DISSERTATION

TECHNO-ECONOMIC ANALYSIS AND DECISION MAKING FOR PHEV BENEFITS TO SOCIETY, CONSUMERS, POLICYMAKERS AND AUTOMAKERS

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ABSTRACT

TECHNO-ECONOMIC ANALYSIS AND DECISION MAKING FOR PHEV BENEFITS TO SOCIETY, CONSUMERS, POLICYMAKERS AND AUTOMAKERS

Plug-in hybrid electric vehicles (PHEVs) are an emerging automotive technology that has the capability to reduce transportation environmental impacts, but at an increased production cost. PHEVs can draw and store energy from an electric grid and consequently show reductions in petroleum consumption, air emissions, ownership costs, and regulation compliance costs, and various other externalities. Decision makers in the policy, consumer, and industry spheres would like to understand the impact of HEV and PHEV technologies on the U.S. vehicle fleets, but to date, only the disciplinary characteristics of PHEVs been considered. The multidisciplinary tradeoffs between vehicle energy sources, policy requirements, market conditions, consumer preferences and technology improvements are not well understood.

For example, the results of recent studies have posited the importance of PHEVs to the future US vehicle fleet. No studies have considered the value of PHEVs to automakers and policy makers as a tool for achieving US corporate average fuel economy (CAFE) standards which are planned to double by 2030. Previous studies have demonstrated the cost and benefit of PHEVs but there is no study that comprehensively accounts for the cost and benefits of PHEV to consumers. The diffusion rate of hybrid electric vehicle (HEV) and PHEV technology into the marketplace has been estimated by existing studies using various tools and scenarios, but results show wide variations between studies. There is no comprehensive modeling study that combines policy, consumers, society and automakers in the U.S. new vehicle sales cost and benefits analysis.

The aim of this research is to build a potential framework that can simulate and optimize the benefits of PHEVs for a multiplicity of stakeholders. This dissertation describes the results of modeling that integrates the effects of PHEV market penetration on policy, consumer and economic spheres. A model of fleet fuel economy and CAFE compliance for a large US automaker will be developed. A comprehensive total cost of ownership model will be constructed to calculate and compare the cost and benefits of PHEVs, conventional vehicles (CVs) and HEVs. Then a comprehensive literature review of PHEVs penetration rate studies will be developed to review and analyze the primary purposes, methods, and results of studies of PHEV market penetration. Finally a multi-criteria modeling system will incorporate results of the support model results.

In this project, the models, analysis and results will provide a broader understanding of the benefits and costs of PHEV technology and the parties to whom those benefits accrue. The findings will provide important information for consumers, automakers and policy makers to understand and define HEVs and PHEVs costs, benefits, expected penetration rate and the preferred vehicle design and technology scenario to meet the requirements of policy, society, industry and consumers.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1- Introduction

1.1 Background

The first automobile fuel efficiency standards were passed in 1975 by the US Congress as part of the Energy Policy Conservation Act (EPCA). In 1978, this legislation set the minimum acceptable corporate average fuel economy (CAFE) standard at 18.0 mi gal^{-1} (mpg) for passenger cars. EPCA sets a penalty of $5 per vehicle for every 0.1 mpg that the CAFE is below the standard, and sets up credits that are available when a corporation's CAFE exceeds the standards [1]. The CAFE requirements have been incrementally increased to 26.0 mpg in 1985, to 27.5 mpg in 1989, and to 36.5 mpg by 2016 [2]. Automakers have developed vehicles to meet these increasing CAFE standards by continuously developing and incorporating a suite of technologies including light-weighting, improved aerodynamics and hybrid-electric vehicles.

Plug-in hybrid electric vehicles (PHEVs) are hybrid electric vehicles which can draw and store energy from an electric grid. The benefits of plug-in hybrid vehicles are that they displace petroleum energy with multi-source electrical energy. PHEVs are generally characterized by lower petroleum consumption, lower criteria emissions output, and lower carbon dioxide emissions [3].

1.2 Project Overview

The Venn diagram shown at Figure 1 presents the interaction between decision makers in quantifying the cost and benefits of PHEVs.

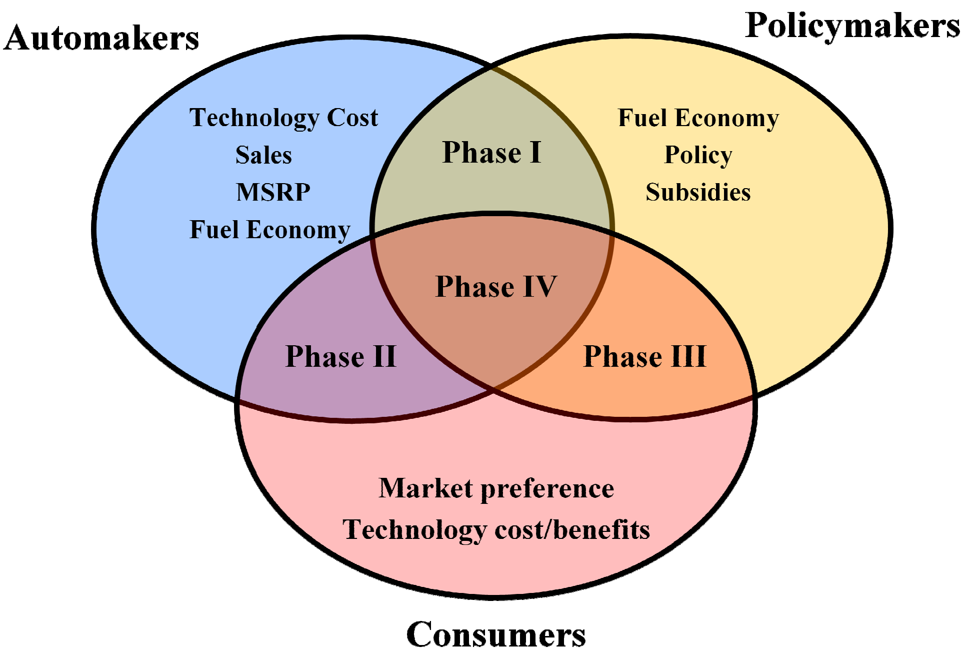

Figure 1. Venn Diagram of Decision Makers' Interactions as Framework for this Study

Decision makers "DM" in Figure 1 are represented by

- Automakers: Vehicle manufacturers who sell vehicles in the US
- Policymakers: US individuals with power to influence or determine public policy at state or federal level
- Consumers: individuals who buy and operate the vehicle in the US

The regions of interaction among these decision makers are labeled in Figure 1 as:

A. Regulation of Automakers interaction: CAFE standards, Low Carbon Fuel standards, EPACT and other legislation influence the market under which automakers design and build vehicles.

B. Vehicle demand and supply interaction: Automakers and consumers interact through the automobile market to determine the types of vehicles that are manufactured and sold in the US.

C. Incentives and Taxes interaction: Consumers and policy interact in a variety of ways. Changes in fuel prices and taxes, government subsidies for advanced vehicles, tax incentives and other means of financial support can influence the consumer automobile decision making process.

D. System level interactions: All decision makers interact to determine the actual characteristics and evolution of the vehicle fleet. All decision makers must be able to meet their individual and collective requirements for an economic, environmental, and sustainable transportation system.

The goals of this study are to calculate the economic value of PHEVs in allowing an automobile manufacturer to meet increasing CAFE standards, to calculate and study the total cost of ownership of the purchase and operation of PHEV to consumers, to review and analyze the primary purposes, methods, and results of studies of PHEV market penetration and to develop a multi-criteria modeling system to help decision makers in evaluating different scenario of vehicle technology that meet their needs and preferences.

1.3 Outline of this Document

This chapter (Chapter 1) provides an introduction to the PHEV system modeling research project and presents the outline of this dissertation.

Chapter 2 presents a literature survey of the state of the field of PHEV modeling and design. Chapter 2 also presents the research questions and tasks required to complete the research project.

Chapter 3 presents a model for CAFE compliance for a major US automaker for the model year 2008. Novel models of HEV and PHEV fuel economy and incremental costs are used to quantify the relative costs and benefits of these vehicle technologies. Results and discussion sections compare the costs of CAFE compliance among HEV technologies, vehicle types, and fuel economy quantification policy options. The results are put into a policy context through comparison of the effectiveness of PHEV CAFE compliance to that of other alternative fuel vehicles for the period 2012-2016. The results of this work can inform automakers, policy makers and technical analysts about the value of PHEVs in allowing automakers to meet CAFE requirements.

Chapter 4 presents a total cost-of-ownership model that will allow consumers to compare and understand CV, HEV and PHEV5-60 technology cost and benefits. The model also educates consumers about the benefits of PHEV technologies and provides an optimized comparison of vehicle technology based on their needs and preferences.

Chapter 5 presents an analysis and evaluation of PHEV market penetration rate studies. This research synthesizes the current understanding of the modeling needs for market penetration studies and the economic feasibility of HEV and PHEV technologies. This research provides information for researchers, automakers, and policymakers to understand and define the modeling components and parameters that need to be integrated into estimation of HEV and PHEV adoption rates.

Chapter 6 presents a multi-criteria modeling system that integrates and interacts with each of the previous models to synthesize an overall understanding of the tradeoffs among all of the decision maker and decision spheres presented in Figure 1.

Chapter 7 provides conclusions to the study and a summary of future work.

Appendix A presents supporting materials for Chapter 3.

Appendix B presents supporting materials for Chapter 4.

Appendix C presents supporting materials for Chapter 6

Appendix D presents a multi-criteria decision support system for informing decision making at vehicle level and at scenario level. The goal of the vehicle decision support system is to determine the most preferred vehicle for a particular consumer, automaker and policy maker. The goal of the scenario level decision support system is to determine the most preferred vehicle penetration scenario including the tradeoffs among the preferences automakers and policy makers under various consumer preference scenarios.

Chapter 2- State of the Field and Research Challenges

This chapter reviews the results of studies of PHEV technology total cost of ownership, penetration rate and multi-criteria decision support system. This is followed by a set of research questions and tasks that are responsive.

2.1 The Integration of PHEV Technology in Automakers Fleets

The benefits of PHEV technology can be understood only if PHEV types (range of vehicle, e.g. 0-60 miles), PHEV class (EPA classification e.g. compact car, mid-size car or mid-size SUV) and fuel economy methods are integrated in an automakers vehicle fleet model in order to increase fleet average fuel economy (CAFE).

To the identified research needs, there are no studies specifically addressing the use of PHEV technology in meeting CAFE standards for an automaker vehicle fleet. Current studies mainly focus on PHEV design and performance. The basis of much of the research in PHEV field is the work by the Hybrid Electric Vehicle Working Group (WG), assembled by the Electric Power Research Institute (EPRI). Two technical reports (EPRI 2001, EPRI 2002) have been completed to provide technical specifications for several vehicle classes, including compact car, mid-size car, mid-size SUV and large-size SUV PHEVs [4,5]. Technical parameters from the EPRI reports are used in this study and updated for new fuel economy methods, utility factors and annual electricity consumption. The EPRI reports present fuel economy methods used to calculate the mpg rating for HEVs. The utility factor (UF) from SAE J1711 and other FE methods can be used if updated with new values provided by the J2841 report [6]. New fuel economy (FE) methods need to be studied and applied. The new FE methods should consider the updated UF and modified conversion factor which has been changed from 33.44 to 82.049kW/g (petroleum-equivalency factor (PEF)). The conversion factor has decreased as the Department of Energy (DOE) has revised its regulation on electric vehicles to provide a petroleum-equivalency factor (PEF) and procedures for calculating the petroleum-equivalent fuel economy of electric vehicles [7]. Another method should consider the weighted gasoline-only fuel economy for a fully charged vehicle.

