-cooled strategy (via external convection) which imposes no auxiliary power demands on the vehicle. Typical BTM strategies are well documented in Rao [147]. The EES model estimates the additional vehicle energy demand that is required to maintain desired battery temperatures. For the air-cooled BTM, the rate at which battery heat is transferred to the cabin is:

$$\dot{Q}_b = (hA)_b \cdot (T_b - (T_{bao} + T_{ac})/2) = \dot{m}_{a,b} \cdot c_{p,ac}(T_{bao} - T_{ac}) \tag{5.15}$$

$$\dot{Q}_b = \dot{m}_{a,b} \cdot (\rho_{ao}/\rho_{ac}) \cdot c_{p,ao} \cdot (T_{ao} - T_{ac}) \tag{5.16}$$

$$\dot{Q}_{tot} = \dot{Q}_{Load} + \dot{Q}_b \tag{5.17}$$

In Eq. (5.15), the product of the heat transfer coefficient and battery module surface area $(hA)_b$ is considered a constant specific to the battery module within the given range of temperatures. For the purpose of this analysis $(hA)_b$ has an approximate value of 16 W/°C based upon empirical observation. The energy balance of Eq. (5.15) quantifies the mass flow of air required to maintain a desired battery outlet temperature. Battery heat generation, $\dot{Q}_b$ (Eq. (5.16)), is then simply equated to $\dot{Q}_{b,cycle}$ (Eq. (5.12)) to connect the thermal and equivalent circuit subroutines. Thus the total HVAC load for the air-cooled system is the sum of cabin and battery loads as shown in Figure 5.4 and Eq. (5.17).

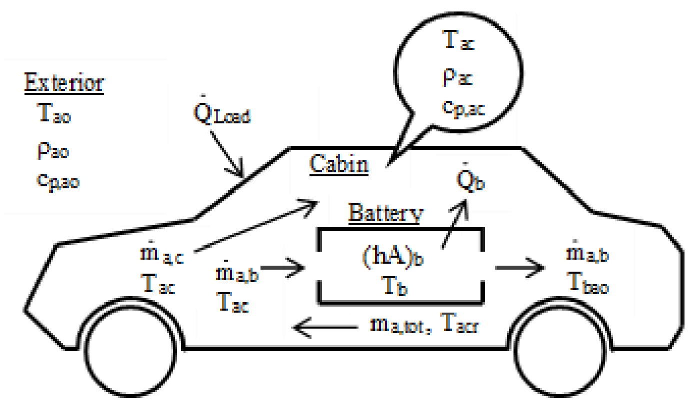

Figure 5.4. Cabin/battery thermal energy flows in HEV-PS with active air-cooling.

For liquid-cooled systems such as PHEV, the energy balance follows the same form as Eqns. (5.15-5.17), but for simplicity, the heat transfer between the battery module and the liquid-liquid heat exchanger is assumed to be perfect. Thus battery heat generation may be added directly to the cabin load: $\dot{Q}_{tot} = \dot{Q}_{Load} + \dot{Q}_{b,cycle}$. For the EV with passive thermal management, $\dot{Q}_{b,cycle}$ is assumed not to contribute to vehicle thermal or energy demands.

In heating mode, the auxiliary power requirements for ICE and HEV in CS mode are zero. In heat pump mode, electrical requirements are determined using the cabin HVAC model in EES. For the EV, additional electrical requirements from the resistance heater below -6°C are included in a linearly increasing demand up to a maximum supplement of 2 kW. No heating benefit from battery heat generation is assumed in any of the vehicle architectures, though it may be possible to harvest some of this waste heat to reduce vehicle power demands in cold weather. For a given vehicle and drive cycle, the battery loss term and resulting auxiliary power demands on the vehicle are determined iteratively as a continuous function of temperature using the MATLAB/Simulink and EES models.

5.2.4 Estimating fuel and electricity consumption as functions of temperature

To determine vehicle energy consumption as a continuous function of temperature within a consistent comparative framework, this study introduces new approaches that derive from established EPA fuel economy rating methodologies [14] in which five weighted cycles are prescribed, including three at 23°C and two intended to account for the effects of hot (35°C) and cold (-7°C) weather operation. A shortcoming of this approach is that a baseline performance is computed for operation under UDDS, US06 and

HWFET driving cycles and adjusted by supplementary “weather” cycles at merely the two discrete temperatures. A final adjustment (equal to -9.5% on a fuel economy basis, or +10.5% on a fuel consumption basis) is applied to correct for “non-dynamometer” effects including road roughness, road grade, tire pressure, vehicle payload, wind and precipitation. The formulae for computing the EPA five-cycle city and highway fuel economy are available in [14] and example equations are provided for reference in Appendix C.

The analysis in the present study retains the relative weightings of the various drive cycles for the city, highway and combined modes, but removes the reliance on discrete data at 35°C and -7°C, instead simulating the core driving cycles across the full range of temperatures. Since one aim of the study is to understand the impact of locality, we distinguish between the aspects that may be dependent on geographic location (such as HVAC use and fuel or energy required at vehicle start-up) from those that are generally independent of geographic location (such as non-dynamometer adjustments). The impact of HVAC and BTM are quantified across a full range of temperatures. So-called “starting fuel” is meant to account for any initial fuel or energy required by the vehicle during its warm-up period to overcome such items as static inertia, viscous and mechanical friction, thermodynamic combustion losses and unburned hydrocarbons prior to reaching steady state, and electrical system losses due to elevated transient resistances. While clearly correlated to ambient temperature, the theoretical system modeling of such losses is complicated and experimental data are often proprietary to component manufacturers and automakers. For the purposes of this study, close approximations of start-fuel estimates as a function of temperature and vehicle architecture are derived from curve-fits to experimental results, such as those found in [14,96]. While these empirically-derived and drive-cycle-weighted start fuel estimates facilitate excellent first order comparisons, it should be noted that this study does not fully consider the trade-off of fuel consumption to ensure acceptable levels of NOx emissions in diesel engines. Though impacts are moderated by highway driving where start fuel levels are substantially lower, this study may slightly underestimate the cold weather energy consumption of diesels as additional fuel use to catalyze NOx is largely neglected. As noted, the non-dynamometer adjustments are not generally dependent upon locality and therefore need not be adjusted from the EPA values.

The following two steps are therefore taken. First, the architecture-specific combined propulsion/battery/thermal model is developed and vehicle simulations are performed under stipulated test conditions (drive cycles at 23°C, -7°C and 35°C) and compared to official estimates using standard five-cycle EPA calculation methods. Second, temperature variability in a range from -16°C to 42°C is imposed upon vehicle simulations under the three core driving cycles (UDDS, US06 and HWFET), with defined analytical and empirical correlations for component and system energy demands. In this way, complicated interactions among the driving cycles and thermal demands of the cabin and battery modules are more accurately characterized, yielding fuel and energy consumption data for each vehicle across a continuous spectrum of outdoor temperatures. The equations used to estimate fuel and energy consumption are represented as follows.

$$FC_i(T) = N_i \cdot \left\{ \left(\chi_j / FE_j(T) \right) + \left(\chi_k / FE_k(T) \right) + FC_{i,start}(T) \right\} \tag{5.18}$$

$$EC_i(T) = N_i \cdot \left\{ \left(\chi_j \cdot EC_j(T) \right) + \left(\chi_k \cdot EC_k(T) \right) + EC_{i,start}(T) \right\} \tag{5.19}$$

Table 5.2. Driving cycles, parameter values and weightings used in Eqns. (5.18) and (5.19).

Weighted average cycle name, i	Non-dynamometer correction, N_i	Weighting, χ_j	Driving cycle, j	Weighting, χ_k	Driving cycle, k
City	1.105	0.89	UDDS	0.11	US06 City
Highway	1.105	0.79	US06 Hwy	0.21	HWFET
Combined	N/A (1.000)	0.43	City	0.57	Highway

This approach utilizes EPA-defined driving cycles and weightings from [14] shown in Table 5.2 to facilitate comparisons among vehicle architectures and rating conventions. It should be noted that electrical energy consumption (EC) for vehicle operation in CD mode involves arithmetic averaging via weighting factors (Eq. (5.19)), in contrast with fuel consumption calculations which use harmonic weightings of constituent fuel economies (FE) during gasoline or CS mode (Eq. (5.18)).

The final step required to facilitate comparison among the vehicle architectures from the standpoint of the vehicle boundary ("vehicle-basis") is to report energy consumption in common units. This is done by converting fuel economy (US mpg) or fuel consumption (L/100 km) to energy consumption per unit distance (Wh/km).

$$EC_{Veh,CS,m}(T) = \left(FC_i(T)/100\right) * LHV_{fuel} \qquad (5.20)$$

In Eq. (5.20), $EC_{Veh,CS,m}(T)$ is the vehicle-basis energy consumption in CS mode for vehicle m at temperature T, $FC_i(T)$ is the simulated fuel consumption of cycle i at temperature T, and LHV_{fuel} is the lower heating value of the relevant liquid fuel, which is 8.9 kWh/L for gasoline and 9.9 kWh/L for diesel. For the majority of the vehicle-level comparisons in Section 5.4, the driving cycle, i, is taken to be the EPA combined city-highway weighting, though the methodology is broadly applicable. Following conversion, vehicles consuming liquid fuels can be equitably compared on a common energy basis with vehicles consuming grid-derived electricity.

5.3 Modeling Approach for Assessing the Impacts of Locality

5.3.1 Estimating vehicle-basis energy consumption by locality

This study estimates average energy consumption values for vehicles and cities of interest using energy consumption as a continuous function of temperature. These *EC(T)* correlations are outputs of the vehicle modeling and inputs to locality estimations. Other inputs to the vehicle-basis locality study include typical driving patterns (such as average trip distances, times, daily and annual vehicle miles traveled, VMT) and climate data (e.g., temperature by city, hour and day of year). A mathematical expression approximating the weighted annual average energy consumption is given by:

$$\overline{EC}_{m,n} = \sum_{p=1}^{365}\sum_{q=1}^{24} \chi_p \cdot \chi_q \cdot EC_m(T_{n,p,q}) \tag{5.21}$$

In Eq. (5.21), $\overline{EC}_{m,n}$ is the annually-averaged energy consumption of vehicle *m* in city *n*, χ_p is the fraction of the total year's driving occurring on day *p*, and χ_q is the fraction of day *p*'s driving occurring in hour *q*. The sum of all χ_p over the year is equal to unity, as is the sum of all χ_q over the day. Finally, $EC_m(T_{n,p,q})$ is the energy consumption for vehicle *m* associated with the temperature in city *n* on day *p* and in hour *q*. In the MATLAB/Simulink environment, a matrix of $EC_m(T)$ (for $-16°C \leq T \leq 42°C$) is established from the vehicle simulations of each architecture and then used as a lookup table for the integrations (piecewise summations) performed in Eq. (5.21).

The hourly use fraction of a vehicle on a typical day is derived from the U.S. Department of Transportation Household Survey [136]. The daily use fraction is derived from annual vehicle miles traveled (VMT) data in the DOT survey and monthly driving information described in EPA's label regulation [14]. It is assumed that the average driving frequency on every day of the week is the same throughout a given month; however, each month is unique with greater driving distances common during summer. Plots used to determine the hourly and daily VMT share allocations are provided in Appendix D.

Weather data for 22 of the most populated U.S. urban areas are extracted from the U.S. Department of Energy, NREL Typical Meteorological Year (TMY3) database [148]. It is our aim to estimate typical, rather than extreme, responses to varying ambient temperatures, for which the TMY3 database is ideal [149]. Temperature data by running hour of the typical year for a given city is accessed in sequence, energy consumption for a given vehicle at the given temperature is obtained from the simulation output, and the hourly and daily fractions are applied. This process is repeated following the form of Eq. (5.21) for every hour of the year, for each vehicle m and city n. Notional depictions of temperature vs. running hour of the year for three cities (IND, LA and MIA) and diurnal temperature variations (for IND) are included in Appendix E.

5.3.2 Estimating system-equivalent energy consumption by locality

In order to compare net or equivalent system-level energy consumption, a simplified variation of a Life Cycle Analysis (LCA) is applied. It considers vehicle-basis energy requirements as well as energy to deliver the liquid fuel or electricity to the vehicle, back to the level of the extracted raw material. Though not a complete wells-to-wheels (W2W) basis, this is a reasonable assumption for this comparative study because it avoids uncertainty associated with sources and origins of raw materials, but captures primary factors such as the refining of liquid fuels and the electrical generation of fossil-fuels and non-fossil fuels. Estimates for equivalent energy consumption, EC_{SysEq}, in units of [Wh/km] are given for the CS and CD modes are derived according to:

$$EC_{SysEq,CS,m}(T) = EC_{Veh,CS,m}(T) / (\eta_{liqref,n} \cdot \eta_{liqtr}) \quad (5.22)$$

$$EC_{SysEq,CD,m}(T) = EC_{Veh,CD,m}(T) / \left(\eta_{chg} \cdot \eta_{trans,n} \cdot \eta_{gen,n}\right) \quad (5.23)$$

Here, $EC_{SysEq,CS,m}(T)$ and $EC_{SysEq,CD,m}(T)$ are the system-level equivalent energy consumption for vehicle *m* at temperature *T* in CS and CD modes, respectively. Efficiency terms are introduced for liquid fuel refining efficiency for city *n* ($\eta_{liqref,n}$) and liquid transport efficiency (η_{liqtr}) for CS-mode operation, and wall- or station-to-vehicle charging efficiency (η_{chg}), electricity transmission efficiency ($\eta_{trans,n}$) in city *n*, and electricity generation efficiency in city *n* for CD operation ($\eta_{gen,n}$). Thus, this study assumes that efficiencies for refining, transmission of electricity from power planta to charging stations and generation are locality-dependent, but assumes a national average value for the transport of refined fuel liquids to fueling stations, $\eta_{liqtr} = 0.992$ [21], and a representative value of 0.87 for the external charging efficiency of EVs (η_{chg}) based upon typical efficiencies of Level 1, 2 and 3 charging systems [150]. Source data for liquid fuel refining efficiencies by city ($\eta_{liqref,n}$) is derived from Elgowainy et al. [151] and Argonne National Laboratory's GREET1_2014 Fuel-Cycle Model database [19]. The efficiencies of transmission and distribution of electricity from power plants to charging stations by locality ($\eta_{trans,n}$) are obtained via regional grid loss data reported in the U.S. EPA Emissions & Generation Resource Integrated Database, eGrid [22] for the most recent year available,

2010. Efficiencies for generating electricity by city ($\eta_{gen,n}$) are derived from state and regional data on sources and heat rates from the Energy Information Administration Electric Power Annual [152] and assessments of renewable energy technologies [153] for the most recent year available, 2013. A generalized expression for system-equivalent energy consumption of vehicle m, $EC_{SysEq,m}$, is provided in terms of the relevant utilization factors (UF) for the CS (ICE/HEV) and CD (EV) modes as:

$$EC_{SysEq,m}(T) = UF_{CS,m} \cdot EC_{SysEq,CS,m}(T) + UF_{CD,m} \cdot EC_{SysEq,CD,m}(T) \tag{5.24}$$

In turn, an average system-equivalent energy consumption for vehicle *m* and city *n* can now be computed as follows:

$$\overline{EC}_{SysEq,m,n} = \sum_{p=1}^{365}\sum_{q=1}^{24} \chi_p \cdot \chi_q \cdot EC_{SysEq,m}(T_{n,p,q}) \tag{5.25}$$

This locality-specific system equivalent energy consumption computation is similar to the locality-specific vehicle basis energy consumption. In Eq. (5.25), $\overline{EC}_{SysEq,m,n}$ is the annually-averaged system-equivalent energy consumption of vehicle *m* in city *n*, χ_p and χ_q are as before, and $EC_{SysEq,m}(T_{n,p,q})$ is the system-equivalent energy consumption for vehicle *m* at the temperature associated with city n, day p, and hour q. This time, a matrix of $EC_{SysEq,m}(T)$ (for -16°C ≤ T ≤ 42°C) is established from the vehicle simulations and then used as a lookup table for the double summation of Eq. (5.25).

5.3.3 Estimating system-equivalent emissions by vehicle type and locality

Estimates of vehicle emissions consider both tailpipe and upstream sources back to the level of the extracted raw material (i.e., not including extraction). Due to differences in the upstream fuel and electricity cycles, three expressions are employed in this analysis as follows:

$$\overline{EI}_{ICE-SI,n} = \overline{EC}_{SysEq,ICE-SI,n} \cdot EI_{gasoline} \tag{5.26}$$

$$\overline{EI}_{ICE-CI,n} = \overline{EC}_{SysEq,ICE-CI,n} \cdot EI_{diesel} \tag{5.27}$$

$$\overline{EI}_{EV,n} = \left(\frac{\overline{EC}_{EV,n}}{\eta_{chg} \cdot \eta_{trans}} \right) \cdot EIEG_n \tag{5.28}$$

In Eq. (5.26), $\overline{EI}_{ICE-SI,n}$ represents the average Emission Intensity (EI) for the ICE-SI in city n measured in grams of CO2 equivalent per kilometer [$gCO2_{eq}$/km]. $\overline{EC}_{SysEq,ICE-SI,n}$ is as determined previously by Eq. (5.25), and $EI_{gasoline}$ is the emission intensity associated with the combustion of gasoline, defined by EPA to be approximately 0.264 $gCO2_{eq}$/Wh [154]. Eq. (5.26) is valid for the HEV as well. Eq. (5.27) is substantively similar to with exception that EI_{diesel} is the average emission intensity associated with the combustion of diesel, defined by EPA to be approximately 0.272 $gCO2_{eq}$/Wh [154].

In Eq. (5.28), $\overline{EI}_{EV,n}$ represents the average Emission Intensity for the EV in city n measured in grams of CO2 equivalent per kilometer [$gCO2_{eq}$/km]. To estimate this, we divide the vehicle basis energy consumption, $\overline{EC}_{EV,n}$ by the charging and transmission efficiencies and then multiply the result by the Emission Intensity due to Electricity Generation for city n ($EIEG_n$ again measured in $gCO2_{eq}$/Wh). Estimates of $EIEG_n$ by city are determined from multiple sources [22,152-153]. The EI of the PHEV is the weighted sum of a CD mode subtotal (Eq. 5.28)) and a CS mode subtotal (Eq. (5.26)). The weightings are given by the Utility Factor introduced in Eq. (5.24). It should be reiterated that the

Emission Intensity comparisons presented in this study are distinct from conventional lifecycle assessments (LCA) which typically include emissions associated with resource extraction.