A U.S. Department of Transportation National Highway Traffic Safety Administration study has examined the costs and benefits of improving passenger car and light truck fleet fuel economy for vehicles models 2011-2016 [2]. The study includes a discussion of technologies that can improve fuel economy and an analysis of the potential impact on retail prices, safety, lifetime fuel savings and their value to consumers, and other societal benefits. NHTSA uses the Volpe Simulation model for their analysis and optimization of fuel economy technologies to meet the proposed CAFE standards. The Volpe model consists of several spreadsheet files that have information about automakers vehicle sales, fuel cost, fuel efficiency, CAFE standards, technology penetration rate, specifications and vehicle fuel improvement. The Volpe model is not intended to be used to test the effect of specific technologies like PHEV, rather is intended to test different technologies using a decision tree method whereby PHEV technology can be selected only after other technologies have been exhausted.

Modeling the integration of PHEV technology into an automaker fleets is computationally demanding. Fuel economy methods and system incremental costs have to be studied to be used in the modeling process. Costs saving to automakers, consumers and society benefits have to be calculated. In order to enroll PHEVs technology in US automakers fleets a new model must be developed and validated.

2.2 PHEV Total Cost of Ownership Modeling and Economic Cost/Benefits Analysis

Studies have examined the potential of technological advances in improving vehicle fuel economy in the United States. Cost/Benefit analysis of fuel economy technologies using analytical economics and automotive engineering methods have been developed and used. Fuel economy improvement could be accomplished either through using more efficient but expensive technologies or by re-designing internal combustion engine (ICE) vehicles.

Automakers have introduced grid-independent HEVs and grid dependent PHEVs to the market [3–5,8]. Some manufacturers have announced plans to develop PHEVs; GM Chevrolet Volt came out in 2010; FORD PHEV Escape in 2012; Toyota PHEV Prius in 2012; NISSAN PHEV in 2012; VOLVO PHEV in 2012; Chrysler PHEV in 2012; Volkswagen PHEV Golf Twin E-Drive in 2011; Saturn PHEV VUE in 2010; Audi PHEV A1 Sport-back in 2011; and Hyundai PHEV Sonata in 2013 [8]. Studies have attempted to assess market potential of PHEVs through an economic analysis. A variety of studies have quantified PHEV fuel efficiency and incremental costs in order to understand their value to consumers [4,5,9–13]. Most of the studies concluded that in order for the PHEVs to be cost effective, their incremental cost has to come down and the gasoline price has to increase above $5.00/gallon [10,14–17]. No studies have considered all of the ownership cost parameters that may affect the cost/benefits value of PHEVs or have included consumers' preferences toward PHEVs. Most of studies cited have included only fuel consumption costs model in their PHEV economic model.

The modeling of fuel economy technologies need to be implemented using a variety of vehicle types, market conditions, driving and policy attributes and parameters. Costs and benefits of PHEV technology should be linked to the consumer market preference surveys. A recent study that compares HEV (Toyota Prius 2001) and ICE (Toyota Corolla 2001) concluded that the HEV Prius is not cost-effective in improving fuel economy or lowering emission. To be attractive to the US consumers the price of gasoline has to be three times more than $1.5/gal and Prius tailpipe emission benefits to regulators and society have to be 14 times greater than 2001 CVs [16]. Based on the PHEV economic model tested in this study, with current fuel costs PHEV technology have more fuel economy benefits than both CVs and HEVs and the consumer payback would be 3-10 years for most vehicle classes. A model of PHEV economic benefits needs to consider options like incentives and tax cuts which reduce the payback period.

Simpson [10] compared the cost/benefits of PHEV to HEV and CV. Battery costs, fuel costs, vehicle performance attributes and driving habits were considered in the valuation of PHEV. Near-term and long-term scenarios were considered. The economic analysis showed that higher gasoline prices and lower PHEV incremental cost would be required to have PHEV favorable over other technologies [10]. Similar but expanded analysis needs to be conducted. For example, the economic analysis needs updated fuel costs and the model should consider more parameters. PHEV fuel efficiency and the utility factor need to be updated. A study by Kammen [15] compared a CV, HEV, PHEV20 and PHEV60 in compact passenger car and full-size SUV classes. PHEVs were found to reduce GHG emissions and oil consumptions and improve oil security. For the PHEV to be economical cost effective under current market conditions battery cost must decline to below $500/kWh or U.S. gasoline must remain at $5/gallon [15]. A comparison between advanced electrical technologies and advanced conventional technologies from 1997 to 2002 studies were discussed in a paper by Santini [18]. Diesel engine, fuel cell, gasoline engine, HEV and hydrogen technologies were compared in terms of fuel economy, incremental cost, and cost effectiveness [18]. A paper by Diamond [19] has examined the impact of government incentives policies in promoting HEVs. For incentives to be effective, the payment had to be upfront and a strong relationship existed between gasoline prices and HEVs adoption [19]. A study by Ogden et al [20] performed a societal lifecycle cost analysis for a variety of alternative automotive engine/fuel options. The study include the vehicle first cost, fuel costs, oil supply security costs, GHG and other emission costs [20].

Relevant economic analysis simulations of PHEV technology to date have not included all of the cost/benefits parameters. Fuel economy of PHEVs used in existing studies needs to be updated with the new ratings tested on a variety of HEV types and classes. New HEV incremental costs that include lithium ion batteries have to be considered. Different scenarios of vehicle purchase have also been overlooked. The benefits of HEVs have to be studied in greater detail, including different scenarios for fuel savings, GHG emission reductions, payback period and consumers preferences. Demand curves of market preferences toward the purchase of PHEVs needs to be included and compared with PHEVs cost/benefits supply curves. A sensitivity analysis of the parameters needs to be included in the economic analysis.

2.3 Market Penetration Rate Modeling

There is a need to forecast the market adoption to HEVs, PHEVs and EVs technology for society, vehicle manufacturers, power companies and policy makers. Society will benefit from more economical and environmental friendly vehicles. Vehicle manufacturers need to meet the CAFE standards and understand the market potential. Power companies need to model future power demands. Policy makers need to adjust CAFE standards, assign new environmental rules and, understand various domestic power demand and foreign oil needs.

Studies have developed models to estimate the penetration rate of the currently available HEV technology and the new PHEV and EV technology in the US market. Four different major modeling techniques used in the literature are agent based model, consumer choice model, diffusion model and time series model. Agent-based modeling (ABM) is a computer based simulation method that creates a virtual environment to simulate the action and interaction of each agent. Agents are entities or individuals with specific characteristics that have control over their interaction behavior with other agents in the system model. It is composed of mathematical models that simulate the actions and interactions of agents within a specified environment. It considers consumer's social behavior and can includes other decision makers interacting in the market such as policy makers, automakers, car dealers, and fuel suppliers [21–23]. The agent based model was applied to new vehicle technology adoption field [18,24–28].

The consumer choice model links consumers demand to a product with their preferences at different market conditions and product criteria [29,30]. Discrete choice models or Logit models have been used in the literature to describe individual's decisions in choosing among alternative products. Discrete choice models calculate the probability of individual choosing a specific alternative by incorporating their behavior and alternative characteristics [29]. The two different logit models used are multinomial logit model (MNL) which is the probability of choosing an alternative over all alternatives [31–39] and nested logit model (NMNL) which is the probability of choosing an alternative over the nest alternative [38,40–44]. The discrete choice model was used to estimate the penetration rate of HEV [19,24,29,44–53].

Finally the diffusion and time series models estimates the adoption rate of a new product based on the interaction of buyers and new buyers [54–59]. Diffusion is defined as the process of accepting a new invention or product by the market. The new-product diffusion model developed to capture the life cycle of new products over time. The speed of the spreads of the new product is called the rate of diffusion. The most widely used models applied to model innovation diffusion are the Bass model, Gompertz model, and Logistic model. These models were used in the literature to model innovation diffusion [37,55,60–80].

The modeling of any new technology is a complex problem especially when no historical sales data exist. PHEV is a new technology without market data and differ from HEVs, though both share fuel savings and lowered GHG emission relative to CV. Modeling consumer actions and behavior in the market needs to include the supplier behavior under varying conditions. The market model needs to use the historical U.S. sales data since it has consumer's preference in regard to vehicle fleet, class, automaker and brand. Additional information could be extracted from existing sales data, such as vehicles MSRP and fuel economy, which could be used to cluster consumer's preferences and economic levels. Consumer's preferences towards different technologies at varying fuel and vehicle MSRP need to be linked in the market model. An estimation of any new technology division rate could be established using similar technology rate such as HEV per each vehicle class and brand. The model needs to support the diffusion of each technology by incorporating the new carline technology to be available in the market with its manufacturer's class share in the market.

2.4 Multi-Criteria Decision Support System and Negotiation Process System

The literature contains a long history of government and academic studies of the transportation energy sector and the ways to reduce its greenhouse gas (GHG) emissions, increase the use renewable energy, and decrease the quantity of imported oil. In general, these goals can only be achieved through cooperation of government, industry and consumers. In this chapter a multi-criteria modeling system will be developed which can allow for modeling of the requirements and interaction of these agents. The purpose of the multi-criteria modeling system is to evaluate the quantitative and qualitative costs and benefits of different technology penetration scenarios. This model investigates different available technology penetration scenarios costs and impacts on US fleets fuel economy, air emissions, energy consumption, and regulatory compliance. The following sections review the state of the art in the field of transportation and energy system modeling.

Transportation system models have been developed to simulate, analyze or forecast vehicles' air emission, economy, fuel economy, energy use and technology penetration. Table 1 provides a summary of the characteristics of some relevant transportation energy system models.

A number of transportation system models have been developed to estimate and simulate the air emissions of vehicles. MOBILE6 is a vehicle emission modeling software used by Environmental Protection Agency (EPA) to generate on-road motor vehicle emissions factors[1]. Motor Vehicle Emission Simulator (MOVES) Model is developed by EPA's Office of Transportation and Air Quality (OTAQ) to estimate emissions from cars, trucks & motorcycles[2]. The Emission FACtors (EMFAC) model is developed by the Air Resources Board as the California version of MOBILE6. Climate Leadership in Parks (CLIP) tool developed by the US National Park Service for the EPA to measure for park's GHG criteria pollutant emissions resulting from solid waste, wastewater treatment, park vehicles, electricity use, visitors and other sources at local level[3]. COMMUTER model developed by EPA to Analyzes the impacts of transportation control measures (TCMs) on vehicle miles traveled (VMT), criteria pollutant emissions, and GHG[4]. National Mobile Inventory Model (NMIM) developed by EPA to estimates the current and future emission inventories for on-road motor vehicles and non-road equipment[5].

1 http://www.epa.gov/otaq/m6.htm
2 http://www.epa.gov/otaq/models/moves/index.htm
3 http://www.dot.ca.gov/hq/env/air/pages/emfac.htm
4 http://www.epa.gov/otaq/stateresources/policy/pag_transp.htm
5 http://www.epa.gov/otaq/nmim.htm

Some models included energy analysis in addition to the air emission analysis. Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) is a life-cycle model developed by Argonne National Laboratory (ANL) to evaluate advanced vehicles technology energy use and wells-to-wheels and the vehicle cycle emissions impacts[6]. Lifecycle Emission Model (LEM) developed by Mark Delucchi at University of California, Davis to estimate energy use, criteria pollutant emissions, and GHG emissions from transportation and energy sources[7]. Long range Energy Alternatives Planning (LEAP) System tool developed in SEI's U.S. center for energy policy analysis and climate change mitigation assessment[8]. World Energy Protection System (WEPS) Transportation Energy Model (TEM) developed by U.S. Department of Energy (DOE), to generates forecasts of transportation sector energy use by transport mode at a national and multi-national region level[9]. VISION Model developed by ANL to estimate the potential energy use, oil use and carbon emission impacts of advanced light and heavy-duty vehicle technologies and alternative fuels through the year 2100[10].

Other models have considered the transportation and energy sectors with an emphasis on economic analysis. National Energy Modeling System (NEMS) developed by the U.S. Department of Energy (DOE), Energy Information Administration (EIA) to estimate energy market behavior and their economic interaction[11]. Intelligent Transportation Systems Deployment Analysis System (IDAS) tool is developed by Federal Highway Administration (FHWA) to estimate the impacts benefits and costs resulting from the deployment of Intelligent Transportation Systems ITS components[12]. It is used to estimates on-road light-

[6] http://greet.es.anl.gov/
[7] http://www.its.ucdavis.edu/publications/2003/ucd-its-rr-03-17-main.pdf
[8] http://www.energycommunity.org/default.asp?action=47
[9] http://climate.dot.gov/methodologies/models-tools.html
[10] http://www.transportation.anl.gov/modeling_simulation/VISION/
[11] http://205.254.135.24/oiaf/aeo/overview/
[12] http://www.fhwa.dot.gov/research/deployment/idas.cfm

duty passenger vehicles to heavy-duty trucks emission rates in California. IDAS can evaluate impacts due to changes in user mobility, travel time/speed, travel time reliability, fuel costs, operating costs, accident costs, emissions, and noise. The MARKAL-MACRO Model developed by the U.S. Department of Energy to link the use of energy and environmental resources to the economy[13].

Other models have been developed to simulate vehicles' energy, economics and technological evolution . ObjECTS GCAM is an economy, energy and land-use model developed by Joint Global Change Research Institute (PNNL)[14]. The National Energy Modeling System (NEMS) developed by Energy Information Administration (EIA) of the U.S. Department of Energy (DOE)[15]. It is a computer-based, energy-economy modeling system of U.S. through 2030. NEMS projects the production, imports, conversion, consumption, and prices of energy. The Volpe model has been developed by DOT's National Transportation Systems Center to support NHTSA's CAFE rulemakings. The model is used by NHTSA to estimates vehicle manufacturers costs, effects, and benefits of technologies that could be added in response to a given CAFE standard[16]. Systems for the Analysis of Global Energy Markets (SAGE) was developed by the U.S. DOE to replace WEPS[17]. It provides a projection of energy consumption to meet energy demand following region's existing energy use patterns and the existing stock of energy. Transitional Alternative Fuels and Vehicle Model (TAFV) developed by University of Maine to evaluate economic decisions among auto manufacturers, vehicle purchasers, and fuel suppliers and to predict the choice of alternative fuel technologies for light-duty motor vehicles[18]. Overall, these modeling efforts

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[13] http://www.iea-etsap.org/web/MrklDoc-II_MARKALMACRO.pdf
[14] http://cfpub.epa.gov/crem/knowledge_base/crem_report.cfm?deid=212503
[15] http://205.254.135.24/oiaf/aeo/overview/
[16] http://www.nhtsa.gov/Laws+&+Regulations/CAFE+-+Fuel+Economy/Volpe+Model+for+Model+Years+2011+and+prior
[17] ftp://tonto.eia.doe.gov/modeldoc/m072%282003%291.pdf
[18] http://www.esd.ornl.gov/eess/energy_analysis/files/tafvsml4.pdf

recognize the multidisciplinary system modeling scope that is required to model the transportation and energy sectors with fidelity. Still, few of these models consider the role of regulation in determining technological changes, and fewer still consider the overarching role of the automotive consumer in enabling a change in the transportation sector

Table 1. Transportation Models Available in the Literature

Model name	Source	Function	Area
Climate Leadership in Parks (CLIP)	U.S. Environmental Protection Agency	Calculates air emission based of fuel consumption and/or vehicle miles traveled	1. Air Emission
COMMUTER Model	U.S. Environmental Protection Agency	Analyzes the impacts of transportation control measures (TCMs) on vehicle miles traveled (VMT), criteria pollutant emissions, and CO_2.	2. Air Emission
EMFAC Model	California Air Resources Board	Calculate emission rates from all motor vehicles, operating on highways, freeways and local roads in California	3. Air Emission
MOBILE6	U.S. Environmental Protection Agency	Produce motor vehicle emission factors for use in transportation analysis and can be used at any geographic level within the U.S.	4. Air Emission
Motor Vehicle Emission Simulator (MOVES) Model	U.S. Environmental Protection Agency	Estimates emissions for on-road and non-road sources for a broad range of pollutants and allow multiple scale analysis.	5. Air Emission
National Mobile Inventory Model (NMIM)	U.S. Environmental Protection Agency	NMIM uses MOBILE6 and NONROAD to calculate emission inventories, to calculate national or individual state or county inventories.	6. Air Emission
Long Range Energy Alternatives Planning (LEAP) System	Community for Energy, Environment and Development	Energy policy analysis and climate change mitigation assessment tool for energy consumption, production, and resource extraction in all sectors of an economy.	7. Air Emission and energy use.
The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model	Argonne National Laboratory	Full life-cycle model to evaluate energy and emission impacts of advanced vehicle technologies and new transportation fuel combinations.	8. Air Emission and energy use.
Lifecycle Emissions Model (LEM)	University of California, Davis	Estimates energy use, criteria pollutant emissions, and CO_2-equivalent GHG emissions from transportation and energy sources.	9. Air Emission and energy use.
National Energy Modeling System (NEMS)	Energy Information Administration (EIA), U.S. DOE	Simulates the behavior of energy markets and their interactions with the U.S. economy with transportation demand module (TRAN).	10. Air Emission, energy use and economy
Intelligent Transportation Systems Deployment Analysis System (IDAS)	Federal Highway Administration	Predict relative costs and benefits for more than 60 types of ITS investments. Evaluated impacts relative to changes in user mobility, travel time/speed, travel time reliability, fuel costs, operating costs, accident costs, emissions, and noise.	11. Air Emission, energy and economy
The MARKAL-MACRO Model	U.S. Department of Energy	Link the use of energy and environmental resources to the economy.	12. Air Emission, energy and economy
World Energy Protection System (WEPS) Transportation Energy Model (TEM)	U.S. Department of Energy	Model for transportation energy use generates mid-term forecasts of the transportation sector's	13. Air emission, energy use, and fuel economy
VISION Model	Argonne National Laboratory	Forecasts energy use until 2050	14. Air emission, energy, and vehicle technology penetration
System for the Analysis of Global Energy Markets (SAGE)	U.S. Department of Energy	Integrated set of regional models that provides a technology-rich basis for estimating regional energy supply and demand.	15. Energy and economy
Transitional Alternative Fuels and Vehicle Model (TAFV)	University of Maine	Economic decisions among auto manufacturers, vehicle purchasers, and fuel suppliers and can predict the choice of alternative fuel technologies for light-duty motor vehicles.	16. Economy, and DSS
Volpe Model	DOT National Transportation Systems Center	Support NHTSA's CAFE rulemakings. Estimates vehicle manufacturer's costs, effects, and benefits of technologies that could be added in response to a given CAFE standard.	17. Technology, policy, economy and Energy

A multi-criteria modeling system for the U.S. new vehicles sales under different HEV and PHEV5-60 technology penetration rate scenarios is developed to simulate and evaluate the achieved fleet CAFE, total cost of ownership, air damages and oil displacement. The first stage starts when each DM revise and change the modeling components for the base case (CVs, HEV and PHEVs incremental costs, fuel economy, fleet volume, fuel price, and discount rate) and then assigning different set of policy and standards to be achieved. The second stage is to set different vehicle technology penetration rate. The modeling system will present the result for each penetration rate scenario and the DMs will compare each scenario based on the costs, benefits and policy standards met.

DMs can negotiate and revise the penetration rate scenario or revise the modeling components within an agreeable components and policy value limits. The model will give a new set of results within the negotiation space. The process will continue as DMs revise each model components and technology penetration rate scenarios. The process will stop when there is a common scenario or DMs agrees on one scenario. Further analysis will be carried and more technologies could be added to the model. Appendix D presents two multi-criteria decision support systems models, vehicle technology level and vehicle technology penetration scenario level.

2.5 Research Questions and Tasks

Based on the challenges identified in the previous section, a primary research question is:

Main Research Question:

IS THERE COMMON GROUND IN BETWEEN THE INTERESTS THAT GOVERN PHEV MARKETPLACE SUCCESS? WHAT SET OF AUTOMAKER, GOVERNMENT AND CONSUMER POLICIES WILL GENERATE A BENEFICIAL MARKETPLACE ENVIRONMENT FOR PHEVS?

In this research effort the question can be answered by establishing methods and a framework for parametric modeling of PHEV types and their integration in US automakers fleets, regulatory compliance needs and consumer acceptability needs. The validation of the models is performed by comparing the results of the analysis with or without PHEV technology to the parameter and analysis performed by EPRI and NHTSA [2,4,5]. The validation of the total cost of ownership model will be performed by comparing the model parameters, assumptions and results to other studies work and tested by performing a sensitivity analysis. At the last stage the results of the validated models will be integrated into a multi-criteria decision support system and negotiation process model to define the optimum technology that will meet and satisfy each decision maker goal.

2.5.1 Research Question 1:

WHAT IS THE VALUE OF INTEGRATING HEVS AND PHEVS INTO AUTOMAKER'S VEHICLE FLEETS TO MEET CAFE STANDARDS?

A variety of studies have quantified PHEV fuel efficiency and incremental costs in order to understand their value to consumers [4,5,9–12]. To date, no studies have considered the value of PHEVs to automakers and policy makers in achieving CAFE compliance [2].

2.5.1.1 Hypothesis 1.1

PHEVs and HEVs represent a net cost of compliance saving to the US automotive industry over other available technologies.

2.5.1.2 Task 1.1: Develop a model of a US automaker fleet and calculate the achievable CAFE.

2.5.1.3 Task 1.2: Update and modify PHEVs fuel economy methods and calculate the hybridization incremental cost using lithium ion batteries for different PHEV types and classes.

2.5.1.4 Task 1.3: Integrate the PHEV technology in the model and calculate the achievable CAFE and the total incremental cost of the technology.

2.5.1.5 Task 1.4: Scenario analysis to calculate the saving/benefits to automakers, consumers and society associated with using PHEV technology of meeting the CAFE standards proposed for 2012-2016.

2.5.2 Research Question 2:

WHAT ARE THE COMPONENTS OF A COMPREHENSIVE PHEV CONSUMER'S TOTAL COST OF OWNERSHIP MODEL, SO THAT WE CAN DEFINE PHEV COST/BENEFIT AND CONSUMER ACCEPTABILITY FOR THE PHEV TECHNOLOGY?

A number of studies have demonstrated the cost and benefit of PHEVs but there is no study that accounts for all of the variables that may affect the cost and benefits of PHEV to consumers [4,5,9–13]. The problem is that the benefits of PHEV are not well defined. In order understand the costs and benefits of PHEVs purchase and use, this study constructs a comprehensive ownership cost model that has the parameters and assumptions needed.

2.5.2.1 Hypothesis 2.1

The payback period of PHEV purchase compared to CV or HEV purchase is not a robust model for consumer acceptability. By incorporating a survey-based, more detailed model of consumer acceptability, we can gain a richer understanding of PHEV consumer preference.