5.4 Results & Discussion

In this section, comparative results are presented in three stages. First, the energy demands of various vehicle technologies are quantified as functions of ambient temperature and driving cycle. Comparisons are made on the basis of common energy units, specifically energy consumed per distance travelled (Wh/km). Second, the energy demands for the vehicle technologies are compared on a vehicle-basis (i.e., the fully-fueled or fully-charged vehicle as a system boundary) for 22 major U.S. urban metropolitan areas. Vehicle-basis comparisons are reported in terms of absolute energy consumption and in terms of "Energy Consumption Locality Multipliers" (ECLMs). Finally, estimates of the "system-equivalent" energy consumption and emissions (i.e., associated with upstream energy supply, processing and transmission) for the selected technologies and cities are presented.

5.4.1 Fuel and electricity consumption sensitivity to drive cycle and temperature

5.4.1.1 Illustrative simulation results for the UDDS driving cycle

For each given drive cycle and vehicle type, dynamic simulations are performed in MATLAB/Simulink to determine the real-time tractive power requirements. At baseline conditions, which assume an ambient outdoor temperature of 22°C and nominal auxiliary power demands, tractive power is plotted for ICE-SI, HEV and EV respectively in Figures 5.5 - 5.7. These representative simulation outputs were generated by imposing a temporal vehicle target velocity that complies with the EPA Urban Dynamometer Driving Schedule

(UDDS), which is included for reference in Appendix F. Note that tractive power demands met by the engine are indicated in purple (for the ICE-SI and HEV), whereas tractive power demands met by the electric machine (either in motoring or generating mode) are indicated in orange (for the HEV and EV). A negative tractive power suggests the vehicle is recovering kinetic energy by virtue of its combined generator/energy storage system (i.e., “regenerative braking”). The UDDS cycle, as compared to the highway or aggressive driving cycles, is known to more fully manifest the energy-recovery capabilities of HEVs and EVs.

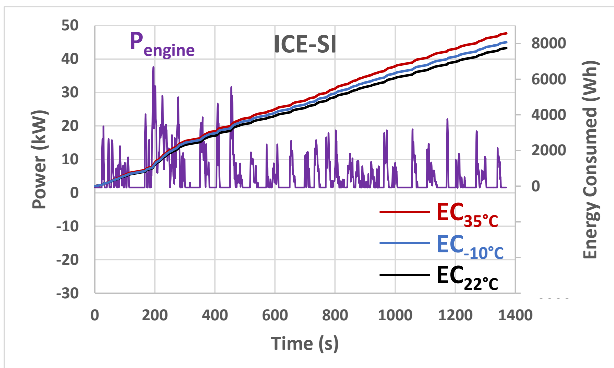

Figure 5.5. ICE-SI Tractive Power and Energy Consumption, UDDS cycle.

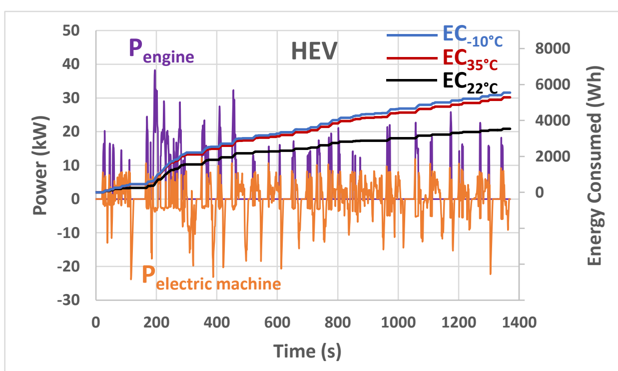

Figure 5.6. HEV Tractive Power and Energy Consumption, UDDS cycle.

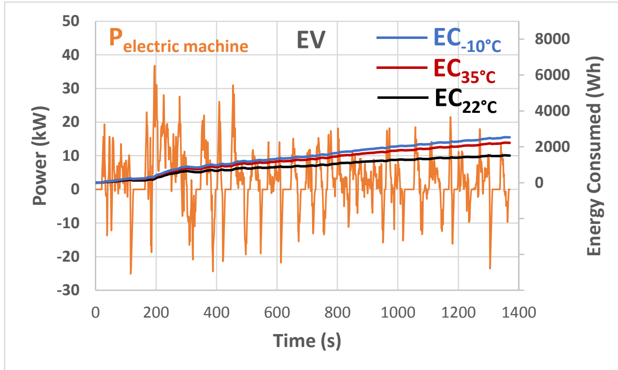

Figure 5.7. EV Tractive Power and Energy Consumption, UDDS cycle.

Figures 5.5-5.7 are also intended to begin illustrating the variation in energy consumption as a function of operation at three selected ambient temperatures for the ICE-SI, HEV and EV respectively. These EC curves are to be read on the right hand y-axes. EC is shown to be a function of temperature, color coded as follows: -10°C (blue), 22°C (black), and 35°C (red). For comparison purposes EC values have been converted to common units at the vehicle boundary using the lower heating value of gasoline. Please note that even though three EC curves are plotted corresponding to operation at different temperatures, only the 22°C tractive power curve is included for reference. In other words, Figures 5.5-5.7 do not show auxiliary or total vehicle power demands for any of the temperature scenarios.

It is not surprising that the ICE-SI has the highest energy consumption and the lowest sensitivity to cold operation. Though required to idle at all times, this vehicle type recovers waste heat to meet cabin heating demands. Conversely, the HEV completes the UDDS cycle, of which an average of 5 complete cycles are shown, by consuming approximately half the energy compared to the ICE-SI. However, it is more energy sensitive to hot and cold weather. At -10°C, engine on-time is increased to maintain sufficient cabin heat, whereas at 35°C additional energy is consumed to maintain proper battery thermal management. For the EV, an average of ten cycles is reported to ensure compliance with net energy change tolerance protocols. Nominal (22°C) EV energy consumption on a vehicle basis is substantially lower than both ICE-SI and HEV. However EV operation at -10°C incurs losses attributable to increased electrical resistances and cabin heating demands, resulting in a larger percentage change compared to either ICE-SI or HEV. This initial analysis of simulated vehicle operation at discrete temperatures provides a foundation for the investigation of energy sensitivity across a continuous spectrum of ambient temperatures.

5.4.1.2 Comparison of vehicles operating on liquid fuel and grid-derived electricity

The vehicle architectures simulated in this study consume energy in one of two forms: liquid fuel during ICE-only or HEV CS mode, or electricity during EV or CD mode. Figures 5.8 and 5.9 illustrate the comparative fuel and energy consumption by vehicle architecture for liquid fuel and all-electric operating modes respectively. These data span a continuous range of outdoor temperatures and now represent the weighted average effect of multiple drive cycles based upon the EPA combined fuel economy calculation methodology described in section 5.2.4 and Appendix C.

Composite weighting of the various city and highway drive cycles confirm that HEVs consume between 25% and 40% less fuel than ICE-SI, ICE-CI and even PHEV40 in CS mode. This trend is essentially consistent across the temperature spectrum because the heat rejection of the hybrid vehicle batteries in CS mode is relatively low, typically between 100 and 200 W. Only during the US06 cycle do HEV batteries in CS mode reach $Q_{b,cycle}$ rates of 400 W. Since these vehicles are equipped with an ICE, waste heat is utilized to satisfy cabin heating requirements during cold weather conditions, as evidenced by the relatively flat responses when the outdoor temperature is between -16 and 20°C.

While all vehicles demonstrate a similar trend during warm weather, the HEV is slightly more sensitive to AC use for two reasons. First, owing to its superior baseline efficiency, it consumes a comparatively higher percentage of energy to maintain the cabin at the desired temperature. Second, its slope is slightly steeper than the other vehicles due to battery thermal management demands (Figure 5.8). HEV fuel consumption at 35°C is simulated to be 21% greater than its baseline at 22°C as compared with increases of 9% for ICE-SI and 12% for ICE-CI, relative to their respective baselines. The CI engine outperforms the SI engine, as may be expected, due to the superior thermal efficiency of the diesel cycle. The PHEV40 in CS mode performs better than the CI vehicle, but due to its 200 kg battery module and additional powertrain mass, its combined fuel consumption is greater than 6 L/100km. The heat generated by its batteries in CS mode is very similar to the HEV.

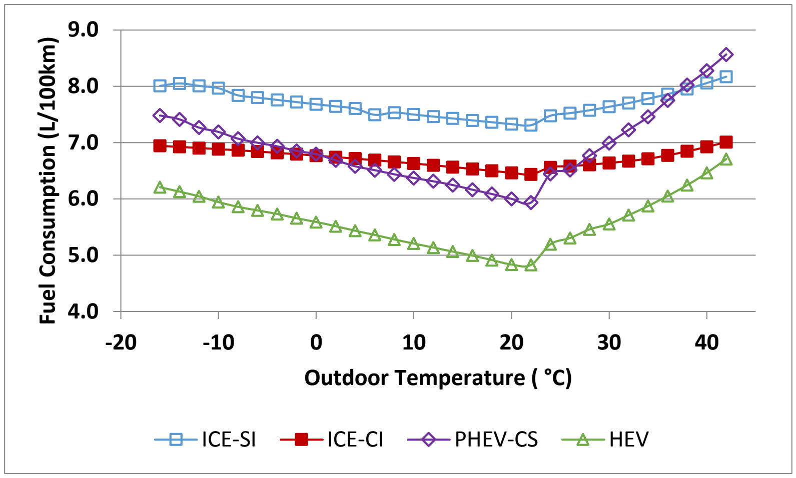

Figure 5.8. Fuel Consumption temperature sensitivity, gasoline or CS mode.

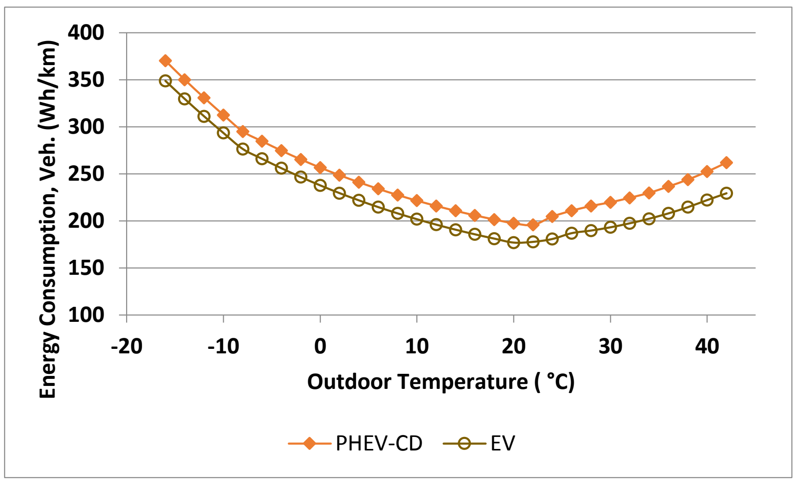

Figure 5.9. Electricity Consumption temperature sensitivity, all-electric or CD mode.

The PHEV and EV can both operate in CD mode, whereby the source of vehicle energy is derived exclusively from electricity stored in the batteries. Figure 5.9 illustrates simulated energy consumption (EC) for the subject vehicle architectures. Vehicle-basis energy consumption, EC_i(T), reflects only the portion available and consumed on-board, and does not account for upstream electrical generation, transmission or charging losses. For CD operation, Figure 5.9 illustrates the substantial energy demanded by the vehicle during cold weather operation. Even though a heat pump with COP > 2 can provide cabin and battery heating down to about 0°C, energy penalties average about 30% for the combined city and highway drive cycles at that temperature in CD mode. In certain city modes, this penalty can exceed 40%. For extremely cold operation ($T_{outdoor}$ < -6°C), an auxiliary resistance heater is employed in certain designs, including the EV and PHEV modelled in the present study. In both of these vehicles, the energy consumption at -16°C increases 90% relative to baseline values, as indicated in the figure by the nonlinear energy consumption trend during extreme cold. Official and simulated range estimates corroborate this finding [132,155].

In warm weather when AC mode is active, the energy consumption trends in Figure 5.9 are qualitatively similar to those illustrated in Figure 5.8, though both the absolute energy consumption and the percent change over the baseline vary by vehicle type. It is noted that the PHEV has a simulated vehicle mass that is 247 kg greater than the EV, owing to its dual powerplant configuration. The simulation confirmed this to be responsible for the largest part of the energy consumption variance, in absolute terms, between the two vehicles. In AC mode at 35°C, the PHEV energy consumption is 19% greater than at 22°C, compared to a 15% change for the EV. This difference in relative terms is attributable to active liquid cooling used in the PHEV, where additional energy is consumed for battery thermal management with increasing ambient temperature. Conversely, the EV uses a passive air-cooled approach, in which energy is not expended to maintain battery cell temperature. Though lower cost and lighter weight, the passive approach may contribute to shortened lifespan or durability concerns.

As discussed in Section 5.2.4, the reporting of energy consumption on a vehicle basis in common units enables a direct comparison among the vehicles of this study which have been selected with relatively equivalent size and power specifications. The comparative sensitivities of energy consumption to temperature by vehicle type and operating mode are illustrated in Figure 5.10. In the figure, relevant driving cycles have been weighted and averaged to a combined city/hwy basis for comparison purposes.

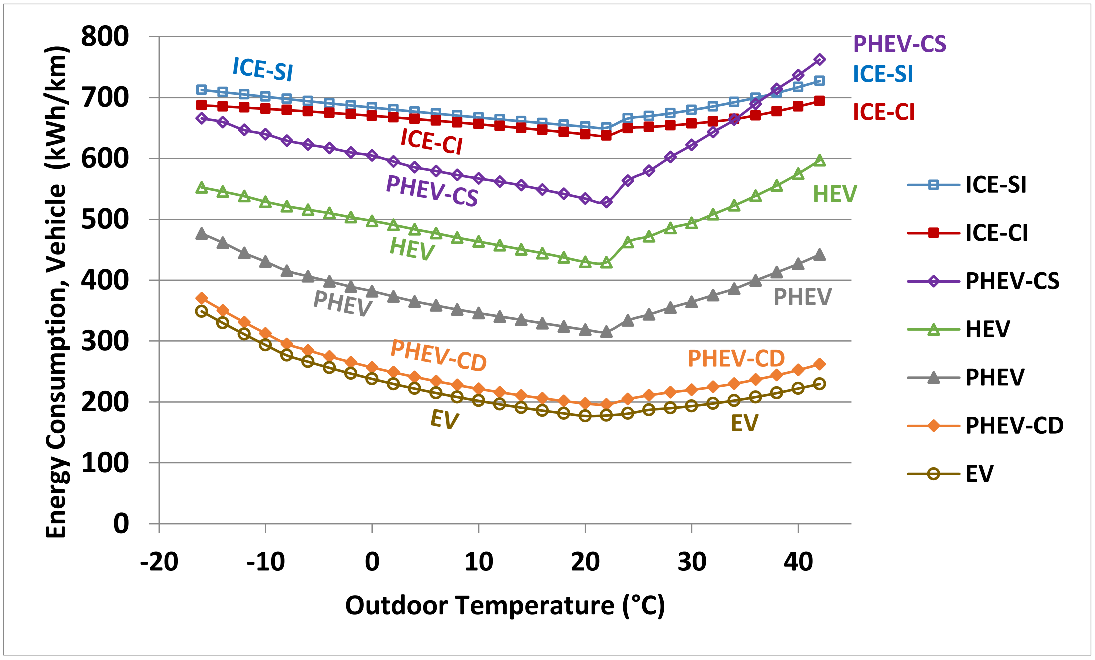

Figure 5.10. Energy consumption on a vehicle basis as a function of temperature by vehicle type.

It is of note that the simulated vehicle-basis energy consumption is extremely similar in magnitude between gasoline (ICE-SI) and diesel (ICE-CI) vehicles. Several reasons explain this result. The vehicles of this study are modelled after actual products (Table 2.1 5.1; [100a-f]) and therefore have slightly different specifications (mass, power, aspiration, etc.). Specifically, the ICE-CI vehicle of this study has a mass that is 10% greater than the ICE-SI evaluated. Diesel vehicles (of equivalent power rating) are known to be heavier than gasoline versions, and this is therefore a fair, real-world representation between the two vehicle technologies. Next, despite superior thermal efficiency and lower fuel consumption in L/100km, diesel fuel has greater energy content by volume. Thus when the energy is converted to a common equivalent Wh/km basis, the higher energy value fuel is accounted for, and the net benefit, *on an energy basis,* is reduced to a level that is only marginally superior to the ICE-SI. Finally, the combined city-highway FE rating mutes some of the efficiency benefit of the diesel which operates very efficiently during steady state operation. While every effort has been made to equitably model representative vehicle architectures, discretion is advised with regard to interpretation of results.

Figure 5.10 demonstrates that conventional gasoline and diesel fueled vehicles are effective at converting waste heat for cabin demands in cold weather, as witnessed by the 7% increase at -7°C as compared to 22°C. At 35°C these vehicles coincidentally experience a 7% increase in energy consumption as well. The ICE-CI outperforms the ICE-SI only slightly since the comparison is on an energy basis and the diesel vehicle has a greater mass. As noted in Section 5.2.4, cold weather EC for ICE-CI in Figure 5.10 may be slightly underestimated due to incomplete consideration of fuel consumed solely to maintain NOx at compliant levels.

In comparison, the HEV demonstrates vehicle basis energy consumption levels that are roughly 40% lower at 22°C than its non-hybrid counterparts. Figure 5.10 illustrates how a portion of this advantage is erased at elevated temperatures, owing to the additional heat load attributable to the in-cabin, air-cooled battery thermal management system. A 24% increase occurs at 35°C as compared to 22°C, and a 20% increase occurs at -7°C as compared to 22°C. The HEV is slightly more sensitive to cold weather operation due to reduced levels of waste engine heat (a result of superior efficiency and engine-off control logic). A key reason the HEV is more sensitive to both hot and cold temperatures is that it operates at lower absolute energy levels, so the auxiliary energy demand for cabin HVAC has a greater proportional impact.

Energy consumption for EV and PHEV-CD shown in Figure 5.10 are identical to Figure 5.9, but it is now obvious how much more efficiently they operate on a vehicle basis compared to the other technologies. For example, their vehicle basis energy consumptions are about 70% lower than ICE-SI and about 55% lower than HEV at 22°C. When operating at these even lower absolute energy levels, however, temperature sensitivity is even greater. Now, operation at 35°C incurs a 15 to 20% increase whereas operation at -7°C incurs a 50% penalty.

For this analysis, a utility factor of 0.64/0.36 (CD/CS ratio) has been used as prescribed in the literature for a PHEV of 40 mile all-electric range [106,132]. This means that electric operation from grid-electricity is assumed for 64% of the use, and HEV operation with gasoline is assumed for the remaining 36%. The curves of PHEV in charge sustaining mode (CS) and in charge depleting mode (CD) qualitatively mirror the responses of the HEV and EV, respectively. Differences are attributable again to the greater vehicle weight, battery thermal management, and other minor variations in vehicle specifications.

5.4.1.3 Drive cycle sensitivity to outdoor temperature

By using standardized EPA cycles (FTP/UDDS, US06 city, US06 hwy and HWFET, Appendix F), an assessment of energy consumption sensitivity to temperature is conducted for each drive cycle as illustrated in Figures 5.11 and 5.12. It may be noted that the figures use different scales to better reveal relative drive-cycle sensitivities to temperature. The PHEV operating in CS mode (Figure 5.11) demonstrates relatively flat energy consumption response to temperature when simulated in the US06 city, US06 hwy and HWFET driving cycles. This suggests that vehicle tractive power requirements are sufficiently high during these driving conditions that HVAC operation does substantially change vehicle efficiency. Conversely, sensitivity is pronounced in the UDDS cycle, where an estimated 45% increase in EC occurs between 22°C and 35°C.

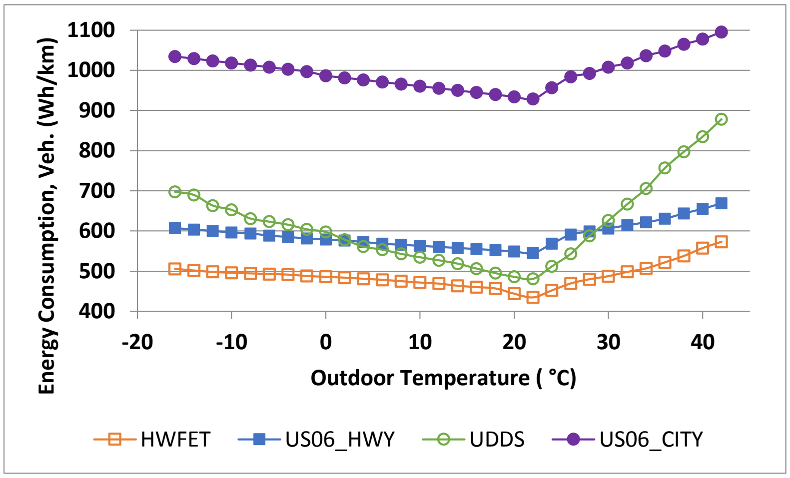

Figure 5.11. PHEV drive cycle sensitivity, CS mode.

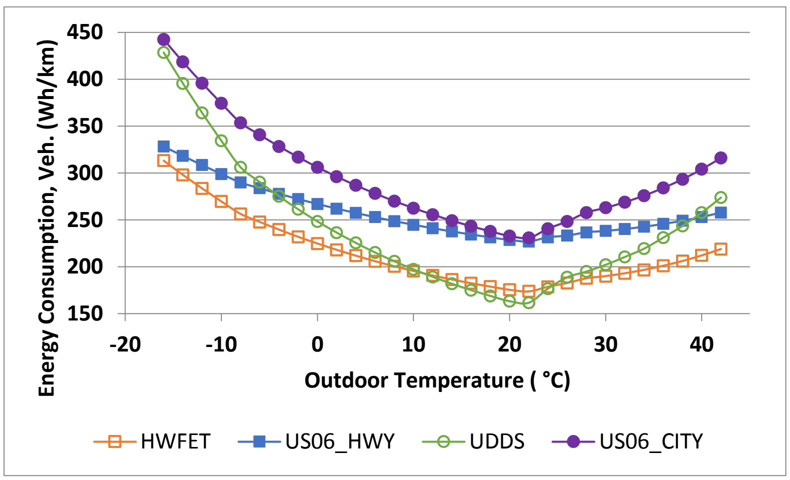

Figure 5.12. PHEV drive cycle sensitivity, CD mode.

A similar penalty is incurred in cold weather operation where waste engine heat is insufficient to maintain cabin heating demands. This suggests that less aggressive urban driving in hybrid modes, which is otherwise comparatively efficient, may be more negatively impacted by extreme temperature operation.

The PHEV is an instructive example since it can be operated in CD mode as well. Figure 5.12 quantifies the extent to which the energy consumption of electric vehicles in electric (CD) mode differs from gasoline (CS) mode as a function of driving cycle and temperature. It is again apparent that energy demand increases at hot extremes, but now a considerable cold weather penalty is incurred and variations with driving cycle are moderated. In the case of UDDS relative to a 22°C baseline, energy consumption can be nearly 40% greater at both 4°C and 35°C, and is nearly double at -10°C. The two city modes appear more sensitive to temperature, having the greater slope for both heating and cooling demands. The city modes are also more heavily impacted by energy consumed overcoming friction and start-up transients. Cooling requirements are correlated to the combined demand of cabin AC and battery heat generation, which is dependent upon driving cycle. As a fraction of vehicle tractive power, Figure 5.12 also illustrates the extent to which driving cycle and temperature interact to compound system energy demands. Battery thermal management and resistance effects during CD operation in urban driving cycles demonstrate significant departures from baseline performance when exposed to extreme outdoor temperatures.

Figure 5.12 suggests that city energy consumption for a PHEV in CD mode can actually exceed that of certain highway mode energy consumption in extreme climate conditions. In real-world driving, hybrid vehicles typically demonstrate superior efficiency in city driving where loads are relatively low and kinetic energy is frequently restored (as compared to highway driving). These energy savings are substantially reduced or eliminated by some combination of excessive cabin and battery thermal demands and resistive losses below -7°C and above 35°C. In CS mode with mild battery use, Figure 5.11 illustrates that PHEV fuel consumption is lower in highway mode, where the engine can operate near its optimal thermal efficiency. The effect of elevated temperature is estimated to be more than twice as great in the UDDS cycle compared to US06 cycle for both CS and CD operation, a potentially noteworthy finding.

5.4.2 Vehicle-basis energy consumption by locality

5.4.2.1 Vehicle-basis energy consumption for selected U.S. cities

The correlations between energy consumption and temperature, Eqns. (5.18-5.20), are used to estimate the average vehicle-based energy consumption by city for each vehicle architecture according to Eq. (5.21). These results are presented in Table 5.3.

Table 5.3. Estimated vehicle-basis energy consumption by locality and vehicle type.

	ICE-SI	ICE-CI	HEV	PHEV-CS	PHEV-CD	PHEV	EV-PAC
	Wh/km	Wh/km	Wh/km	Wh/km	Wh/km	Wh/km	Wh/km
Reference*	660	647	441	556	212	335	190
ATL	667	652	466	586	215	349	193
BAL	668	654	470	589	221	353	200
BOS	669	656	468	589	225	356	205
CHI	671	657	473	596	230	362	209
DAL	670	654	474	597	217	354	194
DC	669	654	469	591	221	354	199
DEN	670	656	472	595	225	358	204
DET	671	657	473	595	230	361	210
HOU	669	652	470	592	214	350	191
IND	671	656	473	596	229	361	208
LA	656	644	441	554	203	329	183
MIA	669	651	472	593	212	349	187
MIN	674	659	478	603	239	370	218
NYC	668	654	466	586	221	353	201
PHA	669	655	468	590	222	354	201
PHX	679	659	492	625	222	367	197
PIT	670	656	469	591	226	358	206
SD	657	644	442	555	203	329	183
SEA	664	653	458	577	217	347	197
SF	660	648	449	565	209	337	189
STL	671	656	473	595	224	358	203
TAM	668	651	469	590	212	348	188
MEAN	668	654	467	589	220	352	198
STDEV	5.1	4.0	11.4	15.4	8.9	10.3	9.2
MIN	656	644	441	554	203	329	183
MAX	679	659	492	625	239	370	218
Spread	23	15	52	72	36	41	36

In terms of absolute energy consumption on a vehicle basis, the EV and PHEV-CD consistently perform best in all cities, followed by HEV and PHEV-CS, and finally ICE-CI and ICE-SI. However, the greater sensitivity to temperature of the EV, PHEV and even HEV suggested in Figure 5.10 is now manifested in Table 5.3 in terms of variances in energy consumption by locality. The spreads between minimum and maximum values for EV and HEV may be noted compared to ICE vehicles. In general, sensitivity results in larger variances and mean values that are higher than the simulated reference values, which is the theoretical output of the model for each vehicle assuming a 5-cycle EPA estimation method. The minimum, maximum and median values are depicted by vehicle type in Figure 5.13 .

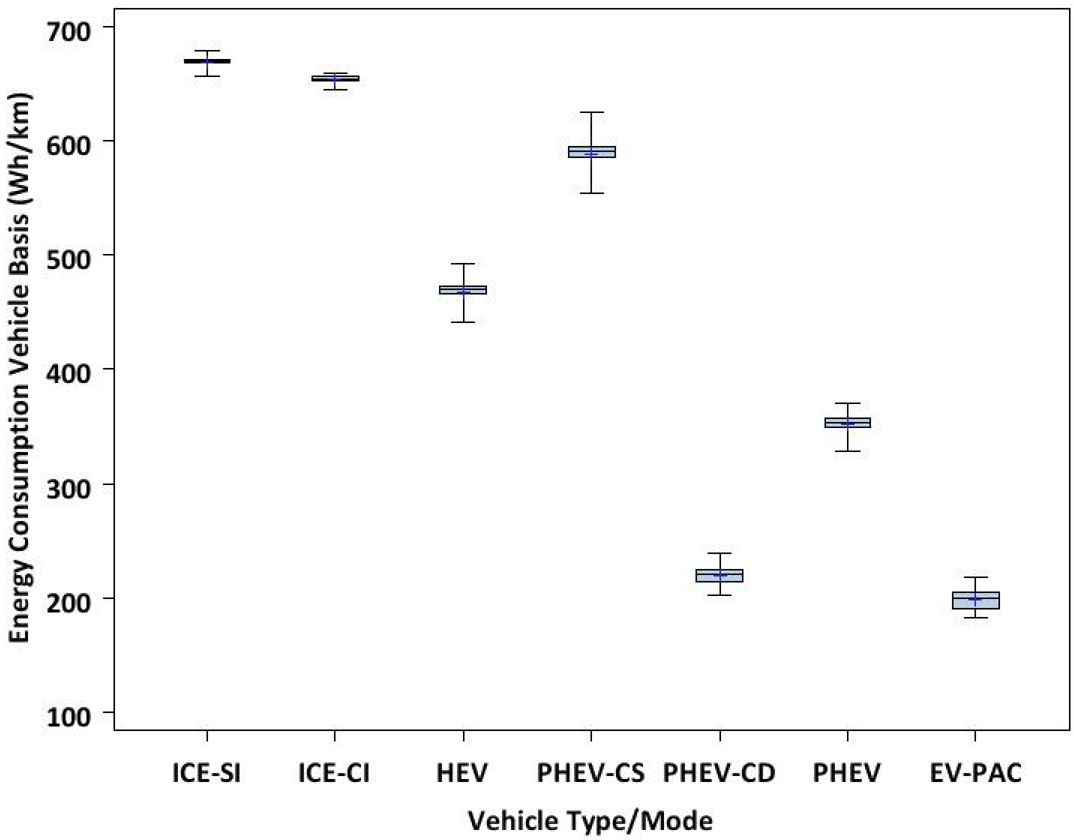

Figure 5.13. Vehicle-basis Energy Consumption by vehicle type across major U.S. localities.

Figure 5.13 confirms that the median values are consistent with vehicle labelling methodologies, and helps the visualization of the larger spreads among different localities.

Variation for ICE-SI and ICE-CI is the lowest as expected, since EPA fuel economy methodologies have historically been developed and adapted to characterize vehicles with internal combustion engines, which still account for 99% of new vehicle sales. While the variation in vehicle basis energy consumption may not appear significant in absolute terms, this variation forms a much larger percentage of the energy use for vehicles operating in hybrid and all-electric modes. Exploring this phenomenon for each vehicle type individually is therefore warranted.

5.4.2.2 Vehicle-basis energy consumption locality multiplier (ECLM)

To quantify the extent to which energy consumption varies as a fraction of the absolute energy consumption for a reference case, this study introduces a metric entitled Energy Consumption Locality Multiplier (ECLM). This is defined as the ratio of the vehicle basis energy consumption for vehicle m in city n ($EC_{m,n}$) and the simulated reference value for vehicle m ($EC_{m,ref}$).

$$ECLM_{m,n} = \overline{EC}_{m,n} \Big/ \overline{EC}_{m,ref} \tag{5.29}$$

The reference values used to estimate $ECLM_{m,n}$ are generated by the baseline simulation models of this study; this helps ensure that locality-specific simulations follow a consistent methodology and facilitate fair comparisons. ECLM can be thought of as the number by which to multiply the rated energy consumption to adjust for locality. An ECLM of unity suggests that the 5-cycle methodology accurately characterizes real-world energy consumption for the given vehicle and city (assuming driving cycle weightings are reflective). ECLM > 1.0 implies energy consumption for the given vehicle and locality will be greater than that predicted by the 5-cycle method. Figure 5.14 presents a comparison of ECLM values by vehicle type for the 22 different large U.S. cities.

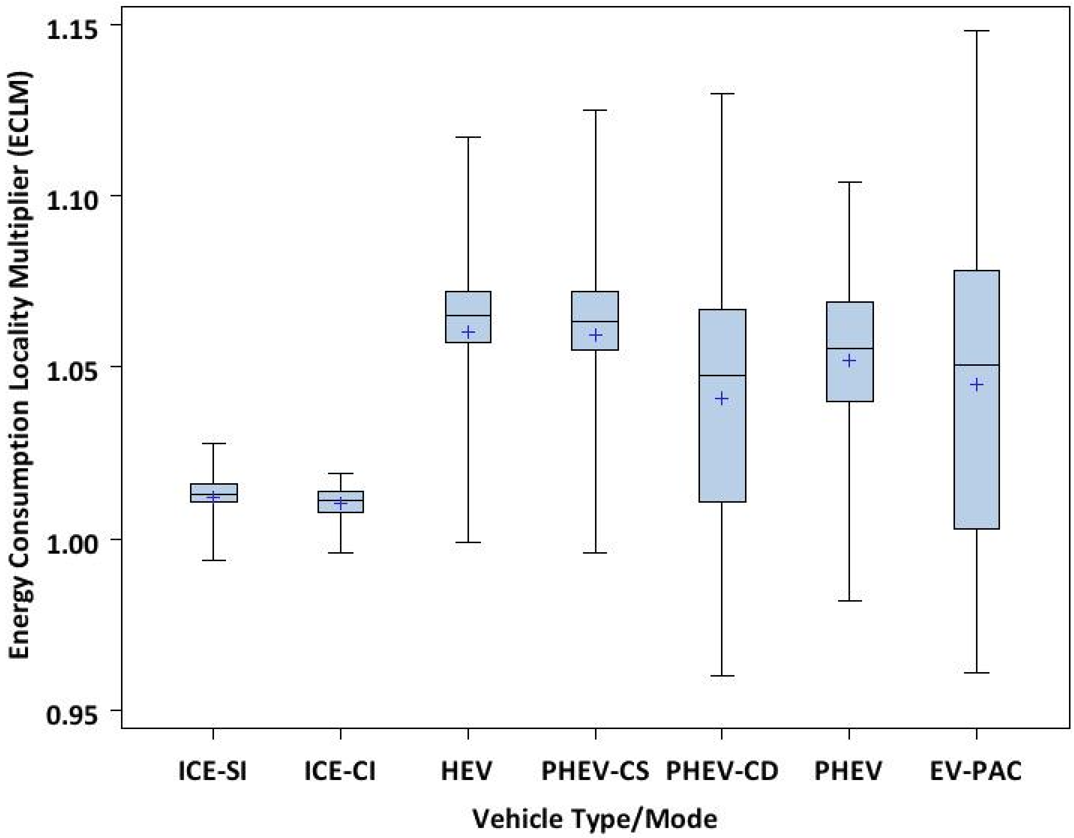

Figure 5.14. Energy Consumption Locality Multiplier (ECLM) by vehicle type for a range of U.S. cities.

The box-plot comparison of ECLM values confirms that the vehicle-basis energy consumption mean values (denoted by + in Figure 5.14) are higher for the hybrid and electric vehicles, and that they vary by city to a much greater extent than conventional vehicles. ECLMs range from 0.99 to 1.03 for ICE-SI and ICE-CI, 1.00 to 1.12 for HEV and PHEV-CS, and 0.96 to1.15 for EV and PHEV-CD. A table of ECLM by vehicle type and city is included in Appendix G. The results indicate that ECLM for the HEV is 1.00

for Los Angeles and San Diego, 1.12 for Phoenix, 1.07 for Chicago and Detroit, and 1.08 for Minneapolis. It is further noted that ECLM for the EV is 0.96 for cities like Los Angeles and San Diego, 1.04 for Phoenix, 1.10 for Chicago and Detroit, and 1.15 for Minneapolis. Thus, localities with mild weather yield no correction or a downward correction to the "reference value" whereas localities with more extreme weather require an upward adjustment. The EC vs. outdoor temperature trends of Figure 5.10 are transformed into a practical tool by which to compare technologies and localities.

5.4.3 Upstream and system-equivalent energy consumption and emissions by locality

5.4.3.1 System-equivalent energy consumption by locality

Having now obtained vehicle-basis energy consumption, estimates that include upstream energy and emissions impacts can now be obtained. The approach described in Section 5.3.2 is applied to every vehicle *m* and city *n* in the study, despite the disparate sources and pathways of the upstream energy. Locality-dependent and locality-independent efficiency factors are derived, for which national average and city-specific summaries are included in Appendix G.

While many cities exhibit upstream efficiency characteristics similar to one another and the U.S. national average ("US avg") as expected, specific cities have distinct traits. Taken in view of the sensitivity to weather by vehicle type, this reveals the practical ramifications of the key interactions between vehicle type and locality. These results are presented in graphical format in Figure 5.15. These results are also included in matrix format for each city and vehicle architecture pairing in Appendix G.

The first major conclusion is that for a system-equivalent basis in common energy units as defined, the HEV generally performs with superior energy efficiency. Across the

22 cities investigated, the HEV has a mean $EC_{Sys\text{-}Eq}$ of 516 Wh/km, compared to 738, 722, 670 and 615 Wh/km for the ICE-SI, ICE-CI, PHEV-combined mode (denoted simply as "PHEV"), and EV, respectively.