2.5.2.2 Task 2.1: Develop a total cost of ownership model for a purchase with loan of CVs and HEV 0-60 miles of range. The model should account for down payment on vehicle MSRP, a loan, vehicle salvage value, maintenance cost, title and registration cost, insurance cost, fuel costs, annual vehicle miles traveled, utility factor and adjusted fuel economy. The model should calculate the annual costs of each vehicle and the payback period of HEV 0-60 and compare it to CV or HEV 0.

2.5.2.3 Task 2.2: Construct a sensitivity analysis to measure the effects of the model parameters and assumptions on each vehicle payback period and cost/benefits.

2.5.2.4 Task 2.3: Develop a supply demand curves of the market preferences towered HEV, PHEV20 and PHEV60 cost/benefits.

2.5.2.5 Task 2.4: Develop a user friendly total cost of ownership (TCO) model.

2.5.3 Research Question 3:

WHAT ARE THE COMPONENTS OF A COMPREHENSIVE PHEV PENETRATION RATE MODEL, SO THAT WE CAN IMPROVE AND MINIMIZE THE UNCERTAINTY IN ESTIMATING PHEVS ADOPTION RATE?

Results of recent studies have examined the importance of PHEVs in the near future. The diffusion rate of hybrid electric vehicle (HEV) and PHEV technology into the marketplace has been estimated by existing studies using various tools and scenarios with wide variations of the results between the studies.

2.5.3.1 Hypothesis 3.1

The penetration rate forecasts of HEV, PHEV and EV are invalid because they do not consider the role of government and automakers in the marketplace.

2.5.3.2 Task 3.1: Provide a comprehensive literature review of HEVs penetration rate studies.

2.5.3.3 Task 3.2: Present the result of each HEVs penetration rate model study.

2.5.3.4 Task 3.3: Provide a set of recommendations and conclusions to improve the HEVs penetration rate modeling and minimize uncertainty and variability among studies.

2.5.4 Research Question 4:

WHAT SET OF AUTOMAKER, GOVERNMENT AND CONSUMER POLICIES WILL GENERATE THE MOST BENEFICIAL MARKETPLACE ENVIRONMENT FOR PHEVS?

2.5.4.1 Hypothesis 4.1

A multi-criteria modeling system can be used to experiment and discover the preferred policy, vehicle technology, and consumer marketplace conditions for PHEV market success.

2.5.4.2 Task 4.1: Update and upgrade the CAFE model to calculate the achieved U.S. new vehicle sales CAFE using CV, HEV and PHEV5-60 vehicle technology over the period 2010-2030.

2.5.4.3 Task 4.2: Update and upgrade the TCO model to calculate the total cost of ownership of the U.S. new vehicle sales using CV, HEV, and PHEV5-60 technology over the period 2010-2030.

2.5.4.4 Task 4.3: Develop air emission and oil displacement model to calculate the U.S. new vehicle sales air emission and oil displacement quantities and value over the period 2010-2030.

2.5.4.5 Task 4.4: Develop a multi-criteria modeling system that interact with Task 4.1-4.3 models and calculates the U.S. new vehicle CAFE, TCO, air damages, oil displacement and gasoline tax lost under different criteria and vehicle technology scenarios.

2.6 Research Plan

A four phase research plan is proposed to address the problems defined. Each phase is independent but indirectly builds on each other. Each phase of this research will be presented in an individual research paper.

2.6.1 Phase 1:

Involves the development of a PHEVs model for US automakers with new fuel economy methods to quantify the benefits and calculates the saving of the integration of PHEV technology in automaker vehicles fleet.

2.6.2 Phase 2:

Involves an economic cost/benefits analysis to the consumers accounting for different scenario and including a sensitivity analysis of the parameters.

2.6.3 Phase 3:

Involves constructing a comprehensive literature review of PHEV penetration rate model studies.

2.6.4 Phase 4:

Involves the developing the multi-criteria modeling system.

Chapter 3- Analysis of Corporate Average Fuel Economy Regulation Compliance Scenarios Inclusive of Plug in Hybrid Vehicles

3. Chapter Summary

The US corporate average fuel economy (CAFE) standards dictate the fleet fuel economy that must be achieved by automakers that manufacture and sell automobiles in the US. CAFE standards have increased by 24% (for the passenger car fleet) – 35% (for the light-truck fleet) over the period 2012-2016. This study compares the effects of 3 designs of plug in hybrid electric (PHEV) and hybrid electric vehicles to estimate the cost of CAFE compliance with PHEVs as a component of the domestic passenger car fleet and as a component of the domestic light truck fleet. Results show that in many vehicle classes, PHEVs with 20 miles of electric vehicle range have a lower cost of CAFE compliance than both grid-independent HEVs and PHEVs with 60 miles of electric vehicle range. Passenger car PHEVs are shown to provide reduced costs of CAFE compliance than the suite of conventional technologies used to benchmark CAFE compliance costs. Overall, results show that PHEVs can contribute to a reduction in the costs of CAFE compliance for domestic automakers and should be considered in near-term regulatory and industrial analyses of CAFE compliance strategies.

3.1 Introduction

The first automobile fuel efficiency standards were passed in 1975 by the US Congress as part of the Energy Policy Conservation Act (EPCA). In 1978, this legislation set the minimum acceptable corporate average fuel economy (CAFE) standard at 18.0 mi gal^{-1} (mpg) for passenger cars. EPCA sets a penalty of $5 per vehicle for every 0.1 mpg that the CAFE is below the standard, and sets up credits that are available when a corporation's

CAFE exceeds the standards [1,81]. CAFE requirements have been incrementally increased to 26.0 mpg by 1985, to 27.5 mpg by 1989, and to 37.8 mpg by 2016 in the passenger car fleet [2]. Automakers have developed vehicles to meet these increasing CAFE standards by continuously developing and incorporating a suite of technologies including light-weighting, higher efficiency, and alternative fuel vehicles.

Historically, numerous studies have debated the cost effectiveness of CAFE regulations in effectively improving fleet fuel economy. Whereas some studies found that higher CAFE standards are responsible and effective for improving fleet fuel economy [82–84], others find that the CAFE standard has unintended consequences to fleet makeup [85,86], job displacement [87], increased vehicle purchase price [85], and consumer choice [31] that dilute the regulation's effectiveness. These techno-economic or econometric studies rely on technology-specific cost and fuel economy estimates. The costs of CAFE compliance has been quantified for technologies including clean diesel engines [88], alternative fuels [89], passenger cars [90], light trucks [90], and other developing light-weighting and efficiency-improving technologies [91]. The debate regarding the effectiveness of CAFE has been reinvigorated due to the recent increases in CAFE requirements [2]. Again, researchers and policy makers are debating the cost effectiveness of regulatory compliance using the emerging suite of fuel economy improvement technologies that will be available in the near future.

Plug-in hybrid electric vehicles (PHEVs) are one of these emerging technologies whose impact on a manufacturer's CAFE compliance costs must be analyzed. PHEVs are hybrid electric vehicles which can draw and store energy from an electric grid. The benefits of plug-in hybrid vehicles are that they displace petroleum energy with multi-source electrical energy. PHEVs are generally characterized by lower petroleum consumption, lower criteria emissions output, and lower carbon dioxide emissions than conventional vehicles [3]. A variety of studies have quantified PHEV fuel efficiency and incremental costs in order to understand their value to consumers [4,5,9–12]. To date, no studies have considered the value of PHEVs to automakers and policy makers in achieving CAFE compliance [2]. Some studies have made low-order assumptions positing a limited role for PHEV's in CAFE compliance. Cheah and Heywood (2011) considered only one PHEV design, and lumped PHEV compliance costs with the costs of other HEV technologies [91]. NHTSA includes PHEVs in some vehicle classes of the VOLPE CAFE compliance costs model [2], but incremental costs (>$16,215 for the midsized car) and benefits (fuel consumption increase for the midsized car of <48%) are outside of the ranges found in recent reviews [3,92]. Only PHEVs with 20 miles of ZEV range was considered, and NHTSA uses outdated PHEV utility factors to represent weighted fuel consumption. A more rigorous quantification of the value of PHEVs in meeting CAFE regulations would allow consideration of CAFE costs in PHEV retail price equivalent models [4], in automaker CAFE compliance models [93], and in PHEV market diffusion studies [18,23,24,28,94–96].

Based on this understanding of the field, the goal of this study is to calculate the economic value of PHEVs in allowing an automobile manufacturer to meet increasing CAFE standards. This study describes a model of the CAFE compliance of a major US automaker for model years 2012-2016. Updated models of HEV and PHEV fuel economy and incremental costs are used to quantify the relative costs and benefits of these vehicle technologies. Results and discussion sections compare the costs of CAFE compliance among HEV technologies, and vehicle types. The results of this work can inform automakers, policy makers and technical analysts about the incentives to PHEV production that are implicit in current CAFE regulations.

3.2 Methods

To understand the value of PHEVs in meeting CAFE requirements, we must construct an analysis environment that can connect individual PHEV fuel economy and costs to the CAFE compliance costs of a vehicle manufacturer. To determine the effect of HEV and PHEVs on CAFE standards and on the US passenger-vehicle market, a baseline analysis is performed using Ford Motor Company fleet data for the 2008 model year.[19] In this baseline analysis we have included vehicle prices (based on manufacturer's suggested retail prices, MSRP), unit sales, and unadjusted EPA fuel-economy ratings (mpg) for 2008 model year vehicles sold in the US by Ford Motor Company.[20] The baseline analysis is then extended to measure the value of PHEVs in meeting the proposed NHTSA CAFE standards for 2012-2016.

The inputs to the analysis are PHEV market penetration, PHEV fuel economy, PHEV type (HEV 0, 20, 60), and the PHEV class (compact car, midsized car, midsized SUV and large SUV).[21] The output from the analysis is the CAFE and the total and incremental costs of compliance with the CAFE regulation. The model is composed of 4 sub-models: the Vehicle Classification Model, the CAFE Calculation Model, the PHEV Incremental Cost

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[19] Ford Motor Company experienced a variety of changes to its corporate fleet over the course of MY 2008 which complicate the modeling of Ford's CAFE compliance for that year. In MY 2008 Ford Motor Company owned Mercury, Lincoln and Volvo vehicles. Ford Motor Company sold Jaguar and Land Rover to Tata Motors on June 2, 2008, the cars and trucks from those vehicle marques are included up to May 31, 2008 in the imported passenger cars or trucks fleets. Ford Motor Company owns some stake in Mazda Company and quantities of the owned vehicles are included in the model. The assignment of domestic or imported "I" vehicle types to each class is listed in Table 1. Table 10 of Appendix A lists the volume, MSRP and fuel economy of each domestic and imported carline modeled.

[20] Calendar-year unit sales: www.autonews.com, 'U.S. light-vehicle sales by nameplate, December & 12 months 2008'. Manufacturers' suggested retail prices (MSRP) for many configurations of each vehicle model: www.thecarconnection.com, www.autoguide.com, 'New Car Pricing' for 2008 model year. Model-year combined estimated fuel economy for actual driving conditions (i.e., as indicated in the new vehicle window sticker), for multiple configurations of engine size, transmission type, drive wheels: EPA, Office of Transportation and Air Quality, www.epa.gov/otaq/fedata.htm, 2008 model year.

[21] Pickup trucks and minivans are excluded from consideration for conversion to PHEVs because no examples of consumer-oriented PHEV minivans or pickup trucks exist in literature. Examples of PHEV compact cars, midsized cars, midsized SUVs, and large SUVs have been proposed and demonstrated [3].

Model, and the PHEV Fuel Economy Model. Each sub-model is described in detail in the following sections.

3.2.1 Vehicle Classification

To generalize the results and group vehicles of similar fuel economy and costs, every manufactured vehicle for the model vehicle manufacturers is allocated to a vehicle fleet, and vehicle class. The four vehicle fleets considered are domestic passenger cars, domestic light-trucks, imported passenger cars, and imported light-trucks. The division into vehicle classes for Ford Motor Company 2008 model year is shown in Table 2. These vehicle classes define groups of vehicles with similar functionality, fuel economies and costs. Vehicle class categories are based on the US EPA classifications with two additional vehicle class categories (luxury small, and luxury large) as in [90]. The luxury small car class is formed from mid-sized cars with an MSRP greater than $30,000. The luxury large car class is formed from full-sized cars with an MSRP greater than $30,000. The luxury vehicles have higher prices at lower fuel economy than their mid-sized or full-sized class median counterparts. The light truck fleet is made up of trucks with GVWR at 8,500lb or less. Based on their footprint area, SUVs are classified into small (less than 43 sq ft), mid-size (43 to 47 sq ft) and large classes (48 to 55 sq ft).[22]

Because each vehicle sold has a large variation in engine size, transmission type, even within makes and models, the price and the fuel economy rating for each class defined as the class median of each vehicle price and the class median of each vehicle fuel economy rating [90]. Table 2 lists the summary characteristics of the baseline fleets.

[22] Table 10 and 11 of Appendix A lists the classification of each domestic and imported carline for the 2008 Ford Motor Company model.

3.2.2 CAFE Calculation

For this study, the calculation of CAFE is performed as shown in (1)

$$\text{CAFE} = \frac{\text{Total Fleet Production}}{\sum_{i}^{n} \frac{\text{Sum Of Class "}i\text{" Vehicle}}{\text{Fuel Economy Of Class "}i\text{" Vehicle}}} \tag{1}$$

Where *i* is the vehicle class and *n* is the number of vehicle classes in the fleet. All calculations performed in this study are compliant with the most recent CAFE standards [81].

Table 2. Ford Motor Company 2008 Fleet Characteristics

Fleet	Vehicle Class	Quantity Sold (CY 2008)	Class Median MSRP, 2010$	Class Median Unadjusted FE (mpg)
Domestic Passenger Cars (DP)	Subcompact Cars	91,251	$19,901	25.21
	Compact Cars	195,823	$14,579	36.78
	Midsize Cars	238,457	$19,362	30.78
	Large Cars	147,177	$24,089	25.41
	Luxury Small	12,982	$45,838	24.87
	Luxury Large	15,653	$41,393	22.83
Light Trucks (GVWR is 8,500lb or less) (LT)	SUV Mid-Size	195,418	$21,815	31.91
	SUV Large	321,980	$27,143	24.56
	Small Pickup	66,581	$15,205	23.40
	Large Pickup	520,144	$23,294	21.05
Imported Cars (IP)	Two-Seater	6,085	$20,899	31.27
	Mini Compact Cars	1,307	$75,792	24.58
	Subcompact Cars	1,548	$26,773	24.20
	Compact Cars Mazda	49,129	$14,073	36.15
	Compact Cars	25,190	$27,158	30.00
	Midsize Cars	22,475	$44,348	25.89
	Luxury Cars	12,171	$51,926	24.54
Imported Light Trucks (IT)	Minivan	10,561	$18,225	31.13
	SUV Mid-Size	22,452	$34,420	22.51
	SUV Large	36,212	$42,909	20.71

The results of the CAFE calculation for the baseline fleet are presented in Table 3. The 2008 required CAFE standards are 27.5 mpg for the passenger car fleet and 22.5 mpg for the light car fleet. To validate the fleet classification and CAFE calculation we can compare the predicted and actual fuel economy and sales volumes [97] for Ford Motor Company for calendar year 2008. Table 3 shows that the modeled CAFE for Ford Motor Company 2008 calendar year is 29.61 mpg for the passenger car fleet and 23.51 mpg for the light truck fleet. These results are comparable to Ford's CAFE as estimated by NHTSA of 30.1 mpg for the passenger car fleet and 23.6 mpg for the light truck fleet [97]. This comparison generally validates the effectiveness of the CAFE compliance model for prediction of the CAFE of Ford Motor Company. Discrepancies between the modeled and actual CAFE are due to the fact that the CAFE compliance calculations performed for each automaker are not publically available. The model is an approximation of a large US automaker's CAFE, which is based on the data for Ford Motor Company, but it does not represent any automaker with perfect precision.

Table 3. CAFE Calculated from the CAFE Compliance Model for Ford Motor Company 2008 MY

	CAFE (mpg)		Sales Volumes	
Fleet	Predicted from this work	Reported in NHTSA 2011	Predicted from this work	Reported in NHTSA 2011
DP	29.61	30.1	701,343	699,957
LT	23.60	23.6	1,104,123	1,266,265
IP	30.43	31.1	117,905	202,811
IT	22.44	N/A	69,225	N/A

3.2.3 Plug-in Hybrid Electric Vehicle Incremental Costs

With a validated CAFE compliance calculation model, we can consider the effect of PHEV sales penetration on the costs of CAFE compliance. In this section, we present the methods used to calculate the incremental cost to the manufacturer of production of PHEVs. The base price for each CV is taken to be the median of its manufacturer suggested retail price (2008 MSRP) for the different designs within each vehicle class. The incremental cost for production of each PHEV includes the costs of electric drive, electric accessories, energy storage systems, and charger.

The primary reference for incremental PHEV costs are the series of PHEV design studies performed by EPRI [4,5]. The component size and incremental cost for all components except the battery is derived from these reports, inflated to 2010$. The retail price equivalents (RPE) reported here are the average of the "Base" and "ANL" methods at production levels of 100,000 units per year, inflated to 2010$. Battery costs for modern lithium-ion (Li Ion) batteries are derived from [98] under the production scenario of 100,000 packs per year. This reference is chosen as is more conservative (in terms of higher cost per kWh and cost per mile of EV range) than other primary information sources on battery production costs [99–101]. The costs for each Li Ion battery are inflated to 2010$ and added to the incremental component cost to represent the incremental cost of PHEV production in 2011, shown in Table 4. These costs are comparable to other recent studies of PHEV incremental manufacturing costs, and as in other recent PHEV studies, the PHEV technology is estimated to be applicable to all vehicles in the vehicle fleet [102].[23]

The incremental costs are assumed constant over the time period of this study (2012-2016). Battery subsidies, vehicles subsidies, and short-term alternative fuel CAFE multipliers are not considered in this study because they are subject to modification, are short-lived, and represent an economic transfer, not an economic efficiency. Infrastructure costs are not included in the MSRP of the vehicle in accordance with current automakers' policy, none of whom support infrastructure costs.

[23] For example, ANL calculates the incremental cost of a mid-sized PHEV 20 series vehicle (this study considers parallel vehicles) as $4,701 in 2015, and $7,347 in 2010 [102].

Table 4. Characteristics and Incremental Retail Price Equivalent (Incr. RPE) for HEVs in 2010$ **[4,5,98]**.

Class	HEV type	Battery Rated Capacity (kWh)	Electric Motor Power (kW)	Incr. RPE with Li Ion Battery (2010$)
Compact Car	HEV 0	2.2	23	$4,050
	PHEV 20	5.1	37	$6,487
	PHEV 60	15.4	61	$10,528
Mid-Size car	HEV 0	2.9	44	$3,881
	PHEV20	5.88	51	$5,714
	PHEV60	17.9	75	$9,791
Mid-Size SUV	HEV 0	4.1	51	$5,577
	PHEV 20	7.9	84	$8,355
	PHEV 60	23.4	89	$11,616
Full-Size SUV	HEV 0	5.2	65	$5,634
	PHEV 20	9.3	98	$7,487
	PHEV 60	27.7	117	$12,197

3.2.4 PHEV Fuel Economy

The SAE J1711 fuel economy method is the recommended practice for measuring the exhaust emission and fuel economy of hybrid vehicles. SAE J1711 defines a number of concepts required for the reporting of a single number for PHEV fuel economy: 1) a series of urban and highway utility factors (UF_U and UF_H , described in Table 5) which defines the ratio of distance travelled powered by electricity to the total miles traveled for each driving type [6], 2) fully charged test energy consumption (FCT_U and FCT_H) in units of kWh mi^{-1}, and 3) partially charged test fuel economy (PCT_U and PCT_H) in units of mi gal^{-1}.

Table 5: Utility Factor as defined in J2841 **[6]**.

	PHEV20	PHEV60
UF_U	0.54	0.90
UF_H	0.23	0.55

The following formulae define the J1711 utility factor weighted petroleum-only fuel economy for ZEV-range capable PHEVs for whom FCT_U and $FCT_H = 0$.

$$\text{UF Urban} = \frac{1}{\frac{1-UF_U}{PCT_U}} \tag{9}$$

UF Hwy = $\dfrac{1}{\dfrac{1-UF_H}{PCT_H}}$ (10)

UF Petroleum FE = $\dfrac{1}{\dfrac{0.55}{UF\_Urban}+\dfrac{0.45}{UF\_Hwy}}$ (11)

This method places no fuel economy cost on electricity since the petroleum content of marginal electricity is negligible [3] and is the method proposed in current CAFE regulations [2]. The fuel economy ratings for the compact car, mid-sized Car, mid-sized SUV and large-sized SUV vehicle classes are calculated using this fuel economy method. The results are listed in Table 6. The values of FCT_U, FCT_H, PCT_U and PCT_H for each vehicle class are derived from [4,5].

Table 6. Passenger Car and Light Truck Utility Factor Weighted Petroleum Fuel Economy (EPA Unadjusted mpg)

Vehicle Class	HEV 0	PHEV 20	PHEV 60
Compact Car	49	90	226
Mid-Size Car	42	74	186
Mid-Size SUV	33	59	146
Large-Size SUV	28	50	123

3.3 Baseline Results

The results from the baseline analysis describe the status of the modeled automaker in the 2008 calendar year and using modified version of NHTSA modeled fleets. These results present the sensitivity of the metric of $ per CAFE-mpg to variation in the characteristics of the PHEVs introduced to the fleet (vehicle class, HEV type). All costs presented in this study are presented in constant 2010 USD.

To calculate the $/mpg CAFE, the percentage of the vehicle fleet is incremented from 0% to 5% HEV/PHEV penetration for the modified NHTSA 2011 forecasted fleet.[24] The metric of $ per CAFE-mpg is the ratio of the incremental compliance costs of the new vehicle fleet to the incremental CAFE increase. All comparisons are made relative to the modified NHTSA Ford Motor Company CAFE compliance model for 2011. These results show the relative cost-effectiveness of PHEVs in contributing to an increase in CAFE. In comparing among vehicle fleets and HEV types, the lower the compliance costs of achieving a 1 mpg increase in CAFE, the more effective the vehicle is at meeting CAFE standards.