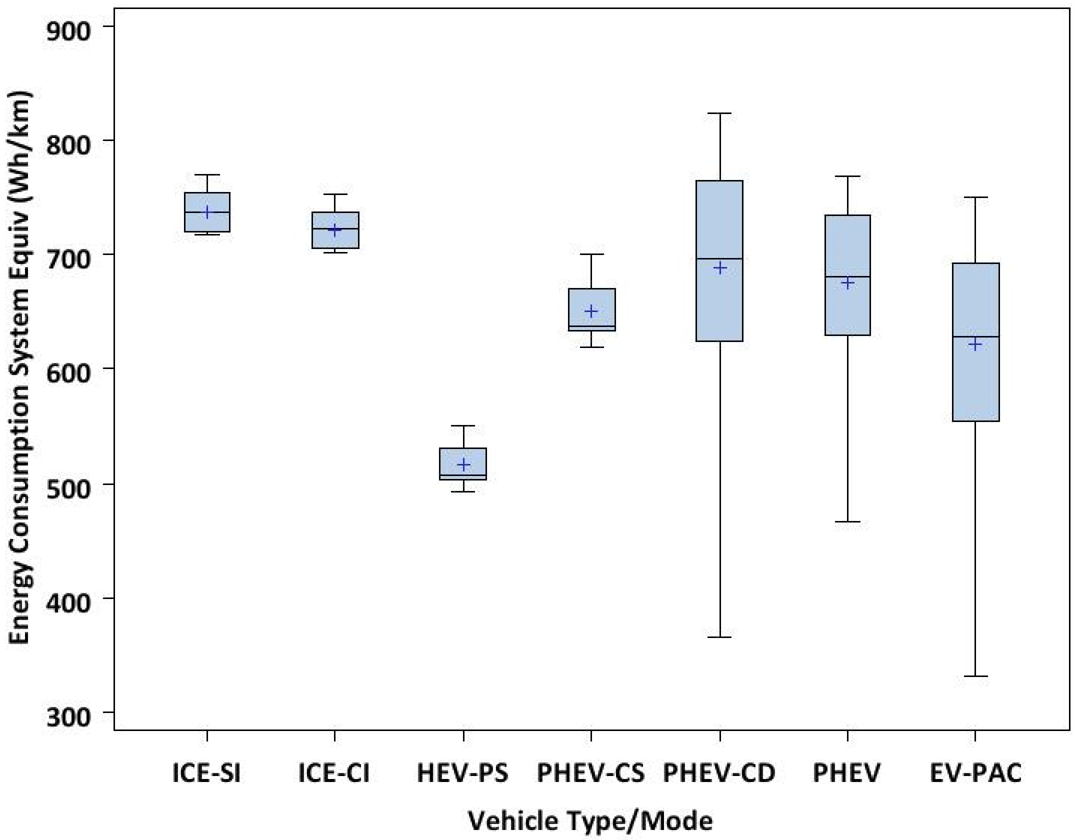

Figure 5.15. System-Equivalent Energy Consumption by vehicle type across major U.S. localities.

A second conclusion is that the $EC_{Sys\text{-}Eq}$ averages for EV and PHEV-CD operation are much higher than the vehicle basis EC values might have suggested. While this is not surprising given typical thermal efficiencies of upstream electricity generation, we now have a quantitative basis for making fair comparisons to vehicles of similar class and performance.

The $EC_{Sys\text{-}Eq}$ variation among all cities falls in a narrow band (less than about ±35 Wh/km) for vehicles operating with an internal combustion engine in a liquid fuel or CS mode (Appendix G). Conversely, $EC_{Sys\text{-}Eq}$ variation among all cities for EV and PHEV-CD is of the same order of magnitude as the absolute energy consumption values. $EC_{Sys\text{-}Eq}$ for EV ranges from 332 to 750 Wh/km (i.e., mean−290 to mean+128 Wh/km) depending on locality, and $EC_{Sys\text{-}Eq}$ for PHEV-CD ranges from 366 to 823 Wh/km (i.e., mean−323 to mean+134 Wh/km). The box plot of Figure 5.15 shows that the lower and upper quartiles for each vehicle type operating in electric mode have widespread variation from their mean and median values. The figure is also useful in graphically contrasting locality-dependent variations of $EC_{Sys\text{-}Eq}$ among all simulated vehicle types.

This analysis reinforces the importance of considering the combined effects of energy sensitivity by vehicle type and the variability of weather and energy profiles by locality. It could suggest to consumers, OEMs and policymakers, for example, where certain technologies yield highest energy benefits from a geographical and regional perspective.

5.4.3.2 System-equivalent emissions by locality

System-equivalent emissions by locality are a metric of interest closely related to system-equivalent energy consumption. Given that a major motivation for the introduction of alternative vehicle architectures is to not only reduce, but replace, liquid fuel with grid-derived electricity, upstream emissions are an important gauge by which to compare quantitative results. Figure 5.16 presents results of Emission Intensities ($EI_{m,n}$) by vehicle and city following the methodology described in Section 5.3.2.

As compared to Figure 5.15, Figure 5.16 suggests that the EV has a mean EI that is marginally superior to the other vehicle types. PHEV-CD is next, followed by HEV and PHEV-combined.

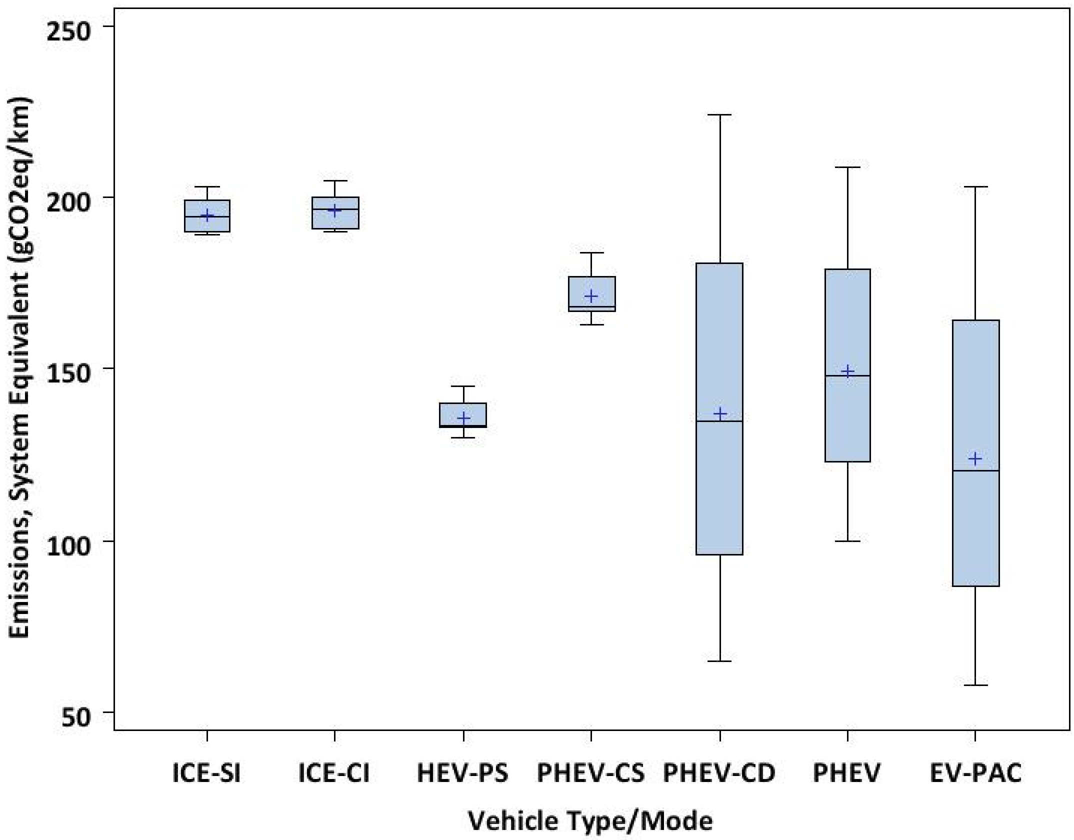

Figure 5.16. System-Equivalent Emissions by vehicle type across major U.S. localities.

To the extent that the 22 cities provide a fair representation of performance nationally, this suggests that vehicles operating solely on electricity can contribute to reductions in emissions for the transportation sector. However, it is important to note that variations as a proportion of the absolute emissions are even larger than in the case of system-equivalent energy consumption. For example, EI can range from 46% of mean (in San Diego) to 164% of the mean (in Denver). In this contrast, the results are heavily influenced by interaction of the milder temperatures and cleaner grid in California on the one hand with the colder and more carbon-intensive grid in Colorado. These comparisons along with a complete listing of the equivalent system level emissions by city and vehicle type (or $EI_{m,n}$) are shown in Table 5.4.

Table 5.4. System-equivalent emissions by locality and vehicle type.

CITY	ICE-SI	ICE-CI	HEV	PHEV-CS	PHEV-CD	PHEV	EV-PAC
	$gCO2_{eq}$/km	$gCO2_{eq}$/km	$gCO2_{eq}$/km	$gCO2_{eq}$/km	$gCO2_{eq}$/km	$gCO2_{eq}$/km	$gCO2_{eq}$/km
ATL	189	191	132	166	153	158	138
BAL	190	191	133	167	125	140	113
BOS	190	192	133	167	86	115	78
CHI	199	201	140	177	182	180	165
DAL	198	199	140	177	139	152	124
DC	190	191	133	168	124	140	112
DEN	203	205	143	180	224	209	203
DET	199	201	140	176	197	190	179
HOU	198	199	139	175	136	150	122
IND	199	200	140	177	181	179	164
LA	194	196	130	163	65	100	59
MIA	190	190	134	168	133	146	118
MIN	200	201	142	179	193	188	176
NYC	190	191	132	167	72	106	65
PHA	190	191	133	167	117	135	106
PHX	200	200	145	184	137	154	122
PIT	190	192	133	168	179	175	162
SD	194	196	130	164	65	101	58
SEA	196	198	135	170	96	123	87
SF	195	197	132	167	67	103	61
STL	199	200	140	176	213	200	193
TAM	190	190	133	168	134	146	119
MEAN	195	196	136	171	137	150	124
STDEV	4.5	4.5	4.5	5.9	49.1	33.0	44.7
MIN	189	190	130	163	65	100	58
MAX	203	205	145	184	224	209	203
Spread	13.5	14.2	15.3	21.2	159.5	108.1	145.0

The integration of component simulations with system-level approaches of this study for both energy and emissions reveals comparative data and insights that are novel and previously lacked quantification. A high-level graphical comparison of the results of the present study to energy consumption estimates given by CAFE and EPA Label calculations for the representative vehicles considered herein can be found in Appendix G. The findings emerging from this work can be used to improve decision-making and facilitate improved alignment between scientific data, consumer behavior and government policies.

5.5 Uncertainty, Assumptions and Limitations of the Study

This study is largely based upon representative characteristics of actual 2014 model-year production vehicles. This facilitates comparison with published research and accounts for inherent first-order differences among the vehicle architectures (such as weight). As such, key aspects of vehicle utility, such as classification size, footprint, and rated power are considered similar enough for the purposes of comparison. Three exceptions worth noting relate to characteristics unique to the electric vehicle: the reduced rated power of the EV (80 kW vs. an average of about 100 kW for other vehicles), the single-charge range limitation of the EV (about 1/5th that of competing technologies), and the time required to re-charge (about 8-15 hours for EV vs. 5-10 minutes for liquid-fueled vehicles). Finally, vehicle capital and operating costs, while significantly different among the selected architectures, are not considered in this study.

The intent of the vehicle simulations is to balance fidelity with computational intensity, and thus the simplified control strategies and battery characteristics discussed in Sections 5.2.1 and 5.2.2 are deployed. The purpose is to model vehicle architectures with the characteristics and operational traits of representative mass-production vehicles. Thus, slight variances between the simulations and laboratory-test results for actual vehicles are expected. As an example, the simulated reference energy consumption for the various vehicles are within 5% of the EPA-label methodology for HEV and ICE-CI, and within 2% for all others. Since locality simulations are compared against the reference simulation from this study, the slight departures from actual label ratings of actual vehicles are not relevant in the comparisons.

A constant relative humidity (RH) of 40% was assumed to keep conditions consistent with the prescribed environmental conditions for actual dynamometer tests. Real-world variations in RH by locality have not been considered in the study because they are of second order to temperature and their impact on the comparative results is minor.

While initial fuel and energy requirements during warm-up have been estimated as a functions temperature and vehicle architecture from experimental results, this study does not fully consider the additional consumption of fuel that may be necessary in diesel engines during cold operation to ensure NOx emission levels are compliant.

As noted in footnote 36 for PHEV and EV, estimates of battery resistances as a function of temperature are based curve fits of experimental results for cells and modules from the literature. Cell characteristics specific to the representative vehicles were not considered; however, this approach is deemed acceptable for the comparative purposes of this study.

Of the 22 cities considered in the locality study, only Denver has an elevation of greater than 1200 feet above sea level. For this reason, altitude effects have been neglected.

In terms of driving behavior, the study develops drive-cycle-dependent energy consumption from the vehicle simulation. Though this is explored in section 5.4.1.3, the remainder of the comparative results are presented on a common drive-cycle basis, built on the stipulated weightings of the EPA methodology that result in a combined city/highway rating. This approach is adopted due to the familiarity and prevalence of such ratings in prior studies, and to facilitate the ECLM comparisons on a consistent basis. The effect of the combined city-highway drive cycle assumption is to moderate the extreme combination of effects drive cycle with ambient temperature and locality.

As noted, the system-equivalent energy consumption and emission intensity comparisons presented in this study do not include energy losses or emissions associated with resource extraction or the transportation of raw resources (crude oil, bulk natural gas, raw coal) to the point of refining or generation. Due to the uncertainty associated with location, methods and technologies for extracting resources, we excluded this from consideration so as not to skew the locality-based comparisons. This could lead to lower estimates for energy use and emissions than would be predicted by a full LCA, and it is suggested that future work consider locality-appropriate factors for resource extraction and transportation.

By comparing liquid-fueled vehicles to grid-recharged ones on the basis of common energy units, consideration of the social or geopolitical value of energy sources is ignored in this study and the basis for energy comparisons is therefore a purely thermodynamic one. However, the comparative assessment of emissions uses a standard practice by comparing common units of $CO2_{eq}$, which are broadly understood and widely used, regardless of the energy source.

5.6 Summary of Key Findings

The energy demands of various vehicle technologies are quantified as functions of ambient temperature and driving cycle using an iterative modeling approach. The study models the interactions for vehicle tractive, thermal, and auxiliary energy demands under a range of conditions, and develops correlations for vehicle-based energy consumption as a continuous function of temperature. These correlations enable equitable comparisons among the vehicle architectures at the level of the vehicle type as well as for defined upstream system boundaries.

The vehicle-basis energy consumption of EV for combined city/highway modes, at about 190 Wh/km is superior to HEV and ICE vehicles, which average about 440 and 660 Wh/km, respectively. However, the energy sensitivity of alternative vehicles is highly correlated with the battery module capacity, its thermal management system, and resistive losses in extreme temperatures. Thus, while vehicle energy requirements are 10% to 40% lower for hybrid and EV when operated under moderate driving cycles and temperatures, their energy use is substantially more sensitive to driving cycles and extreme hot or cold temperatures. EV energy consumption can increase by up to 20% for an increase in outdoor temperature from 23°C to 35°C relative to a 7% increase in conventional vehicles; this increase can be 50% at -7°C for EV, but only 7% for conventional vehicles. In addition, city modes appear more sensitive to temperature for both heating and cooling demands. Cold weather operation is clearly problematic for EV due to higher resistances and no option of converting waste engine heat for cabin heating needs.

A framework for quantifying the impacts of locality on both a vehicle-basis and a system-equivalent basis is introduced based upon the derived dependence of energy consumption by vehicle type upon ambient temperature. The results indicate that the variations in average vehicle-basis energy consumption are higher for the hybrid and electric vehicles, and that they vary by city to a much greater extent than in the case of conventional vehicles. An Energy Consumption Locality Multiplier (ECLM) is introduced as a factor by which to multiply official energy consumption estimates made by EPA 5-cycle methods, as an indication of the impacts of locality. It is observed that ECLMs range from 0.99 to 1.03 for ICE vehicles, from 1.00 to 1.12 for hybrids, and from 0.96 to 1.15 for vehicles operated in all-electric mode.

The results are further extended to consider the system-equivalent energy impacts and emissions by locality. It is concluded that on a system-equivalent basis, the HEV is the most energy-efficient architecture of those considered. Across the 22 cities investigated, the HEV has a mean $EC_{Sys\text{-}Eq}$ of 516 Wh/km, compared to 738, 722, 670 and 615 for the ICE-SI, ICE-CI, PHEV-combined mode, and EV, respectively. While the average values are of interest, equally telling is the wide range of variation characterizing the equivalent system-level energy consumption. Conventional ICE vehicles and HEV exhibit a variation among all cities that falls in a narrow band of less than about ±35 Wh/km from the average. Conversely, $EC_{Sys\text{-}Eq}$ variation among all cities for EV and PHEV-CD falls in ranges from 300 Wh/km below the average to 130 Wh/km above the average depending on locality.

This same effect is observed for simulated system-equivalent emissions computed from the point of the extracted resource. Whereas the emissions intensities of ICE vehicles are highest overall at about 195 $gCO2_{eq}$/km, the average emissions intensities of HEV are similar to PHEV and EV, in the 110-140 $gCO2_{eq}$/km range. This suggests that, for average operation in the selected cities, alternative vehicles can contribute to reduced emissions by approximately 28-44%. However, variations are significant enough that this benefit can range from a 70% improvement to no improvement compared to ICE vehicles, depending upon locality. The integration of physics-based modeling with multi-step component and system-level simulations represents a useful approach by which to compare technologies and localities. The research provides novel methodologies for informing energy planning, technology development, and policy decision-making with regard to emerging vehicle markets.

CHAPTER 6. CONCLUSIONS, PERSPECTIVES AND FUTURE WORK

The primary outcome of this dissertation is an enhanced understanding of cross-cutting efforts to reduce energy and emissions in vehicular transportation. The present assessment of strategic vehicle technologies reveals that their comparative technological and economic performance are critical and interdependent factors in achieving compliance with future regulatory requirements. The interdisciplinary approach taken in this research has enabled a more comprehensive characterization of parallel yet distinct objectives, such as the need to reduce oil consumption and emissions, the preference of many domestic consumers toward acceleration over fuel economy, the financial viability of emerging technologies, the regional sensitivity to vehicle energy consumption, and the outlook for continued compliance. Through findings revealed by disaggregating factors among vehicle types, trim levels, attributes, localities, and specific technologies, it is clear that no single, ideal solution has emerged. Instead, the research strongly suggests that numerous opportunities exist for accelerating progress in strategic domains, while informing and potentially re-directing poorly aligned combinations of technology, economics and policy in other domains. This chapter synthesizes major findings elucidated in the dissertation, amplifies perspectives and implications of the present work, and proposes several avenues of future research. The chapter concludes with closing thoughts regarding progress towards a more sustainable transportation future.

6.1 The Future of Fuel Economy: Synthesis, Implications and Future Work

The multiple complementary investigations presented in this dissertation are intended to more completely articulate and quantify trade-offs incurred toward higher levels of fuel economy. This research establishes critical linkages that touch on social, economic and regulatory impacts of advanced technologies. For example, the analysis of Chapter 3 first finds that automotive innovation has been substantive and effective, guided in part by technological capability, in part by consumer demand, and in part by regulatory requirements. An historical perspective is useful in considering contemporary and potentially even future trends. Second, innovation has been achieved very affordably. Third, valuations of fuel economy and periods of aggressive regulation may be correlated. Fourth, it was hypothesized and demonstrated that consumers' valuation of fuel economy and acceleration are neither equal to one another nor constant over time. In other words, the findings suggest a non-linear correlation between consumers' willingness to pay for given attributes and independent variables such as vehicle footprint and time period.

Using a robust 2014 data set, price elasticities reflecting consumers' willingness to pay were presented for several vehicle classification categories. The author's initial analyses of similar data for 2013 suggest that additional insight can be attained by considering the time-dependency of the relevant price elasticities as summarized in Table 6.1. An additional table which presents price elasticities by vehicle classification for the 2013 model years is included in Appendix B.

Table 6.1. Comparison of price elasticities for major vehicle attributes by vehicle classification, 2014 and 2013.

Model Year		2014	2013
Vehicle Category		**All Cars**	**All Cars**
Footprint (FP) Min		26.8	26.8
Footprint (FP) Max		56.4	56.4
FP, Wtd. Mean		45.8	45.7
Data Set		Table 3.2	2013
MSRP, Wtd. Mean		$27,841	$27,007
Sales Vol., Units		7,868,192	8,055,136
Sales Revenue, $B		219.1	217.5
Response Variable		ln(MSRP)	ln(MSRP)
Hedonic Model		Eqn (3.9)	Eqn (3.9)
Estimator		WLS	WLS
Observations		814	759
R^2		0.781	0.775
Attribute	**Coeff.**	**Param. Est.** (Std. Error)	**Param. Est.** (Std. Error)
Intercept	β_0	**1.626***** (0.478)	**2.584***** (0.466)
ln(FC)	β_1	**-0.306***** (0.044)	**-0.393***** (0.047)
ln(ACCEL)	β_2	**-0.526***** (0.048)	**-0.577***** (0.053)
ln(CWT)	β_3	**1.403***** (0.058)	**1.312***** (0.055)
RWD	β_4	**0.227***** (0.022)	**0.219***** (0.023)
AWD	β_5	**0.198***** (0.026)	**0.249***** (0.026)
TRIMBASE	β_6	**-0.072***** (0.015)	**-0.098***** (0.014)
TRIMPREM	β_7	**0.113***** (0.015)	**0.094***** (0.015)

Note: ***denotes significance to the 1% level

Table 6.1 shows a modest reduction of about 20% in consumers' willingness to pay for reductions in fuel consumption (β_1) between 2013 and 2014. It should be noted that this phenomenon may be reflecting exogenous factors not included in the modeling, such as the price of fuel, household income, or dealer incentives. Notwithstanding such factors, modeling that captures temporal responses of attribute valuation as functions of vehicle classification proves to be powerful as a tool for projecting future costs and consumer preferences in response to continued regulatory constraints. Furthermore, future models could readily be adapted to account for key exogenous factors.

A sense of the comparative valuation between two given attributes can be attained from a ratio of their price elasticities with respect to total vehicle price. A new indicator is introduced by the author and referred to as the "fuel consumption to acceleration performance elasticity ratio" or simply "FAER." This indicator is defined as the absolute value of the ratio of the price elasticities of fuel consumption with respect to vehicle price and acceleration time with respect to vehicle price as follows:

$$FAER = \left| \frac{\beta_1}{\beta_2} \right| \tag{6.1}$$

In Eq. (6.1), β_1 represents the price elasticity of fuel consumption with respect to total vehicle price, and β_2 represents the price elasticity of acceleration time with respect to total vehicle price. Recall that these elasticities were the coefficients of the hedonic price regression model from Chapter 3, Eq. (3.5). Having already established methodologies for hedonic pricing characterization and generalized attribute weightings, the FAER indicators can be expressed as functions of time, vehicle classification and footprint. In this way, novel trajectories for revealed market trends are quantified and may be utilized for analyzing contemporary behavior, and potentially the projection of future trends. Figure 6.1 illustrates a plot of the dimensionless ratio FAER as a function of vehicle classification for the 2014 model year data set.

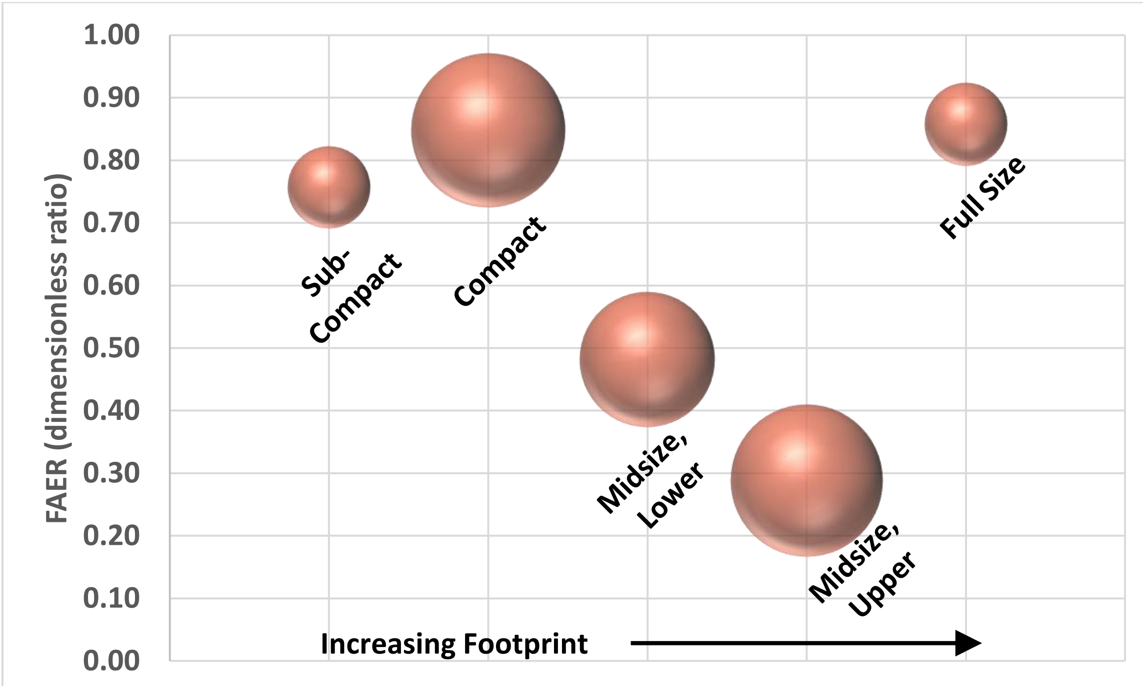

Figure 6.1. Fuel Consumption to Acceleration Performance Elasticity Ratio (FAER) as a function of vehicle classification and sales volume, 2014.

In Figure 6.1, the bubble size indicates the comparative sales volume. Note that the large mid-size vehicle segments which collectively account for approximately 53% of the passenger car market have FAER indices that are lower than the average value of all 2014 passenger cars which is computed to be about 0.58. These findings may have significant implications in view of progressive CAFE standards that call for largely uniform and linear increases in fuel economy by vehicle class over time as shown in Figure 6.2. If consumers in high volume market segments continue to more highly value acceleration than fuel economy, certain footprint-based targets may become increasingly difficult to achieve.

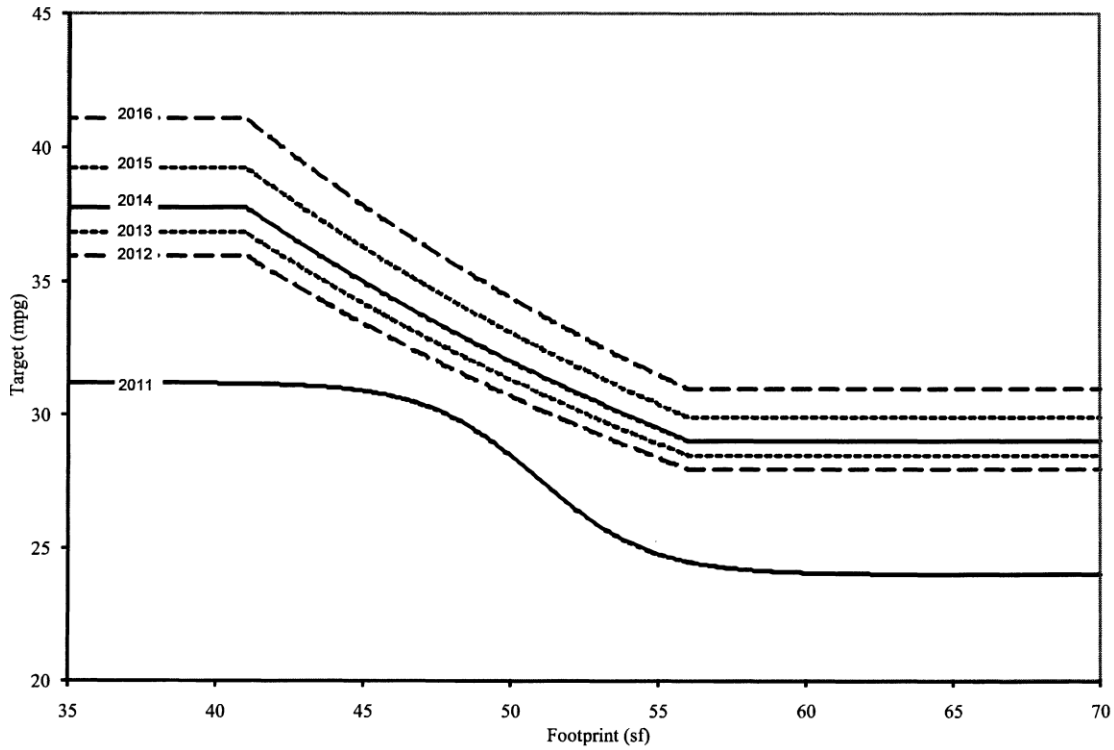

Figure 6.2. Model year 2011-2016 passenger car fuel economy targets [15].

While automakers may have some latitude to cross-subsidize losses in one classification with profits in another, such product slate strategies are unlikely to be sustainable over the ensuing decade. In terms of possible future study, two scenarios are envisioned that could leverage these insights toward improved projections of future market responses. First, trends could be extrapolated with the assumption that their response during recent years will continue along some analytically-derived trajectory with respect to price and FAER. In a second scenario, a compliance constraint could be imposed, whereby price and FAER are permitted to deviate from current trajectories in order to satisfy regulatory requirements. These scenario analyses would be valuable as they would quantify the implications of future compliance tradeoffs for all stakeholders. Additional controls and external factors such as the price of fuel, actual vehicle selling prices, and other macro-economic data could be included as appropriate.

The hedonic modeling of Chapter 3 is viewed together with the benefit-cost modeling of Chapter 4 to provide an improved understanding of consumers' implicit valuation of fuel economy. Table 6.2 summarizes key results of the analysis in these two chapters as organized again by vehicle classification. For this comparison, prices associated with a 4.3% fuel economy increase are modeled because that level represents the average *annual* increase called for by CAFE regulations on passenger cars in the 2014-2018 time frame.

Table 6.2. Prices associated with a 4.3% increase in fuel economy by various estimation methods.

				Estimation Method and [Source]				
				Hedonic Modeling	**Benefit-Cost, Implicit**	**Benefit-Cost, Breakeven**	**NHTSA**	**EPA**
Vehicle Classification	**Market Share** (%) 2014	**Footprint Range** (sq ft) Min	Max	[Chapter 3] 2014$ WTP	[Chapter 4] 2014$ WTP	[Chapter 4] 2014$ IRPE	[15] 2014$ IRPE	[15] 2014$ IRPE
Sub-Compact	9	26.8	42.0	584				
Compact	30	42.1	44.7	271				
Midsize, Lower	23	44.8	46.9	414				
Midsize, Upper	29	47.0	49.0	42				
Compact + Midsize	82	42.1	49.0		370	190-266		
All passenger cars	100	26.8	56.4	349			201	205

The hedonic modeling column of Table 6.2 quantifies the observation above that 2014 consumers in the upper footprint bin of the midsize class had very little willingness to pay for fuel economy, whereas sub-compact buyers had a great deal. The "benefit-cost, implicit" column of Table 6.2 suggest that consumers who opted to purchase fuel economy were willing to pay slightly more for it as compared to the average WTP among all passenger cars predicted by the hedonic modeling. This is in part because the benefit-cost study specifically evaluated fuel saving technologies among the top 20 best-selling vehicles, whereas the hedonic pricing study reflected all technologies across the entire passenger car market. The break-even column suggests that consumers' benefits and costs would be equal within a price range of about $190 to $266 under baseline assumptions, which includes initial gasoline prices at $2.50 and $3.50 per U.S. gallon respectively (please see Chapter 3 for all the baseline assumptions). One eventual implication of this for OEMs is that new technologies may not be commercially viable if consumers' benefits are lacking, or if consumers' real or implied willingness to pay does not offset the costs of delivering new technologies.

Also shown for reference in Table 6.2 are NHTSA and EPA estimates of the average increase in vehicle prices associated with an annual 4.3% increase. These prices reflect the incremental vehicle cost estimates from government agency analyses marked up by a standard retail price equivalent multiplier value of 1.5 to account for automaker and supply chain profits [156]. It is of note that prices estimated by the federal agencies are toward the low end of the break-even estimates, suggesting that consumers would largely benefit from investing in fuel economy technologies at these levels. Not reflected in Table 6.2 are the true manufacturing costs or OEM retail prices associated with the given level of fuel economy increase, which could be much higher than government estimates judging from market-based incremental retail price equivalents and reasonable RPE multipliers. While selected groupings of current passenger car consumers may be more willing to pay for fuel economy today than technology price estimates by regulators, results are highly sensitive to fuel prices, miles driven and interest rates. As a result, further study is required to assess future technology costs and their implications on economic practicability.

While this investigation has concentrated on passenger cars, fuel saving technologies in light duty trucks are an active area of research that have significant implications on the energy consumption and emission of future fleets. In 2014, trucks accounted for about 50% of new light duty vehicle sales in the U.S. market and a disproportionately larger share of transportation fuel consumption [122]. The methodologies presented in this dissertation can be readily applied to similar light duty truck investigations in the future. The light duty truck segment is less homogeneous than passenger cars, with a much wider slate of utility attributes and uses, presenting challenges to research efforts.

As compared to passenger cars, the correlation between consumer utility and fuel economy appears to be much weaker, and light truck consumers often replace an interest in acceleration with demands for torque, towing, and off-road use. Such demands typically require greater fuel consumption whether or not they are needed on an everyday basis. Figure 6.3 shows sales-weighted data comparing vehicle technologies and their associated impact on fuel economy for light duty pickup trucks.

It has a uniquely different characteristic than the passenger car profiles evaluated in Chapter 4.

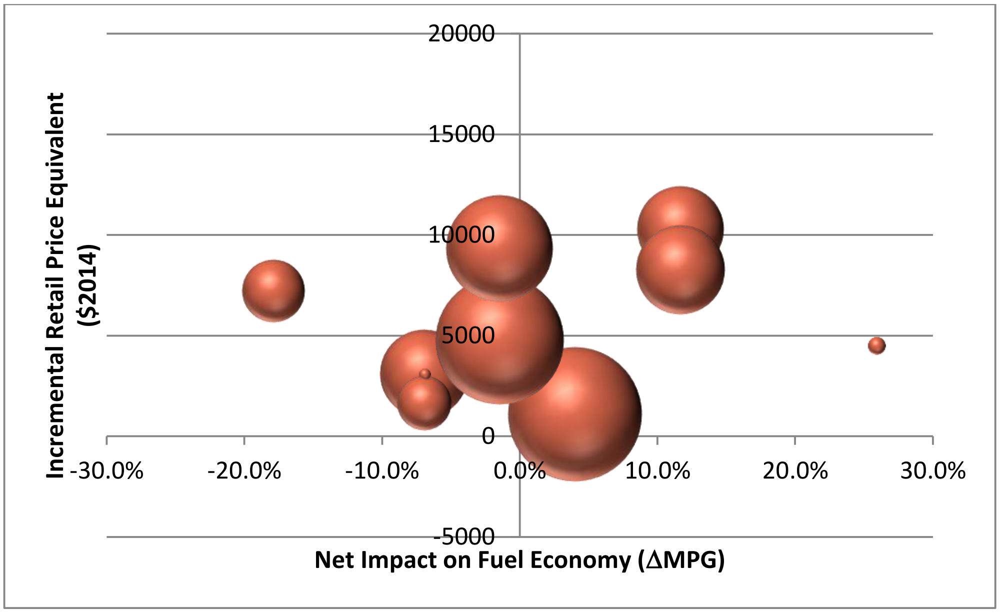

Figure 6.3. Cost of pickup truck technologies that impact fuel economy, sales-weighted.

On the other hand, profit margins in this vehicle segment have traditionally been superior to cars, suggesting that substantial opportunities for economic optimization in view of fuel economy regulations are possible. Finally, from a fleetwide policy perspective, it is obvious that the largest absolute levels of fuel and emissions reductions are likely to result from improvements to vehicles with the lowest fuel economies. Due to the increasing number of fuel saving technologies being deployed in passenger cars, and the conventional wisdom that early efficiency gains are often the most impactful and lowest cost, leveraging the forgoing research toward light truck analysis would be timely and have considerable merit.

6.2 Energy Consumption, Emissions and Locality: Synthesis, Implications and Future Work

Chapter 5 quantified the energy sensitivity of advanced vehicle architectures to operational driving demands, ambient temperature as well as other locality-dependent factors. A key contribution is the iterative simulation algorithm that predicts vehicle energy consumption as a continuous function of outdoor temperature. Using driving schedule weightings based upon established regulatory conventions, this contribution facilitates comparison of vehicle energy consumption from the thermodynamic system boundary of the fully-fueled or fully-charged vehicle. The simulation matrix accommodated five unique vehicle architectures, up to ten driving cycles capable of multiple consecutive replications, and a continuous range of temperatures. The multi-step simulations involving propulsion and thermal energy subroutines were performed at very low cost with efficient use of computational capacity and time. The methodology readily accommodates temporal simulation of vehicle performance under seasonal weather conditions for selected cities.

The introduction of the energy consumption locality multiplier (ECLM) is another important contribution that can be viewed as the number by which to multiply the rated energy consumption to adjust for locality. While HEV, PHEV and EV have substantially lower energy consumption from the thermodynamic basis of the vehicle itself, this research identifies the magnitude of variations attributable to combined thermally-induced battery and resistive loads. By accounting for additional locality-dependent factors such as electricity generation profiles, transmission and distribution losses, and petroleum refining characteristics, simulations of system equivalent energy consumption and emissions are presented.