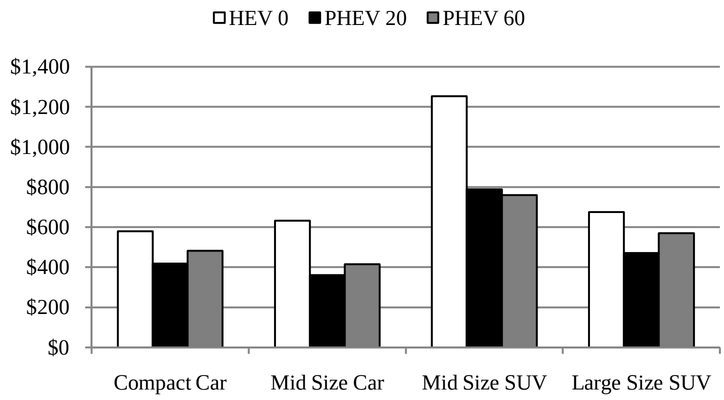

Figure 2. Cost of increasing the modified NHTSA fleet CAFE one mpg with a 5% fleet penetration of HEV/PHEVs (in millions of 2010US$)

For these baseline results presented in Figure 2, we have incremented HEV/PHEV penetration in the compact and mid-sized car classes of the passenger car fleet, and in the mid-sized and large-sized classes of the light truck fleet. The variation in the incremental cost of CAFE compliance for every vehicle fleet is due to the fact that each class has different sales quantities, fuel economy rating, HEV fuel efficiency improvement, and incremental cost. In the passenger car fleet, the incremental cost of improving the fleet fuel economy by

[24] Modifications made to the NHTSA Ford Motor Company model include the transfer of light-trucks from the passenger car fleet to the light-truck fleet, and the removal of imported vehicles from the domestic passenger and light truck fleet. Appendix A show the detailed makeup of the modeled Ford Motor Company fleet

1 mpg ranges from $360M to $417M using PHEV 20 and $415M to $481M using PHEV 60. In the light truck fleet it ranges from $471M to $789M using PHEV 20 and $570M to $760M using PHEV 60. The PHEV 20 has the lowest compliance cost per 1 mpg increment in CAFE in the compact, mid-sized, and large SUV classes. The PHEV 60 has lowest costs in the mid-sized SUV class. Among vehicle classes, hybridization of the mid-sized car is more CAFE cost effective than hybridization of other vehicle classes. Within the truck fleet, hybridization of the large SUV class is more CAFE cost effective than hybridization of smaller SUVs.

The costs of achieving a 1 mpg increase in CAFE depend on the technology choices that automakers might make among HEV/PHEV technologies. The results from this baseline scenario analysis suggest that there may be benefits to PHEVs relative to HEVs in terms of the costs of CAFE compliance. For example, using the Utility Factor Weighted Petroleum Fuel Economy method to evaluate PHEV FE, the automaker's costs of CAFE compliance can be decreased by selling PHEVs rather than HEVs. The savings from manufacturing PHEV20s rather than HEVs ranges from $97M to $272M per CAFE-mpg in the passenger car fleet, and from $105M to $493M per CAFE-mpg in the truck fleet.

Based on these results, we can prioritize which types of vehicles and fuel economy metrics should be developed in order to meet increasing CAFE standards. Overall, the PHEV20 in the mid-sized car class is the most cost effective hybrid type for meeting increasing passenger car CAFE standards. The PHEV20 in the large SUV class is the most cost effective means to meet increasing light truck CAFE standards.

3.4 Discussion

The results of these baseline analyses show that PHEVs may have value as a means to achieve CAFE compliance for a major automaker in the MY 2011. This section provides discussion and scenario analyses that use the expanded results of the CAFE compliance analysis environment to provide guidance to policy makers and automakers regarding the relative value of PHEVs in a CAFE-constrained framework.

3.4.1 Comparison of PHEV Inclusive Scenarios to NHTSA Preferred Alternative Scenario

In the coming years, automakers will choose among a suite of technologies to devise a portfolio of vehicles which can meet the proposed CAFE regulations with minimal costs. NHTSA, in studies used to develop the CAFE regulations, models the costs of CAFE regulation compliance for each automaker using the VOLPE model [2]. VOLPE uses a decision tree model of automaker decision making to predict which technologies each automaker might use to meet future CAFE regulations. The decision making within VOLPE is based on a variety of decision criteria including technological readiness, CAFE effectiveness, and cost. The result of the VOLPE analysis is a set of technological improvements that the automaker can make to their fleet which allows the automaker to meet CAFE regulations. The most likely and cost effective of these scenarios is called the NHTSA preferred alternative CAFE scenario [2]. The NHTSA preferred alternative CAFE scenario includes no PHEV sales between the present and 2016 because VOLPE estimates that automakers will not implement PHEVs for CAFE compliance in that time frame. In fact, limited-production PHEVs have been introduced in 2004 [103] and full-production PHEVs have been introduced for 2011 model year (Chevrolet Volt). These data suggest that PHEVs should be considered in predicting possible near-term CAFE costs of compliance.

NHTSA has proposed new footprint-based CAFE standards [81]. The CAFE standard for 2012-2016 was applied to Ford Motor Company 2008MY fleets using NHTSA 2011 reported footprint-based CAFE target coefficients. The proposed calculated CAFE standards for 2012-2016 are presented in Table 7 for Ford Motor Company passenger car and light truck fleet using a modified NHTSA fleet model under the preferred alternative CAFE scenario.

Table 7. Modeled CAFE Standards Proposed for the Ford Motor Company Fleet Model

Modified NHTSA Preferred Alternative Model Fleet	2012	2013	2014	2015	2016
Passenger Car	32.66	34.73	34.62	35.98	37.05
Light Truck	27.35	27.93	28.23	29.58	30.40

To compare the cost effectiveness of a CAFE compliance scenario which includes PHEV technology to the NHTSA preferred alternative technology portfolio, we can model both scenarios in the CAFE compliance analysis developed for this study. Comparisons within this framework are preferable because a direct comparison within VOLPE is muddied by the requirements of the VOLPE decision tree.

To define the cost of compliance under the NHTSA preferred alternative CAFE scenario, the penetration rate, incremental costs, proposed fleet volumes, and fuel efficiency of NHTSA preferred alternative CAFE scenario are input to the CAFE compliance analysis environment. The total cost of compliance and CAFE is calculated for the passenger car fleet and light truck fleet for the years 2012-2016. The cost of CAFE compliance for the NHTSA preferred alternative CAFE scenario can then be directly compared to the cost of CAFE compliance under various PHEV-inclusive scenarios. For the PHEV-inclusive scenarios, the incremental costs and fuel efficiency of the PHEV fleet is derived using the methods presented in Section 2. To enable a direct comparison between NHTSA preferred alternative scenario and the PHEV-inclusive scenarios, the same fleet model and sales volumes are used.

To find the optimal number of PHEVs that are needed to meet the preferred alternative required CAFE for Ford Motor Company, we have formulated the problem as a mathematical optimization problem. The optimization minimizes the cost to achieve Ford

Motor Company's required CAFE using HEV, PHEV20 and PHEV60 where applicable with no other technological advancements made to the fleet. The problem is cast as a linear programming (LP) model, which is run for each fleet (Passenger Car, and Light Truck) and for each year (2012-2016) by specifying the, carlines, carlines volumes, carlines fuel economy, technology cost, technology fuel economy and required fleet CAFE. The (LP) model is presented below:

Minimize $V_k = \sum_{j=1}^{n} \sum_{d=1}^{m} c_d x_{djk}$

Subject to

$\sum_{d=1}^{m} x_{djk} = a_{jk}$ (for all j, $j = 1, \ldots, n$)

$$\frac{\sum_{j=1}^{n} a_{jk}}{\sum_{j=1}^{n} \sum_{d=1}^{m} \frac{x_{djk}}{FE_{djk}}} = CAFE_k$$

$x_{djk} \geq 0$ (all integers)

Where,

c_d = d technology cost;

x_{djk} = carline j with technology d volume at year k;

a_{jk} = the forecasted carline j volume at year k;

FE_{dj} = the unadjusted fuel economy carline j with technology d;

$CAFE_k$ = the required planned fleet CAFE at year k;

j = the carline within the fleet analyzed (*j* = 1, 2, …., *n*);

d = the technology type (*d* = 1, 2, .., *m*), CV =1, HEV = 2, PHEV20 = 3, PHEV60 = 4,

k = the year at which the CAFE standard and fleet is proposed (2012-2016);

n = the total number of carlines;

m = the total number of technology types;

The output of the LP model is the makeup of a minimum cost CAFE compliant fleet for the Ford Motor Company model for 2012-2016. The yearly costs of compliance for the PHEV-inclusive passenger car fleet for each of the years 2012-2016 are shown in Table 8. The total cost of using NHTSA preferred alternative technologies for the period 2012-2016 can be summed to $8.78 billion using the modified NHTSA PC fleet. This summed cost of CAFE compliance is comparable to a $5.7 billion cost of CAFE compliance inclusive of PHEVs.

Table 8. Comparison of PHEV Costs of CAFE Compliance to NHTSA Preferred Alternative Costs of CAFE Compliance Using the Modified NHTSA Passenger Car fleet (In Millions of 2010US$)

CAFE	Year	PHEV Inclusive Scenario	NHTSA Preferred Alternative CAFE Scenario
32.66	2012	$784	$1,816
34.73	2013	$1,125	$1,597
34.62	2014	$1,093	$1,639
35.98	2015	$1,279	$1,776
37.05	2016	$1,410	$1,952
Total	2012-2016	$5,691	$8,781

In the light truck fleet, the yearly costs of CAFE compliance for both NHTSA preferred alternative and PHEV-inclusive scenarios are shown in Table 9. The total costs of CAFE compliance under the NHTSA preferred alternative CAFE scenario is $6.23 billion when using the modified NHTSA LT fleet. By adding mid-sized and large SUV PHEV, the total costs of compliance is $12.02 billion. Unlike the results for the passenger car fleet, the costs of CAFE compliance for the light-truck fleet are increased by using PHEV technology.

Table 9. Comparison of PHEV Costs of CAFE Compliance to NHTSA Preferred Alternative Costs of CAFE Compliance Using the Modified NHTSA Light Truck Fleet (In Millions of 2010US$)

CAFE	Year	PHEV Inclusive Scenario	NHTSA Preferred Alternative CAFE Scenario
27.35	2012	$2,060	$888
27.93	2013	$2,043	$965
28.23	2014	$2,035	$1,062
29.58	2015	$2,964	$1,591
30.40	2016	$2,923	$1,727
Total	2012-2016	$12,025	$6,233

This analysis shows that PHEVs can be a technological means for reducing the costs of CAFE compliance for US automakers when used in the Passenger Car fleet. Between 2012 and 2016, the manufacture and sale of PHEV to meet CAFE regulations can reduce the costs of compliance for our modeled auto manufacturer by up to $3.09 billion for the passenger car fleet. In the light truck fleet, conventional fuel economy technologies are more cost effective at achieving CAFE compliance.

In planning and implementing the introduction of advanced technology vehicles, automakers must make multi-objective, multi-criteria decisions which take into account new technologies' consumer acceptability, mix-shifting, banked credits, historical profitability of products, technology development ramp-up rates, and more. As in other studies of CAFE costs of compliance for a particular technology [1,90] no attempt is made to model these decisions explicitly. Instead, these scenarios are meant to be informative of the decision making process, but not inclusive of all decision making criteria.

3.4.2 Per Vehicle Accounting of Reduced CAFE Compliance Costs

Previous research has attempted to quantify the value of each PHEV sold in terms of its value to the consumer lifecycle costs savings to the consumer [4,5] and its environmental and social value to society [12]. The results of this study have now quantified the direct value to automakers of CAFE compliance costs which can be avoided through development and sales of PHEVs. To consider the total value of each PHEV against its total incremental costs, we must consider the avoided costs of CAFE compliance as a value attributable to PHEV.

The methods of this study are used to calculate the avoided costs of CAFE compliance. These avoided costs can then be normalized by the number of PHEVs sold in each scenario to determine the value added of each individual PHEV. The value of the reduced CAFE compliance costs for each PHEV sold between 2012 and 2016 is presented in constant 2010US$ in Table 10. For both passenger cars and light trucks, the reduction in CAFE compliance costs to the automakers is approximately 50% of the average incremental PHEV retail price in the passenger car fleet, significantly reducing the incremental cost of PHEV production to the automaker.