The study reveals that at 35°C, EV energy consumption can increase by up to 20% relative to a 7% increase for conventional vehicles; at -7°C, the increase can be as high as 50%. Annualized integration of this temperature-dependence reveals that vehicle-based energy consumption can vary 2-3% by locality for internal combustion vehicles, 12-13% for hybrids, and up to 18% for EV. Extension of energy use to include upstream factors reveals that system-equivalent variations reach 7% by locality for internal combustion vehicles, 11-12% for hybrids and 45-70% for electric vehicles. Depending on the weather and utility profiles of the city, the variation in system-equivalent CO_2 emissions for EV ranges from a 70% improvement to no improvement as compared to conventional vehicles.

A major implication of this study is that on a thermodynamic basis, hybrids perform extremely well in a wide range of operating conditions. The comparative analysis conveys that battery size and capacity are critical factors in trading-off primary benefits of hybrids, PHEVs and EVs such as kinetic energy recapture and engine shut-off capabilities against certain drawbacks including increased thermal management demands, resistive losses, limited range and potentially reduced acceleration. Another important implication of the research is that in spite of generally superior performance, all vehicle technologies are certainly not optimized for use in all localities. The extent of their suitability by type and locality is quantified.

Three areas of future work can be organized under technological, economic and policy studies. Research to extend the scope of the present work could readily investigate PHEVs with differing all-electric range or duty cycles, as well as EVs that use active cooling and ICE vehicles with downsized and turbocharged engines.

Because the models have been developed parametrically, variations in vehicle mass and power and their impacts could readily be explored. An investigation of the various control schemes used to optimize energy consumption in various vehicle-locality-drive cycle combinations would also be of great value. There is a growing literature to address optimized control strategies, and multi-variable optimization should extend beyond energy consumption to include a consideration of overall costs for ownership and operation as well as the implications of time-of-day charging on energy efficiency, emissions and costs. Thus, many of the potential pathways to additional work require a system-level approach, and perhaps include experimental analysis to corroborate and tune estimates of simulated performance.

In terms of follow-on economic analysis, the author has developed useful first order discounted cash flow rate of return models to estimate comparative costs of ownership and operation associated with advanced vehicles. An example is shown in Table 6.3 derived from the author's independent work disclosed in [30].

By combining the system-equivalent energy and emissions methodology of Chapter 5 with economic models, a more complete assessment of total system operating costs could be readily prepared. Such a study would introduce locality-dependent economic factors including the price of energy commodities and federal, state and local incentives and subsidies. In this way, uncertainty would be reduced via sensitivity analysis and via locally appropriate assumptions. The impact of subsidies can be significant, as shown in Table 6.3, where the Federal $7500 subsidy [82] is sufficient to reduce the total cost of ownership and operation of the Nissan Leaf such that it becomes the most financially attractive option in the simple illustrative comparison with other vehicle technologies. Absent such subsidies, which are federally capped by OEM unit sales, the estimated ownership and operation costs for the Nissan Leaf are approximately 30% higher.

Table 6.3. Comparative estimated costs of ownership and operation for representative vehicle technologies, 2013 model year.[37]

Vehicle Type	Example Make/Model	Federal $7500 Subsidy?	2013 MSRP (2013$)	Operating Cost Per Mile Scenario 1[38] $/mile	Operating Cost Per Mile Scenario 2[39] $/mile	EPA Label Fuel Economy mpg / mpg_e
Gasoline	**Ford Focus**	**No**	$16,200	$0.365	$0.462	31
Diesel	**VW Jetta TDI**	**No**	$22,990	$0.462	$0.538	34
Hybrid	**Toyota Prius**	**No**	$24,200	$0.427	$0.487	50
EV	**Nissan Leaf**	**No**	$28,800	$0.445	$0.455	115
EV	**Nissan Leaf**	**Yes**	$21,300	$0.339	$0.349	115
PHEV[40]	**Chevy Volt**	**No**	$39,145	$0.624	$0.661	67
PHEV[40]	**Chevy Volt**	**Yes**	$31,645	$0.518	$0.551	67

This field of research stands to benefit greatly from more coordinated economic and policy assessment. As an example, in addition to the large Federal subsidy available for PHEV and EV with sufficiently large batteries (>12 kWh), many direct and indirect state incentives are also available.

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[37] Assessment assumes a seven year life (84,000 miles) and residual value at end of life equal to twenty percent of initial capitalized cost (in nominal terms). Operating cost calculations include ownership and energy operating costs only. Assumed are a nominal discount (interest) rate of eight percent; inflation rate of two percent; annual real price increase for gasoline, diesel, and natural gas of three percent; annual real price increase for electricity of one-half percent. MSRP represents manufacturer's suggested retail price in US market in then-current 2013 dollars. Additional information available in [30]. Federal subsidy of $7500 applies to PHEV and EV of >12kWh [82].

[38] Scenario 1 sets initial (year 1) fuel/energy prices as follows: gasoline at $3.50/gal; diesel at $3.85/gal; electricity at $0.12/kWh

[39] Scenario 2 sets initial (year 1) fuel/energy prices as follows: gasoline at $6/gal; diesel at $6/gal; electricity at $0.15/kWh.

[40] PHEV assumes operation in EV/Gasoline modes at 64/36 share.

Table 6.4 shows several representative states and the respective estimated emissions for the vehicle architectures discussed in Chapter 5. It also includes columns for total consumer subsidies for PHEV and EV which combine the Federal $7500 subsidy with direct state subsidies that were available in 2014.

Table 6.4. Notional state-level comparison of estimated vehicle emissions and relevant subsidies.

STATE	**ICE-SI** **Emissions** $gCO2_{eq}/km$	**ICE-CI** **Emissions** $gCO2_{eq}/km$	**HEV** **Emissions** $gCO2_{eq}/km$	**PHEV** **Emissions** $gCO2_{eq}/km$	**Total Subsidy for PHEV** 2014$	**EV** **Emissions** $gCO2_{eq}/km$	**Total Subsidy for EV** 2014$
CALIFORNIA	194	196	131	101	$9,000	59	$10,000
COLORADO	203	205	143	209	$12,500	203	$13,000
GEORGIA	189	191	132	158	$7,500	138	$12,500
ILLINOIS	199	201	140	180	$11,400	165	$10,500
MISSOURI	199	200	140	200	$7,500	193	$7,500
PENNSYLVANIA	190	191	133	155	$9,500	134	$9,500
TEXAS	198	199	139	151	$7,500	123	$7,500
WASHINGTON	196	198	135	123	$9,500	87	$7,500

Notes: Information on Federal subsidy available in [82] and State subsidies in [157]. Estimated emissions rates by vehicle and state drawn from the analysis in Chapter 5.

An initial observation of the data in Table 6.4 is that states' efforts to incentivize the purchase of PHEV and EV may not categorically be well-aligned with the potential energy and emissions impacts predicted by this study. While many states, like California and Washington have comparatively clean grids that can best leverage the benefits of PHEV and EV, other states such as Colorado or Illinois appear to have aggressive fiscal supports in spite of potentially neutral or adverse emissions impacts.

A simple financial analysis is performed for a few representative states to determine the implicit cost of carbon based upon the avoided emissions and the combined federal and state subsidy. The results are shown in Table 6.5.

Table 6.5. Implicit Cost of Carbon for PHEV and EV Subsidies in Selected States.

STATE	PHEV Avoided Emissions vs. ICE-SI gCO2eq/km	Total Subsidy for PHEV 2014$	Implicit Cost of Carbon $/MT	EV Avoided Emissions vs. ICE-SI gCO2eq/km	Total Subsidy for EV 2014$	Implicit Cost of Carbon $/MT
CALIFORNIA	93	$9,000	$573	135	$10,000	$439
COLORADO	-6	$12,500	UNDEF	-1	$13,000	UNDEF
GEORGIA	32	$7,500	$1,434	52	$12,500	$1,452
ILLINOIS	19	$11,400	$3,556	34	$10,500	$1,830
MISSOURI	-1	$7,500	UNDEF	6	$7,500	$7,407
PENNSYLVANIA	35	$9,500	$1,608	56	$9,500	$1,005
TEXAS	47	$7,500	$946	75	$7,500	$593
WASHINGTON	73	$9,500	$771	109	$7,500	$408

Notes: For this analysis, it is assumed that the real interest rate is 7%, the inflation rate is 2%, vehicle life is 18 years, VMT are 13,851 in years 1-2, 12,042 in years 3-5, 10,741 in yrs 6-9, and 7,401 for each successive year as per [136].

Table 6.5 demonstrates the utility of this techno-economic approach in quantifying estimated carbon costs associated with relative emission improvements and subsidies of advanced vehicles. This analysis makes it clear that even the low-end estimates begin at about $400/ton, a level that is an order of magnitude greater than U.S. government estimates for the Social Cost of Carbon (SCC) [158]. The $400/ton range is also up to several times greater than estimates for carbon prices implied by stationary electrical power technologies. Table 6.5 also shows that certain states have implicit carbon prices well in excess of $1000/ton, and that some have undefined values given that the avoided emissions of PHEVs and EVs are effectively zero as compared to an ICE-SI vehicle baseline. While there are other motivations for incentivizing advanced vehicles beyond emissions reductions such as energy diversification, this type of analysis serves a critical purpose in assessing the alignment of technology and economics with policy mechanisms. This admittedly broad field of research can benefit greatly by emphasizing the need to coordinate a wide array of scientific studies and findings with economic and policy research, so as to have a greater impact and avoid any negative consequences of government policies.

6.3 Closing Thoughts

The findings in this dissertation confirm that technological improvements are responding to stringent fuel economy regulations, a more informed consumer base, and social concerns regarding constraints and environmental impacts associated with energy used for transportation. Clearly innovation in vehicle efficiency has and will continue to play a vital role in the reduction of sector energy and emissions. Today’s passenger cars deliver increasing value at stable and affordable prices in each successive year. The set of characteristics that contribute to utility, such as performance, safety, fuel economy, and aesthetic value, has not changed substantially in domestic markets, but consumers’ relative weighting and implicit valuation of them certainly have.

The findings presented in this dissertation are nuanced, since technological deployment is a driving force behind energy reductions, but sustained fleet-wide gains will be complicated, time consuming, and costly. EPA assessments of the policies suggest that such costs are controllable and outweighed by benefits [15,27,156]. Increased Corporate Average Fuel Economy (CAFE) standards are indeed facilitating research, development and deployment of higher efficiency internal combustion engines, reductions in vehicle weight and friction, and unprecedented levels of advanced hybrid and electric powertrains.

Research-spawned, market-driven, and policy-guided innovation is not bound by a single approach, powertrain, or energy resource. Despite obvious inherent limitations, internal combustion engines and petroleum-derived fuels have unique capabilities that remain dominant in today's global fleet. Advancements in engine efficiency are being leveraged synergistically with hybrids to enable emerging technologies [16]. The commercial success of HEVs has leveraged dramatic reductions in energy consumption and emissions while offering the consumer little or no compromise in performance. In the span of a single decade, HEVs have demonstrated fuel economy increases of 50% over similarly sized conventional vehicles. ICE technology will advance and complement future hybrid technologies [16]. EVs will continue to face challenges associated with range, infrastructure, and costs, and will need to scientifically demonstrate increasing levels of overall efficiency and value to compete with conventional vehicles on a stand-alone basis. Energy and emissions accounting for new vehicle classifications must improve to ensure that the intended benefits are truly bankable.

Despite the tremendous progress on the technological front, economic considerations imply that oil price volatility presents substantial challenges to all stakeholders. The findings of the dissertation demonstrate how consumer benefit cost ratios can flip from favorable to unfavorable merely on the basis of fuel price uncertainty. At the same time, consumers' willingness to pay for fuel economy is highly correlated to the regulatory context. It has also been demonstrated that future costs will hinge largely on market factors which ultimately will determine the value of a given technology and the future worth of associated energy savings.

An overarching theme worth re-emphasizing is that no single research discipline is likely to fully address the broad challenges of energy in transportation. As such, this dissertation presents coordinated approaches and perspectives, from rigorous technological and economic analyses, to the critical implications of policy. It is the author's hope that this dissertation, its methodologies, findings, and their implications will contribute not only to continued research, but also to constructive dialogue and meaningful action, especially as a means to more fully equip decision-makers in the near term. Efforts to objectively and comprehensively assess the balance of cross-cutting trade-offs toward better and better system outcomes are particularly needed. It remains clear that fossil-fuel based transportation will not be sustainable in the long run, and that a diversity of options over time will be imperative. Efforts to conserve must become second nature, as efforts to consume less are encouraged and regulated, while longer term solutions are invented and executed.

And thus, we arrive at both the conclusion and the commencement of this work. Work that most certainly includes continued investigation and research; but also an equal share of scientifically-informed, conscientious, and intentional action. As my father says, it's time to walk and chew gum. As my mother says, look both ways. As my wife says, don't be late, but be sure to enjoy the ride. As my daughter says, a kid's work is never done. And the journey beckons still.

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APPENDICES

Appendix A Definitions and Approaches for Estimating Fuel Economy, Fuel Consumption, Energy Consumption and Emissions

In the United States, fuel economy is a familiar vehicle characteristic and is expressed in miles per U.S. gallon (mpg) of gasoline or diesel fuel. The Environmental Protection Agency (EPA) utilizes three different definitions for fuel economy depending on the context and use. These include: EPA laboratory test fuel economy, EPA adjusted fuel economy, and the National Highway Traffic Safety Administration (NHTSA) Corporate Average Fuel Economy (CAFE) [13-15]. These represent the estimate determined by standardized dynamometer evaluation, the adjusted value to correct for real-world driving, and the value used to calculate regulatory compliance by automaker, respectively.

In many other regions of the world, including continental Europe, a fuel consumption value, or fuel consumed to travel a given distance, is more commonly reported, often in units of liters per 100 kilometers (L/100km). The conversion is straightforward and is given by:

$$FE = \frac{235.21}{FC} \tag{A.1}$$

In Eq. (A.1), FE represents fuel economy in miles per U.S. gallon and FC represents fuel consumption in units of Liters per 100 km (L/100km). While the conversion is straightforward, the inverse scales are different ways of relating to efficiency or consumption respectively, and can give rise to confusion.

Fuel or energy consumption per distance travelled for hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs) operating in gasoline-only or “charge sustaining" (CS) mode can be directly compared with conventional internal combustion engine propelled vehicles. However, PHEV or electric vehicle (EV) operation in "all-electric" or "charge depleting" (CD) mode introduces substantial unknowns related to the native energy source employed for electric charging. As noted in Section 1.5, the concept of equivalent fuel economy has been introduced in order to provide a baseline reference from the standpoint of the vehicle boundary itself. Expressions for converting between energy consumption per unit distance travelled and equivalent fuel economy are given as:

$$EC_{kWh/km} = \frac{20.9}{MPG_e} \tag{A.2}$$

$$EC_{kWh/mi} = \frac{33.7}{MPG_e} \tag{A.3}$$

In Eq. (A.2), $EC_{kWh/km}$ represents energy consumption in units of kWh/km and MPG_e represents equivalent fuel economy in units of miles per U.S. gallon equivalent. The numerator represents the calorific value of gasoline per unit volume. In Eq. (A.3), $EC_{kWh/mi}$ has units of kWh/mi, but all other terms are the same as Eq. (A.2). To make these conversions for vehicles with diesel engines, the numerators would be multiplied by about 1.11 to account for the greater volumetric energy density of diesel fuel.

It should be noted that MPG_e can be a source of potential confusion [16-17] because it excludes consideration of energy sources upstream of the vehicle itself. From a thermodynamic perspective, it is essential to evaluate energy efficiency using consistent system boundaries, methodologies and bases regardless of the upstream energy resource. The Department of Energy (DOE) studied U.S. average fossil-fuel electricity generation efficiency in 2000, determining it to be approximately ≈ 0.328 [79] and suggesting a method for calculating a petroleum-equivalency factor (PEF) that would provide an incentive to vehicles that employ electricity. The PEF is equal to 1/0.15, or about 6.7, as is intended to incentivize OEMs to produce and sell electric vehicles, and provide opportunities for significantly boosting CAFE compliance. The factor, however, does not accurately reflect the energy intensities of EV vs. ICE vehicles, nor does the mpge rating.

For this reason, lifecycle energy and emissions analyses are invaluable to researchers and development engineers. However, many of today's consumers and even some policymakers are less familiar with these approaches suggesting that cross-cutting studies should remain scientifically rigorous yet capable of being readily understood by broader audiences. As such, the present work approaches the measurement and comparison of vehicular energy efficiency in a robust yet pragmatic manner.

As with energy efficiency, the measurement of vehicle emissions has traditionally been very straightforward due to the dominance of petroleum fuels in passenger cars. Tailpipe emissions estimates per unit volume are given in [18-21] for the complete combustion of gasoline, diesel and ethanol. Emissions accounting must also use consistent system boundaries, methodologies and bases regardless of the upstream energy resource. As noted in Chapter 1, source emissions have signatures tied to the relevant energy conversion technologies and can be approximated from sub-region data for domestic utility networks as described in the EPA eGrid 2010 assessment [22]. Though vehicle operation generally results in a variety of gaseous and particulate emissions, this study will primarily focus upon equivalent CO2 emissions (CO2eq). As with energy efficiency, vehicle-related emissions are also be shown to have distinctive regional implications.

With the increasing demand for and innovation in advanced vehicle architectures, it is imperative to understand that a vehicle's energy use is highly sensitive to a number of variable and potentially compounding factors including powertrain technology, auxiliary power for heating, cooling and electronics, ambient temperature, locality, and driving cycle. In addition to robust energy and emission accounting methodologies, the research employs standardized drive cycles to assess vehicle operation and response. Numerous standardized driving cycles have been established to mimic scenarios representative of the real-world, such as stop-and-go, city, highway, aggressive, and comprehensive modes of driving. Their use therefore improves replicability and makes direct comparisons possible. In this dissertation, standardized EPA driving cycles and their relative weightings have been employed to facilitate such comparisons.

Finally, as noted in Section 5.5, the energy consumption comparisons among unlike sources of energy in Chapter 5 are performed purely on a thermodynamic basis. In other words, the geopolitical and energy security impacts of using petroleum vis-à-vis other energy sources have been neglected. In reality, second order considerations do exist, particularly as it relates to energy operating costs. However, given the emphasis of Chapter 5 on vehicle-level and system equivalent energy consumption, this assumption is deemed appropriate for comparison purposes. The comparative assessment of emissions uses a standard practice by comparing common units of $CO2_{eq}$, which are broadly understood and widely used, regardless of the energy source.

Appendix B Regression Results of Hedonic Price Modeling for 2013 Data

Table B.1. Regression results of the 7-parameter model on 2013 MY data using Eq. (3.9).

Vehicle Category		**All Cars**	**Sub-Compact**	**Compact**	**Midsize, Lower Half**	**Midsize, Upper Half**	**Full Size**
Model Year		2013	2013	2013	2013	2013	2013
Footprint (FP) Min		26.8	26.8	42.1	44.8	47.0	49.1
Footprint (FP) Max		56.4	42.0	44.7	46.9	49.0	56.4
FP, Wtd. Mean		45.7	39.2	43.6	45.9	47.8	51.5
Data Set		2013	2013	2013	2013	2013	2013
MSRP, Wtd. Mean		$27,007	$19,995	$22,047	$27,806	$28,360	$44,442
Sales Vol., Units		8,055,136	658,169	2,423,371	1,935,687	2,355,216	682,693
Sales Revenue, $B		217.5	13.2	53.4	53.8	66.8	30.3
Response Variable		ln(MSRP)	ln(MSRP)	ln(MSRP)	ln(MSRP)	ln(MSRP)	ln(MSRP)
Hedonic Model		Eq. (3.9)	Eq. (3.9)	Eq. (3.9)	Eq. (3.9)	Eq. (3.9)	Eq. (3.9)
Estimator		WLS	WLS	WLS	WLS	WLS	WLS
Observations		759	121	160	159	156	163
R^2		0.775	0.791	0.737	0.795	0.748	0.648
Attribute	**Coeff.**	**Param. Est.** (Std. Error)	**Param. Est.** (Std. Error)	**Param. Est.** (Std. Error)	**Param. Est.** (Std. Error)	**Param. Est.** (Std. Error)	**Param. Est.** (Std. Error)
Intercept	β_0	**2.584*** **	**3.990** **	**0.993**	**0.742**	**-2.560** **	**-10.555*** **
		(0.466)	(1.749)	(0.979)	(1.069)	(1.186)	(2.424)
ln(FC)	β_1	**-0.393*** **	**-0.657*** **	**-0.339*** **	**-0.406*** **	**-0.302**	**-2.276*** **
		(0.047)	(0.133)	(0.060)	(0.125)	(0.075)	(0.300)
ln(ACCEL)	β_2	**-0.577*** **	**-0.807*** **	**-0.369*** **	**-0.647*** **	**-0.504*** **	**-2.052*** **
		(0.053)	(0.136)	(0.081)	(0.127)	(0.082)	(0.229)
ln(CWT)	β_3	**1.312*** **	**1.266*** **	**1.466*** **	**1.586*** **	**1.965*** **	**4.014*** **
		(0.055)	(0.222)	(0.119)	(0.148)	(0.161)	(0.351)
RWD	β_4	**0.219*** **	**0.588*** **	**0.356*** **	**0.254*** **	**0.175*** **	**0.048**
		(0.023)	(0.076)	(0.064)	(0.050)	(0.055)	(0.061)
AWD	β_5	**0.249*** **	**0.195**	**0.024**	**0.237*** **	**0.193*** **	**0.244*** **
		(0.026)	(0.154)	(0.047)	(0.053)	(0.047)	(0.068)
TRIMBASE	β_6	**-0.098*** **	**-0.120*** **	**-0.091*** **	**-0.105*** **	**-0.062*** **	**-0.004**
		(0.014)	(0.032)	(0.020)	(0.030)	(0.023)	(0.052)
TRIMPREM	β_7	**0.094*** **	**0.129*** **	**0.111*** **	**0.089*** **	**0.066*** **	**0.027**
		(0.015)	(0.041)	(0.028)	(0.028)	(0.025)	(0.052)

Appendix C EPA Fuel Economy Computation

Appendix C presents formulae for computing official city, highway and combined fuel economy label estimates per the U.S. Environmental Protection Agency official rule [14].

$$CityFE = 0.905 * \left(1 / \left(StartFC + RunningFC_{City}\right)\right) \tag{C.1}$$

$$RunningFC_{City} = 0.82 * \left[\frac{0.89}{FE_{FTP\_75}} + \frac{0.11}{FE_{US06City\_75}}\right] + 0.18 * \left[\frac{1}{FE_{FTP\_20}}\right] + 0.14 * \left[FC_{AC}\right] \tag{C.2}$$

$$HighwayFE = 0.905 * \left(1 / \left(StartFC + RunningFC_{Hwy}\right)\right) \tag{C.3}$$

$$RunningFC_{Hwy} = 1.07 * \left[\frac{0.79}{FE_{US06\_Hwy\_75}} + \frac{0.21}{FE_{HWFET\_75}}\right] + 0.05 * \left[FC_{AC}\right] \tag{C.4}$$

In Eqns. (C.1-C.4) above, FE=Fuel Economy and FC=Fuel Consumption. Subscripts represent either driving cycles and/or non-standard ambient temperature modes where the number following an underscore indicates the test temperature in °F. The default temperature is 75°F (23.8°C) even if not indicated explicitly. In estimating combined fuel economy, the share of city/highway driving is assumed to be 43/57 for label protocols as per [14]. This differs from the 55/45 allocation used in the calculations of CAFE compliance, which are derived merely from two-cycle lab dynamometer test results [13-15].

Appendix D Share Allocations of Vehicle Miles Traveled

Appendix D presents data used to determine share allocations for hourly and daily vehicle miles traveled (VMT) for annualized averages of energy consumption.

Share allocations for hourly VMT. Figure D.1 is derived from the 2009 Summary of Travel Trends (NHTSA, Santos et al. [136]) and is used to determine the share allocations for hourly VMT during a typical day. The report presents a distribution of vehicle trips by start time of trip. For the purposes of this study, it is assumed that start times by hour as a fraction of total start times in a day roughly equate to the fraction of the day's driving occurring in a given hour. The average daily distance driven is not considered or needed for our estimate of average energy consumption. We simply use the hourly fraction of use as a function of the total day's use (in this case the sum of hourly shares for a full day is unity).

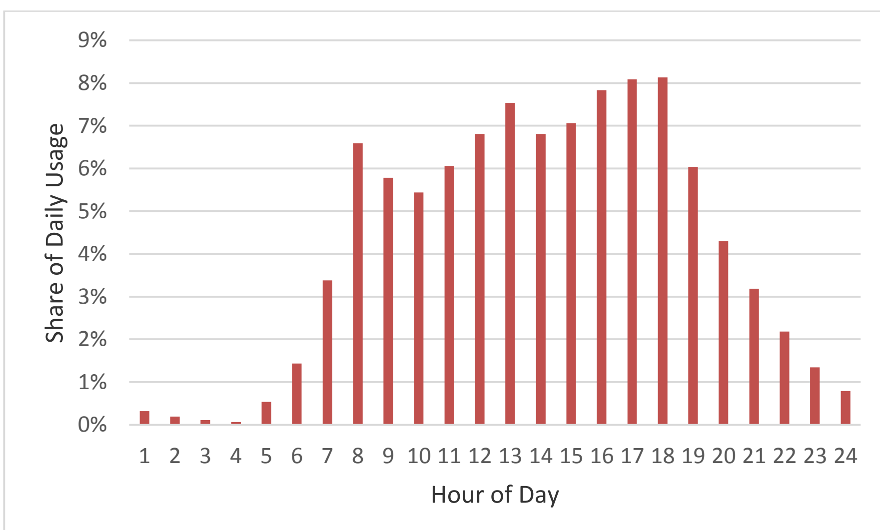

Figure D.1. DOT data used to determine χ_q, the hourly fraction of a given day's VMT.

Share allocations for daily VMT. Figure D.2 is derived from the U.S. Environmental Protection Agency, Final Technical Support Document- Fuel Economy Labeling of Motor Vehicle Revisions to Improve Calculation of Fuel Economy Estimates [14]. It shows the share of VMT by month for a typical year and is used to determine the share of VMT by day during a typical year. For the purposes of this study, it is assumed that the share of driving that occurs on a given day is the given monthly share divided by the number of days in the given month. The result is the daily fraction of use as a function of the total year's use (again, the sum of the daily shares for a full year is unity).

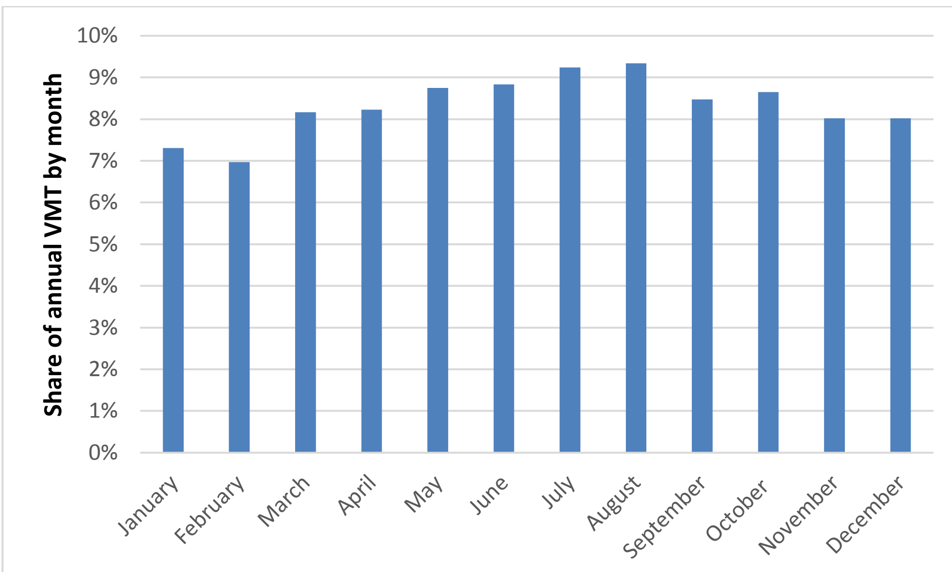

Figure D.2. Information used to determine χ_p, the daily fraction of the year's VMT, assuming consistent driving within each month. Source data from [14].

Appendix E Typical Meteorological Year Weather Data

Appendix E provides illustrative examples of Typical Meteorological Year (TMY) data used to determine ambient temperature inputs by locality.

Typical Meteorological Year (TMY) temperature data for selected cities. This plot illustrates temperature data from the National Renewable Energy Laboratory National Solar Radiation Data Base: 1991-2005 Update: TMY3 [148] for selected cities included in the study. Temperature at each locality and hour of the typical year is extracted for use in energy consumption calculations.

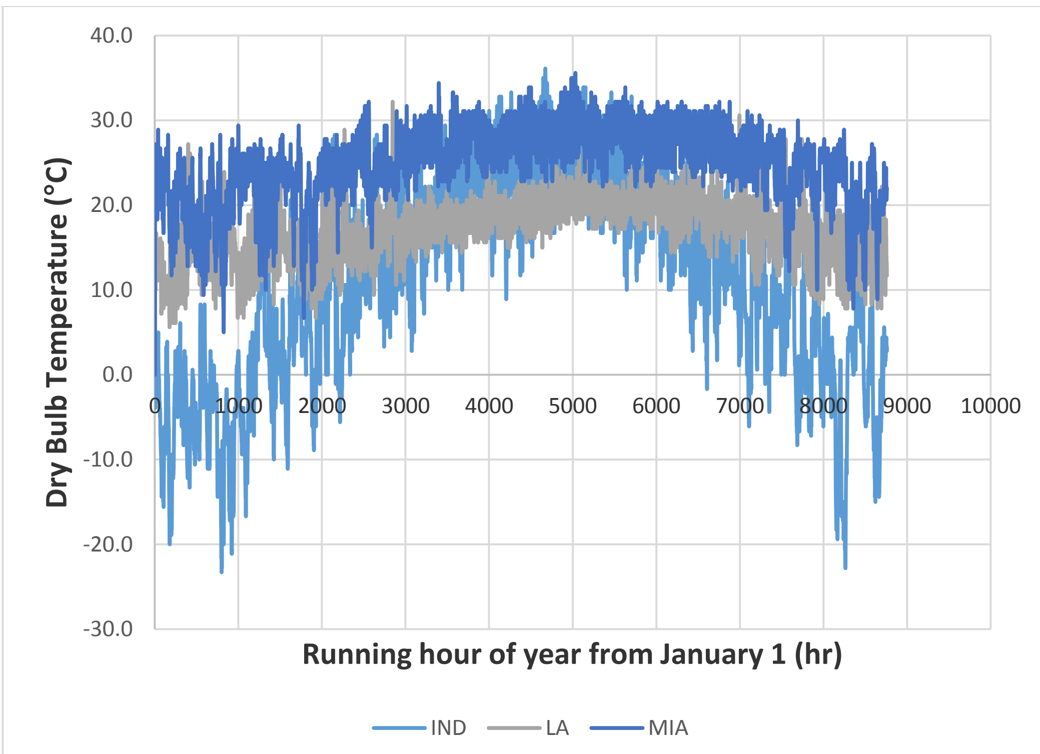

Figure E.1. Example of annual TMY3 temperature data for selected U.S. cities from NREL weather database. Source data [148].

Typical Meteorological Year (TMY) temperature data showing diurnal variations. This plot illustrates temperature data from the National Renewable Energy Laboratory National Solar Radiation Data Base: 1991-2005 Update: TMY3 [148] for the city of Indianapolis during a given two day period. The plot highlights the importance of considering both travel behavior and weather variation by hour and day. Again, temperature at each locality and hour of the typical year is extracted for use in energy consumption calculations.

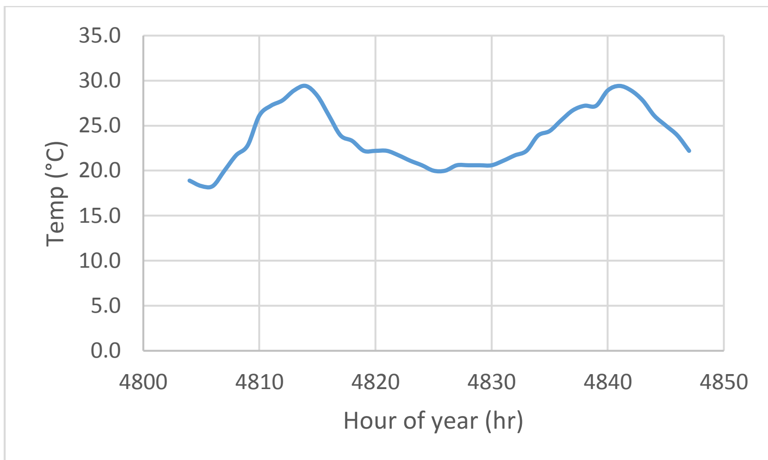

Figure E.2. Example of hourly TMY3 data for IND from NREL weather database. Source data [148].

Appendix F Standardized Driving Cycles

Appendix F illustrates target velocity vs. time profiles for a select few EPA driving cycles employed in vehicle energy consumption simulations [144]. Plots scales differ.

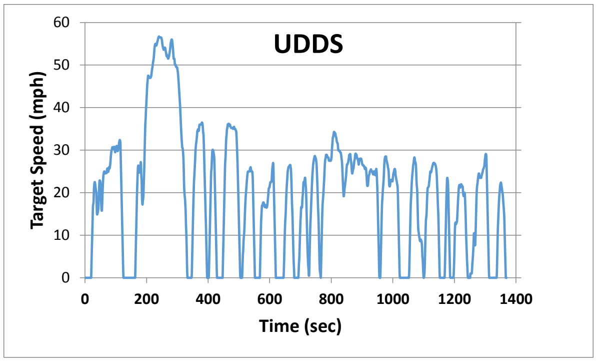

Figure F.1. Urban Dynamometer Driving Schedule (UDDS).

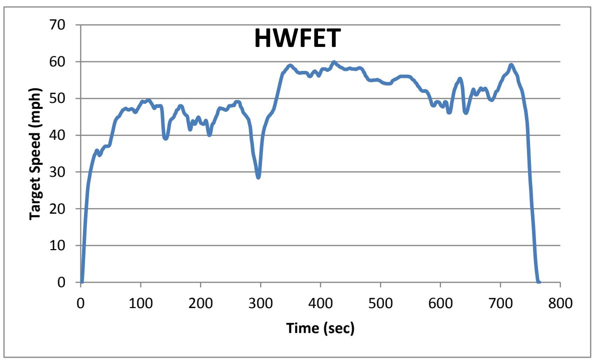

Figure F.2. Highway Fuel Economy Driving Schedule (HWFET).

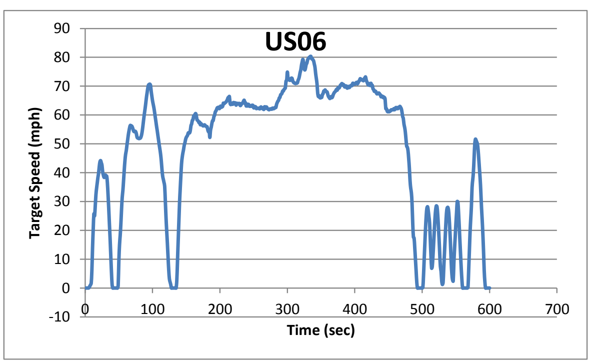

Figure F.3. Supplemental Federal Test Protocol, Aggressive Driving Mode (US06).

Appendix G Vehicle Energy Consumption and Emissions Supporting Data

Appendix G provides additional detail by city and vehicle type for the investigation presented in Chapter 5.

Results of ECLM by locality and vehicle type.

Table G.1. Estimated Energy Consumption Locality Multiplier (ECLM) by city and vehicle type.

	ICE-SI ECLM	**ICE-CI** ECLM	**HEV** ECLM	**PHEV-CS** ECLM	**PHEV-CD** ECLM	**PHEV** ECLM	**EV-PAC** ECLM
ATL	1.010	1.008	1.056	1.053	1.016	1.041	1.018
BAL	1.012	1.011	1.065	1.059	1.043	1.055	1.052
BOS	1.013	1.013	1.061	1.060	1.062	1.063	1.077
CHI	1.017	1.015	1.072	1.072	1.084	1.079	1.101
DAL	1.015	1.011	1.074	1.074	1.025	1.056	1.023
DC	1.013	1.012	1.063	1.062	1.040	1.056	1.047
DEN	1.015	1.014	1.070	1.070	1.063	1.070	1.075
DET	1.017	1.016	1.072	1.071	1.085	1.079	1.103
HOU	1.013	1.008	1.066	1.064	1.008	1.044	1.003
IND	1.017	1.015	1.072	1.072	1.080	1.077	1.095
LA	0.994	0.996	0.999	0.996	0.958	0.983	0.964
MIA	1.014	1.007	1.071	1.066	0.998	1.040	0.986
MIN	1.020	1.019	1.084	1.085	1.126	1.104	1.148
NYC	1.011	1.011	1.057	1.055	1.044	1.053	1.055
PHA	1.013	1.012	1.062	1.060	1.047	1.057	1.057
PHX	1.028	1.018	1.116	1.125	1.045	1.095	1.036
PIT	1.014	1.014	1.064	1.063	1.067	1.067	1.083
SD	0.995	0.996	1.002	0.998	0.957	0.983	0.961
SEA	1.006	1.009	1.039	1.038	1.025	1.035	1.039
SF	1.000	1.002	1.017	1.016	0.987	1.007	0.996
STL	1.016	1.013	1.071	1.071	1.058	1.068	1.068
TAM	1.012	1.006	1.064	1.061	0.998	1.038	0.990
MEAN	1.012	1.010	1.060	1.059	1.037	1.052	1.044
STDEV	0.008	0.006	0.026	0.028	0.042	0.031	0.049
MIN	0.994	0.996	0.999	0.996	0.957	0.983	0.961
MAX	1.028	1.019	1.116	1.125	1.126	1.104	1.148
Spread	0.034	0.023	0.117	0.129	0.169	0.121	0.187

Estimated U.S. electricity generation profile by source and share, 2013. This table presents estimates for the efficiency and share of electricity sources in the U.S. electricity generation matrix for 2013.