Table 10. Average Benefits of a PHEV (In Constant 2010$) Over Each PHEV Sold Using NHTSA Modefied Fleet

PHEV Type	Fleet	Value or costs to Auto Manufacturer in Avoided CAFE Costs	Average PHEV Incremental Cost
PHEV 20	Passenger Car	$2,321	$4,274
PHEV 20 & PHEV 60	Light Truck	-$3,082	$6,398

This type of analysis suggests that the price barriers which are understood to limit the consumer acceptability of passenger car PHEVs can be reduced through accounting for the value of PHEVs as a means to reduce the costs of CAFE compliance. For light trucks, the conversion to PHEVs is not as cost effective as more conventional technologies for fuel economy improvement.

3.5 Chapter Conclusions

This study has calculated the relative value that PHEVs can have in reducing an automaker's costs of CAFE compliance. To perform that evaluation, we have developed a framework for modeling the effect of PHEV fleet penetration on the automaker's cost of compliance with CAFE regulations. The baseline results show that in both the passenger car and light truck fleets, PHEVs have a lower cost of compliance with CAFE regulations than conventional HEVs. A more detailed scenario analysis shows that passenger car PHEVs can enable a lower CAFE cost of compliance than the suite of more conventional technologies considered in NHTSA's preferred alternative scenario. The reduction in CAFE compliance costs to the automakers is approximately 50% of the average incremental PHEV retail price in the passenger car fleet, thereby potentially reducing the incremental cost to the automaker of PHEV production and sale.

These results can be used by automakers and regulators to understand the incentives for PHEV production that are preexisting in the CAFE regulations, but the methods that will be used to reap these incentives will be specific to each automaker's market, regulatory, financial and consumer position.

Chapter 4-Total Cost of Ownership, Payback, and Consumer Preference Modeling of Plug-in Hybrid Electric Vehicles

4. Chapter Summary

Motor vehicles represent one of the widely owned assets in the US. A vehicle's ownership cost includes fixed expenses to purchase and own the vehicle and variable costs to use and operate the vehicle. Policymakers, analysts and consumers are interested in understanding the total vehicle ownership costs of various vehicle types and technologies so as to understand their relative consumer preference and valuation. Plug-in hybrid electric vehicles are an advanced technology vehicle that is presently in limited production, but whose relative cost of ownership is not well-defined. A few studies have attempted to calculate the costs and benefits of PHEVs but none consider the cost and benefits of PHEVs at a level of detail comparable to what has been performed for other vehicle technologies. In order to understand the costs and benefits of PHEVs purchase and use, this study constructs a comprehensive ownership cost model. The model is then used to analyze different PHEV designs within four vehicle classes. This study then performs a sensitivity analysis to understand the sensitivity of total ownership cost and payback period to model parameters and the modeled components of ownership costs. Results show that a more comprehensive PHEV ownership cost model has a lower net cost of ownership than studies to date, resulting in a shorter payback period and higher consumer preference.

4.1 Introduction

Plug-in hybrid electric vehicles (PHEVs) are hybrid electric vehicles which can draw and store energy from the electric grid. The benefits of plug-in hybrid vehicles are derived from their capability to displace petroleum energy for transportation with multi-source electrical energy. PHEVs are generally characterized by lower lifecycle petroleum consumption, lower fueling costs, lower criteria emissions output, and lower carbon dioxide emissions than conventional vehicles [3], but at a higher manufacturing cost than conventional vehicles. Many automobile manufacturers have announced plans to develop PHEVs: GM Chevrolet Volt in 2010, FORD PHEV Escape in 2012, Toyota PHEV Prius in 2012, NISSAN PHEV in 2012, VOLVO PHEV in 2012, Chrysler PHEV in 2012, Volkswagen PHEV Golf Twine-Drive in 2011, Saturn PHEV VUE in 2010, Audi PHEV A1 Sport-back in 2011 and Hyundai PHEV Sonata in 2013 [8].

Despite their recent market introductions, the market potential and consumer acceptability of PHEVs are not well understood. A variety of studies have attempted to assess the market potential of PHEVs through tabulation of the fuel economy benefits and incremental costs of PHEVs [4,5,9–13]. These studies have generally concluded that in order for the PHEVs to reach economic viability, technology advancements must decrease the incremental cost of the vehicle over conventional vehicle costs, and regulation or macro-economic forces must increase the price of gasoline fuels to above roughly \$5.00 gallon^{-1} [10,12,14,16]. This consensus view of PHEV economics must be tempered by an understanding that these studies incorporate a wide range of scopes, vehicle usage models, ownership cost categories, and consumer preference models. Their analyses result in a wide variety of numerical valuations of PHEV economics, and these studies' assumptions and scopes have not been compared or synthesized.

The goal of the research effort documented in this paper is to more systematically synthesize a PHEV total cost of ownership (TCO) and consumer acceptability model so as to test this consensus view. This paper presents such a TCO model and compares it to the primary literature for PHEV techno-economic modeling so as to understand the effects of these studies' scope, methods and assumptions. A more comprehensive TCO model is shown to require significant increase in scope over previous models in literature. The TCO model proposed for this study includes models of various vehicle types, various PHEV types, vehicle purchase cost, loan cost, tax cost, insurance cost, annual registration cost, fuel cost, maintenance cost and salvage value. We then present the sensitivity of TCO and payback period to vehicle characteristics, economic assumptions and model scope. Survey data regarding consumer preference for PHEVs is then enrolled to understand the relationship between costs, benefits and consumers' willingness to pay for PHEVs. Finally, conclusions present a more comprehensive summary of the value, cost and market potential of PHEVs in the near-term.

4.2 Review of PHEV Techno-Economic Studies

Four studies form the primary and most cited sources of information on the techno-economics of PHEVs [10,12,14,104]. Other studies performing PHEV analysis cite these primary studies [9,92]. Model parameters and assumptions for these primary studies and this study are listed in Table 1.

Evaluation and synthesis of the results of these previous studies is complicated by differences in their scopes, assumptions and modeled components of each study. In order to design a more relevant, refined and comprehensive model of PHEV TCO and consumer acceptability, this study proposes to update the scope, vehicle usage assumptions, ownership costs and consumer preference models as shown in Table 11 For most categories, this TCO model is of larger scope than that of previous studies. For example, electricity and gasoline costs are projected rather than constant, this study uses a standardized utility factor (UF) [6] rather than outdated or low fidelity assumptions, and this study uses consumer preference surveys rather than simple cost-benefit analysis to represent the economic viability of the vehicles. In each category of classification shown in Table 11, this study aims to be more comprehensive, higher fidelity, and defensible than previous studies.

Table 11. Model Parameters and Assumption Used in the Primary PHEV TCO Literature.

		Simpson, 2006 [10]	***Lemoine and Kammen, 2006*** [12]	***AEO, 2009*** [14]	***EPRI, 2004*** [104]	***Al-Alawi & Bradley, 2012***
Study Scope	Vehicle Class	Mid-size sedan	Compact Car, Full-size SUV	Low drag, Mid-size sedan	Mid-size Car, Full size SUV	Compact Car, Mid-size Car, Mid-size SUV and Large SUV
	PHEV Type	HEV, PHEV2, 5, 10, 20, 30, 40, 50, 60	HEV, PHEV20	HEV, PHEV5, 10, 15-60	EV, HEV, PHEV20	HEV, PHEV5, 10, 15-60
	Battery Type (Mid-Size PHEV 20 car battery rated capacity)	Li-Ion, (11.8 kWh)	NiMH, (5.1 kWh)	Li-Ion, (8.8 kWh)	NiMH, (5.88 kWh)	Li-Ion, (5.88 kWh)
	Economic Year	2006$	2008$	2007$	2003$	2010$
Vehicle Usage Assumptions	Vehicle Miles Traveled (VMT) Model	15,000 miles/year, constant	11,000 miles/year, constant	14,000 miles/year, constant	117,000, 150,000 mile in total	12,000/year for Cars and 15,000/year for Light Truck, corrected for decline in vehicle usage with age
	Vehicle life	15 years	12 years	6 years	10 years	5 years, 13 years
	Charging assumption	Full recharge each day	Full recharge each day	Full recharge each day	Full recharge each day	Full recharge each day
	Utility Factor, (UF) type	1995 NPTS-derived UF, with a 50% chance of starting the day charged	250 days/year fueled by electricity, the rest fueled by gasoline	None, 37% of VMT assumed fueled with electricity	26% of VMT assumed fueled with electricity (73% gasoline)	SAE J2841 UF
	Fuel Economy Method	Modified J1711, EPRI 2001	MWP Weighted, EPRI 2002	105 mpg CD, 42 mpg CS modes, EPRI 2001	UF weighted	UF weighted gasoline consumption
	Electricity Consumption Method	0.093 kWh/mile for 100% of VMT	Unknown	37% of VMT	26% of VMT	UF weighted electricity consumption
	EPA Adjustment of Fuel Economy	Yes	None	None	Yes	Yes

		Simpson, 2006	***Lemoine and Kammen, 2006***	***EIA, 2009***	***EPRI, 2004***	***Al-Alawi & Bradley, 2012***
Modeled Components of Ownership Costs	Gasoline Cost Model	$5.00/gallon	$2.00/gallon, $3.00/gallon and $4.00/gallon	$3.00/gallon, $4.00/gallon, $5.00/gallon and $6.00/gallon	$1.75/gallon	Forecasted over vehicle life
	Electricity cost Model	$0.09/kWh	$0.05/kWh, $0.10/kWh -$0.30/kWh	$0.10/kWh	$0.05/kWh off peak	Forecasted over vehicle life
	Incremental Cost Model	EPRI	EPRI corrected	Includes tax credit	EPRI 2001, ANL	EPRI, ZEV report ARB
	Vehicle Salvage Value Model	None	None	None	Battery only	Entire vehicle has salvage value
	Maintenance Cost Model	None	None	None	Yes	Yes
	Insurance Cost Model	None	None	None	None	Yes
	Registration Renewal Cost	None	None	None	None	Yes
	Loan Model	None	None	None	None	Yes
	Tax Model	None	None	None	None	Yes
	Discount rate	None	16%, corrects for vehicle depreciation and declining vehicle usage over 12 years, based on 6% interest rate	10%	8%	6%
Preference	Source	Payback Period-based	Payback Period-based	Benefits-based	Benefits-based	Payback Analysis, Benefits Analysis & Consumers Acceptability

4.3 Comprehensive TCO Modeling Methods

To determine the costs and benefits to consumers of a PHEV's purchase and use, we must construct a modeling environment that can connect individual PHEVs costs and benefits components. This study proposes a more comprehensive TCO model that includes all components of ownership costs as modeled in the literature and includes various other relevant ownership costs for PHEVs.

The baseline model is composed of sub-models where each model can be modified and adjusted individually and is described in detail in the sections following the discussion of TCO model scope.

4.3.1 Study Scope

For this study, vehicles of similar fuel economy, functionality size, interior volumes and costs are grouped into vehicle fleets and vehicles classes following EPA vehicle classification methodology[25]. The four vehicle classes considered in our base model are compact car and mid-size car in the passenger car fleet, and mid-size SUV and large SUV in the light truck fleet.

PHEVs can be designed to have different battery capacities, so as to satisfy consumers travel patterns and needs. Because each design will impose different costs and benefits to consumers, thirteen HEVs were designed and analyzed for each class of vehicles. The set of vehicles studied here includes grid-independent HEV0 (conventional hybrid electric vehicles) and grid-dependent PHEVs (of the HEVX-type) with 5 to 60 miles of electric range [3].