Table G.2. U.S. electricity generation profile by source, thermal efficiency, and share ca. 2013. Source data from: [152,153,159].

	Coal	Petrol.	NG	Nucl.	Hydro	Wind	Bio	Geo	Solar	Other
η Thermal	0.326	0.318	0.429	0.327	0.900	0.380	0.350	0.120	0.120	0.350
Share of US mix	0.389	0.007	0.280	0.194	0.065	0.041	0.015	0.004	0.002	0.065

Note: η Thermal represents the thermal efficiency on a first law energy basis with respect to the conversion of the energy resource (i.e., $Energy_{in}/Energy_{out}$). Petrol=Petroleum; NG=Natural Gas; Nucl.=Nuclear, Bio=Biomass, Geo=Geothermal.

Estimated system efficiencies and emissions by city.

Table G.3. Estimated system efficiencies and emissions associated with energy sources in U.S. localities.

CITY	Local System Efficiencies for:					Emissions associated with:		
	Liquid fuel		Grid-supplied electricity			Gasoline	Diesel	Electricity
	Refining	Transport	Generation	Transmission	Wall-Charging	$gCO2_{eq}/kWh$	$gCO2_{eq}/kWh$	$gCO2_{eq}/kWh$
[Source]	[151,19]	[21]	[152-153]	[22]	[150]	[154,132]	[154,132]	[22]
ATL	0.936	0.992	0.377	0.944	0.87	264	272	619
BAL	0.936	0.992	0.373	0.944	0.87	264	272	491
BOS	0.936	0.992	0.412	0.944	0.87	264	272	331
CHI	0.897	0.992	0.342	0.944	0.87	264	272	687
DAL	0.899	0.992	0.380	0.929	0.87	264	272	556
DC	0.936	0.992	0.373	0.944	0.87	264	272	491
DEN	0.878	0.992	0.364	0.932	0.87	264	272	867
DET	0.897	0.992	0.340	0.944	0.87	264	272	745
HOU	0.899	0.992	0.380	0.929	0.87	264	272	556
IND	0.897	0.992	0.341	0.944	0.87	264	272	687
LA	0.901	0.992	0.445	0.932	0.87	264	272	279
MIA	0.936	0.992	0.413	0.944	0.87	264	272	549
MIN	0.897	0.992	0.354	0.944	0.87	264	272	702
NYC	0.936	0.992	0.395	0.944	0.87	264	272	284
PHA	0.936	0.992	0.395	0.944	0.87	264	272	458
PHX	0.901	0.992	0.380	0.932	0.87	264	272	538
PIT	0.936	0.992	0.395	0.944	0.87	264	272	687
SD	0.901	0.992	0.445	0.932	0.87	264	272	279
SEA	0.901	0.992	0.733	0.932	0.87	264	272	385
SF	0.901	0.992	0.445	0.932	0.87	264	272	279
STL	0.897	0.992	0.341	0.944	0.87	264	272	828
TAM	0.936	0.992	0.413	0.944	0.87	264	272	549
US avg	0.902	0.992	0.394	0.938	0.87	264	272	563

The source data used to derive these estimates are drawn from the designated references indicated in the table.

Estimated system-equivalent energy consumption

Table G.4. Estimated system-equivalent energy consumption by locality and vehicle type.

CITY	ICE-SI	ICE-CI	HEV	PHEV-CS	PHEV-CD	PHEV	EV-PAC
	Wh/km	Wh/km	Wh/km	Wh/km	Wh/km	Wh/km	Wh/km
ATL	718	702	501	631	695	672	625
BAL	720	705	506	634	721	690	652
BOS	720	706	504	635	666	654	605
CHI	754	738	531	670	819	765	745
DAL	752	733	531	670	707	693	632
DC	720	705	505	636	719	689	649
DEN	770	753	542	683	765	735	693
DET	754	738	531	669	823	767	749
HOU	750	731	527	664	695	684	620
IND	754	738	531	670	818	765	743
LA	734	721	493	619	563	583	508
MIA	721	701	509	638	624	629	553
MIN	757	741	537	678	820	769	750
NYC	719	705	502	632	683	664	619
PHA	720	705	504	635	685	667	620
PHX	759	737	551	700	720	713	639
PIT	721	706	505	637	698	676	635
SD	735	721	495	621	562	583	506
SEA	743	730	513	646	366	467	332
SF	738	725	502	632	580	599	525
STL	754	737	531	669	801	754	725
TAM	720	701	506	635	624	628	555
MEAN	738	722	516	650	689	675	622
STDEV	17.2	16.6	16.9	22.5	108.6	74.5	100.0
MIN	718	701	493	619	366	467	332
MAX	770	753	551	700	823	769	750
Spread	51.4	52.3	57.8	80.2	457.0	302.5	417.5

Synthesized Energy Consumption Plot. This chart presents estimates for the energy consumption (EC) as given by the following methods: approximate equivalent energy consumption derived from CAFE compliance fuel economy values for representative vehicle m, $EC_{CAFE}(m)$; equivalent energy consumption derived from EPA fuel economy label calculations for vehicle m, $EC_{Label}(m)$; vehicle-basis results from the present study for vehicle m and city n, $EC_{Veh}(m,n)$; system-equivalent results from the present study for vehicle m and city n, $EC_{SysEq}(m,n)$. For the latter two scenarios, data points for all 22 cities are shown but not individually identified.

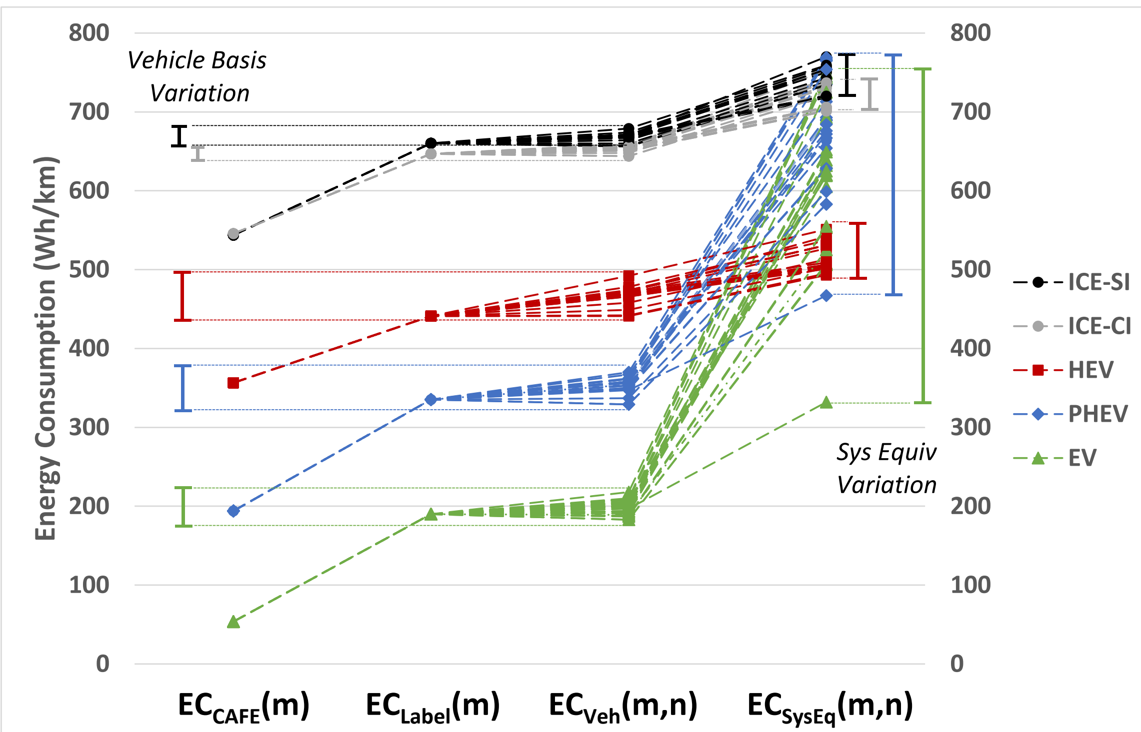

Figure G.1. Energy Consumption Estimates by Vehicle Type by Various Methods.

Appendix H Nomenclature

Table H.1. Nomenclature for Chapter 3.

Symbol	Definition
ACCEL	0 to 60 mph Acceleration Time, in seconds
ANOVA	Analysis of Variance
AWD	All Wheel Drive
CAFE	Corporate Average Fuel Economy
CPI	Consumer Price Index
CWT	Vehicle Curb Weight
FE	Fuel Economy
FC	Fuel Consumption
FP	Footprint of vehicle, sq ft
i	Given vehicle (or given year)
IWT	Vehicle Inertia Weight
j	Given attribute
kg	Kilogram
km	Kilometer
L	Liter(s)
m	Total number of attribute variables
m-n	Number of dummy variables
MPG	Miles Per Gallon
MSRP	Manufacturer's Suggested Retail Price
n	Number of continuous variables
Nominal Price	Price in nominal terms
OLS	Ordinary Least Squares
P_i	Purchase price, vehicle i
PWR	Rated engine power
R^2	Regression coefficient of determination
Real Price_1	Price, inflation adjusted by CPI: all items
Real Price_2	Price, inflation adjusted by CPI: new vehicles
RWD	Rear Wheel Drive
SS_{Error}	Error Sum of squares
SS_j	Sum of squares, attribute j
SS_{Model}	Model Sum of squares
SS_{Total}	Total Sum of squares
SS(F)	Type I Sum of squares for FC
SS(F|A)	Sum of squares, attribute FC given ACCEL
SS(F|C)	Sum of squares, attribute FC given CWT
SS(F|C,A)	Type III Sum of squares for FC
SS(F|A,C)	Type III Sum of squares for FC

Table H.1. Nomenclature for Chapter 3 (cont.).

Symbol	Definition
TRIMBASE	Base Trim Level
TRIMPREM	Premium Trim Level
Utility	Objective function for vehicle utility
U_i	Utility of vehicle i
VOL	Volume of vehicle passenger compartment, cu ft
WLS	Weighted Least Squares
X_{ij}	Attribute j for vehicle i, continuous variable
Y_{ij}	Attribute j for vehicle i, dummy variable

Table H.2. Nomenclature for Chapter 3.

Greek Symbol	Definition
β_0	Intercept of the regression
β_1	Price elasticity of FC wrt vehicle price
β_2	Price elasticity of ACCEL wrt vehicle price
β_3	Price elasticity of CWT wrt vehicle price
β_j	Price elasticity of attribute j wrt vehicle price
ε_i	Residual error
χ_A	Average share of model response explained by ACCEL
χ_C	Average share of model response explained by CWT
χ_F	Average share of model response explained by FC

Table H.3. Nomenclature for Chapter 4.

Symbol	Definition
B/C	Ratio of Benefit:Cost
BCA	Benefit Cost Analysis
CAFE	Corporate Average Fuel Economy
CNG	Compressed Natural Gas
CVT	Continuously Variable Transmission
Diesel	Vehicle with a diesel engine
Δ mpg	Absolute change in fuel economy
Δ %	Percent change in fuel economy
ECO	Economy package, light-weighting or reduced aero drag
EV	Electric Vehicle
FE	Fuel Economy
HEV	Hybrid Electric Vehicle
i	Nominal discount rate
ICE	Internal Combustion Engine
IRPE	Incremental Retail Price Equivalent
MPG	Miles Per Gallon
MPG_{AV}	Fuel Economy of average vehicle baseline
MPG_e	Equivalent fuel economy, in MPG equivalent
MPG_{MS}	Fuel Economy of model specific baseline
MPG_X	Fuel Economy of improved model, X
MSRP	Manufacturer's Suggested Retail Price
NPV	Net Present Value
PEF	Petroleum Equivalency Factor
PHEV	Plug-in Hybrid Electric Vehicle
OEM	Original Equipment Manufacturer
R^2	Regression coefficient of determination
TRANS	Advanced Transmission
TRBDS	Turbocharged Downsized Engine
VMT	Vehicle Miles Traveled
VVT	Variable Valve Timing

Table H.4. Nomenclature for Chapter 5.

Symbol	Definition
A_F	Frontal area
a_{veh}	Vehicle acceleration
C_1	BEC capacitance
C_D	Coefficient of drag
C_{rr0},C_{rr1}	Rolling resistance coefficients
CD	Charge-Depleting
CI	Compression-Ignition
c_{pao},c_{pac}	Air specific heat: outdr, cabin
CS	Charge-Sustaining
$E_{batt,loss}$	Battery energy loss
$EC_{Eq,CS}$	Sys Equivalent Energy Consumption, CS
$EC_{Eq,CD}$	Sys Equivalent Energy Consumption, CD
EC_i	Energy Consumption, cycle i
$EC_{i,start}$	EC during start-up, cycle i
$EC_{m,n}$	Average EC for veh m, city n
$EC_{m,ref}$	Reference EC for veh m
ECLM	Energy Consumption Locality Multiplier
$EI_{gasoline}$	Emission Intensity of gasoline
EI_{diesel}	Emission Intensity of diesel
EI_m	Emission Intensity, vehicle m
$EIEG_n$	Emission Intensity, Electricity Generation, city n
EV	Electric Vehicle
F_{accel}	Force due to acceleration
F_{aero}	Aerodynamic drag force
F_{hill}	Hill climb force
F_{rr}	Rolling resistance force
F_{tr}	Tractive force
FE	Fuel Economy
FC_i	Fuel Consumption, cycle i
$FC_{i,start}$	FC during start-up, cycle i
FTP	Federal Test Protocol
g	Acceleration of gravity, 9.8 m/s2
$(hA)_b$	Battery heat transfer coefficient*area
HEV	Hybrid Electric Vehicle
HVAC	Htg, Ventil'g, Air-Condition'g
HWFET	Highway FE Driving Sched.
I_{cell}	Cell current
$I_{cell,ch}$	Cell current, charging mode
$I_{cell,dch}$	Cell current, discharg'g mode
I_{R1}	Current thru R_1

Table H.4. Nomenclature for Chapter 5 (cont.).

Symbol	Definition
ICE	Internal Combustion Engine
j,k	Given driving cycles
LHV	Lower Heating Value
m	Vehicle type identifier
m_{ac}, m_{ab}	Air mass flow rate: cabin, batt
m_{veh}	Vehicle mass
n	City identifier
N_i	Non-dyno correction, cycle i
N_t	Total number of cells
p	Day of year
q	Hour of day
P_{aux}	Auxiliary/HVAC power
$P_{aux,batt}$	Battery HVAC power
$P_{aux,cabin}$	Cabin HVAC power
$P_{cell,loss}$	Cell power loss
P_{em}	Electric motor power
$P_{eng,max}$	Maximum engine power
P_{total}	Total vehicle power
P_{tr}	Tractive power
$Q_{AC,cabin}$	Cabin AC load
Q_b	Battery heat rate, inst.
$Q_{b,cycle}$	Battery heat generation, cycle
$Q_{htg,cabin}$	Cabin heating load
Q_{Load}	Cabin AC or heat load
R_0 , R_1	BEC resistances
SOC	Battery state of charge
SOC_{init}	Initial state of charge
SI	Spark-Ignition
SysEq	System Equivalent
t	Time
T_{ao},T_{ac}	Air temperature: outdoor, cabin
T_b	Battery module temperature
T_{bao}	Battery air outlet temperature
UDDS	Urban Dyno Driving Schedule
UF	Utilization Factor
US06	Supplemental FTP
V_{C1}	Voltage across C_1
V_{cell}	Cell voltage
Veh	Vehicle
V_{OC}	Cell Open Circuit Voltage
v_{veh}	Vehicle speed

Table H.5. Nomenclature for Chapter 5.

Greek Symbol	Definition
$\eta_{b,rt}$	Roundtrip battery efficiency
η_{ch}	On-board charging efficiency
η_{chg}	External charging efficiency
η_{dch}	On-board discharging efficiency
$\eta_{liqref,n}$	Petroleum refining efficiency, city n
η_{liqtr}	Petroleum transportation efficiency
$\eta_{gen,n}$	Electricity generation efficiency, city n
$\eta_{trans,n}$	Electricity transmission efficiency, city n
θ_{grade}	Hill grade angle
ρ_{ao}, ρ_{ac}	Air density: outdoor, cabin
χ_j , χ_k	Drive cycle weighting factors
χ_p	Drive fraction of day p
χ_q	Drive fraction of hour q

Table H.6. Nomenclature for Chapter 5

Abbreviation	U.S. City
ATL	Atlanta, GA
BAL	Baltimore, MD
BOS	Boston, MA
CHI	Chicago, IL
DAL	Dallas, TX
DC	Washington, DC
DEN	Denver, CO
DET	Detroit, MI
HOU	Houston, TX
IND	Indianapolis, IN
LA	Los Angeles, CA
MIA	Miami, FL
MIN	Minneapolis, MN
NYC	New York City, NY
PHA	Philadelphia, PA
PHX	Phoenix, AZ
PIT	Pittsburgh, PA
SD	San Diego, CA
SEA	Seattle, WA
SF	San Francisco, CA
STL	St. Louis, MO
TAM	Tampa, FL

VITA

VITA

Richard Arthur Simmons received a Bachelor of Science in Mechanical Engineering with Faculty Honors from the Georgia Institute of Technology in 1993. He received a Master of Science in Mechanical Engineering from Purdue University in 1995. Richard received his Professional Engineering licensure in the state of Georgia in 2003. Following a successful multi-disciplined career in engineering and business, Richard served a prestigious AAAS science and technology policy fellowship in the thematic area of energy from 2009-2012 at the U.S. Department of State. Richard returned to Purdue University in 2012 to complete his Doctor of Philosophy in Mechanical Engineering. He is married with one daughter.

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