HEV and PHEV incremental costs are derived by summing the costs of the Battery, Pack Hardware, Pack Tray, Pack Thermal, Traction Electric Motor, Traction Power Electronics, Traction Power Electronics Thermal, Charger, Charger Cable, Engine, Gasoline

[25] U.S. Environmental Protection Agency, "vehicle size classes," available at http://www.fueleconomy.gov/feg/info.shtml#sizeclasses

Storage Tank, Exhaust, Glider and Assembly Costs, Accessory Battery, and Transmission. The retail price equivalents (RPE) reported here are the averages of the "Base" and "ANL" methods at production levels of 100,000 units per year, inflated to 2010 currency [4,5]. Battery costs for modern lithium-ion (Li Ion) batteries are derived from [98] under the production scenario of 100,000 packs per year. The costs for each Li Ion battery are inflated to 2010 and added to the incremental component cost to represent the incremental cost of PHEV produced in 2010. The incremental RPE for every vehicle in this study is presented in Table 12.

Table 12. Incremental price of PHEVs over CVs base price in US$2010[26]

Vehicle Design	Compact Car Incremental RPE	Mid-Size Car Incremental RPE	Mid-Size SUV Incremental RPE	Large SUV Incremental RPE
HEV0	$4,051	$3,882	$5,578	$5,636
PHEV5	$4,661	$4,341	$6,273	$6,100
PHEV10	$5,270	$4,799	$6,969	$6,563
PHEV15	$5,880	$5,258	$7,664	$7,026
PHEV20	$6,489	$5,716	$8,359	$7,489
PHEV25	$6,995	$6,226	$8,767	$8,078
PHEV30	$7,500	$6,736	$9,174	$8,668
PHEV35	$8,006	$7,245	$9,582	$9,257
PHEV40	$8,511	$7,755	$9,990	$9,846
PHEV45	$9,017	$8,265	$10,398	$10,435
PHEV50	$9,522	$8,775	$10,805	$11,024
PHEV55	$10,028	$9,285	$11,213	$11,613
PHEV60	$10,533	$9,795	$11,621	$12,202

4.3.2 Vehicle Usage

The distance driven in the first year of ownership for passenger cars and light-trucks is modeled as 12,000 and 15,000 miles respectively [107]. To account for decline in vehicle usage, yearly VMT declines at a rate that varies between 2.1% and 4.7% as in [108].

[26] These incremental costs are comparable to other recent studies of PHEVs. For example, ANL calculates the incremental costs of a midsize PHEV 20 series vehicle (this study considers parallel vehicles) as $4701 in 2015, and $7347 in 2010 [105,106]

The gasoline fuel economy for CVs and HEVs is calculated using a utility factor (UF) weighted gasoline-only fuel economy method which assumes that the vehicle is charged on a daily basis. This method places no fuel economy cost on electricity since the petroleum content of marginal electricity is negligible. The method uses the SAE J2841 utility factor for urban and highway driving [7]. The gasoline fuel economy and electrical economy ratings were adjusted using EPA labeling discount (10% for City and 22% for highway). The energy consumptions for fully (FCT) and partially charge tests (PCT) are derived from previous work [4,5]. Equations 1 and 2 represent the calculated annual electricity consumption (E_a) and annual petroleum consumption (G_a) for each class and type of PHEV. Where VMT_a is the annual vehicle miles travelled,

$$E_a = VMT_a \cdot \left(0.55 \cdot \left(\frac{1}{0.9} \right) \cdot UF_U \cdot FCT_U + 0.45 \cdot \left(\frac{1}{0.78} \right) \cdot UF_H \cdot FCT_H \right) \tag{1}$$

$$G_a = VMT_a \cdot \left(0.55 \cdot \left(\frac{1}{0.9} \right) \cdot (1 - UF_U) \cdot PCT_U + 0.45 \cdot \left(\frac{1}{0.78} \right) \cdot (1 - UF_H) \cdot PCT_H \right) \tag{2}$$

4.3.3 Modeled Components

In this study we have considered current and forecasted prices of both gasoline and electricity. Gasoline and Electricity prices for 2012-2024 years are based on EIA 2009 [109] estimates and adjusted to $2010. The salvage value of the vehicle represents its value on the used car market and is modeled as equal to the vehicle MSRP depreciated over the life of the vehicle at 13.8% per year, equivalent to the historical rate of depreciation of the Toyota Prius HEV. Charging infrastructure and electricity service upgrade costs are not included in TCO because they are not required for the PHEVs considered in this study.

4.3.4 Maintenance Cost Model

For each vehicle type we have constructed a maintenance schedule which includes periodic vehicle maintenance, 12V electric battery replacement, brake replacement and tire replacement[27],[28] [110]. The present value of the parts cost and labor cost of each maintenance operation is summed over the life of the vehicle to determine the vehicle lifetime maintenance costs[29],[30]. For CV and HEV, the maintenance costs and schedules were derived from the published costs and schedules for 2010 MY vehicles with similar functionality to the vehicles modeled in this analysis. The maintenance schedule for the CV and HEV is a function of distance travelled. The maintenance schedule for the PHEV includes vehicle maintenance operations that are a function of total distance travelled, and engine maintenance operations that are a function of charge-sustaining distance travelled. Neither the HEV nor the PHEV has a scheduled battery replacement [111].

The maintenance costs and schedules for each vehicle type are presented in detail in Appendix B.

4.3.5 Vehicle Insurance Cost Model

Insurance costs vary by state, insurance company, insurance type and vehicle type. This model of insurance costs represents the cost of insurance premiums with liability, comprehensive and collision coverage as provided by major insurers where the personal information for the driver (age, marital status, credit history, driving record, and the garaging address of the vehicle) was not taken into consideration[31]. The insurance costs are modeled

[27] Ford Motor Company, "Ford, Lincoln & Mercury Owner's Manuals, Videos and Guides," https://www.flmowner.com/servlet/ContentServer?pagename=Owner/Page/OwnerGuidePage, accessed 12/29/2011
[28] Edmunds Inc., "Car Maintenance Guide," http://www.edmunds.com/maintenance/select.html, accessed 12/29/2011
[29] Tire Rack, "Upgrade Garage," http://www.tirerack.com/ accessed 12/29/2011
[30] Edmunds Inc., "True cost to own," http://www.edmunds.com/tco.html, accessed 12/29/2011
[31] Edmunds Inc., "True cost to own," http://www.edmunds.com/tco.html, accessed 12/29/2011

as a function of vehicle class and vehicle type. To model the insurance costs within a vehicle class, we surveyed vehicles of the same class that have the similar MSRP to the CV and the PHEV60. Insurance costs are modeled to vary linearly with vehicle retail price equivalent between these endpoints, defining the estimated insurance cost for the HEV and PHEV 5-55 technologies. For this particular study, the insurance costs were calculated for the location of Colorado, 80201, in 2010. Insurance costs are estimated to increase at 3.5% inflation per year over the life of the vehicle.

4.3.6 Registration Renewal Fees Model

Registration renewal fees are generally assessed by US counties. This registration fee model is based on the fee schedule for vehicles registered in Larimer County, Colorado[32]. The registration renewal fee is the sum of an ownership tax based on the age and taxable value of the vehicle, and a license fee based on the weight of the vehicle. The registration renewal fee is paid yearly.

Ownership tax rates are a function of vehicle age. For vehicles in year 1 of ownership, ownership taxes are 2.1% of taxable value, 1.5% in year 2, 1.2% in year 3, 0.9% in year 4 and 0.45% in years 5 through 9. In year 10 and on, the ownership tax is $3 per year. The taxable value of a passenger vehicle is defined as 85% of MSRP.

The license fee schedule for the CV and HEV60 for each vehicle class is presented in Appendix B. The license fee for vehicles between these endpoints is a linear function of vehicle weight.

[32] Larimer County, Colorado Registration Fee & Estimate, http://www.co.larimer.co.us/motorv/estimate.htm

4.3.7 Loan Model

Most of the vehicles in the U.S. are purchased with an automobile loan. The loan model assumes that purchase cost is the sum of MSRP, sales tax and new vehicle registration. The purchaser provides a 10% down payment with the remainder of the purchase costs financed by a 48 month loan with 5% annual interest rate. A discount rate of 6% was used to represent all costs and benefits in 2010 dollars.

4.4 Baseline Results

4.4.1 PHEV TCO Comparison Among Previous Studies

The first result is a comparison of this study's baseline PHEV TCO model to the TCO as presented in the models that form the primary literature. For comparison, we consider the characteristics of a PHEV20 design in the mid-size car class (except in the Lemoine et al., 2006 [12] which only considered the compact car). The results of each study in terms of each component of TCO are presented in Figure 3. All values are inflated to $2010.

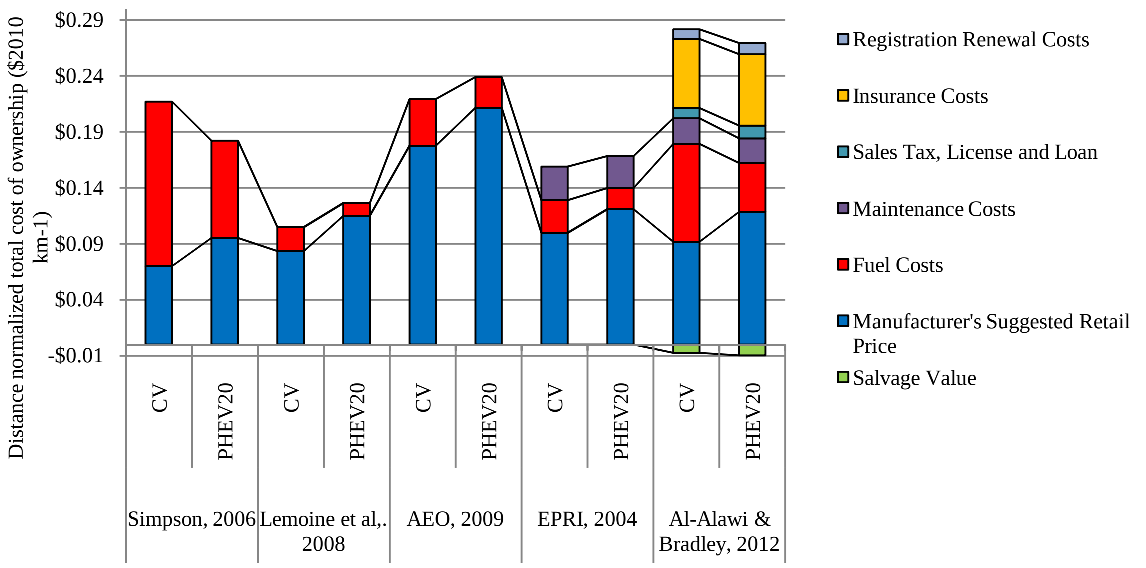

Figure 3. Total Cost in $2010 per mile Using Each Study's Parameters and TCO Model

These results show that discrepancies between studies are due to both differences in the scope of the model and in the assumptions related to each cost or benefit calculation. For example, each model concludes that PHEVs will cost more to purchase than CVs but the incremental costs of the PHEV 20 varies between $4,600 and $9,100. In addition, many of the components of TCO (e.g. maintenance costs, and salvage value) are not represented in all studies.

As an additional basis for comparison, Figure 4 presents a comparison of this study's PHEV TCO model to the TCO models from primary literature with the modification that all parameters of the TCO models are identical. Each TCO model uses the harmonized values of vehicle lifetime, lifetime distance travelled, gasoline prices and electricity price. These parameters are chosen to be equal to the Al-Alawi & Bradley column of Table 11 so as to be representative of a present-day vehicle usage and cost scenario.

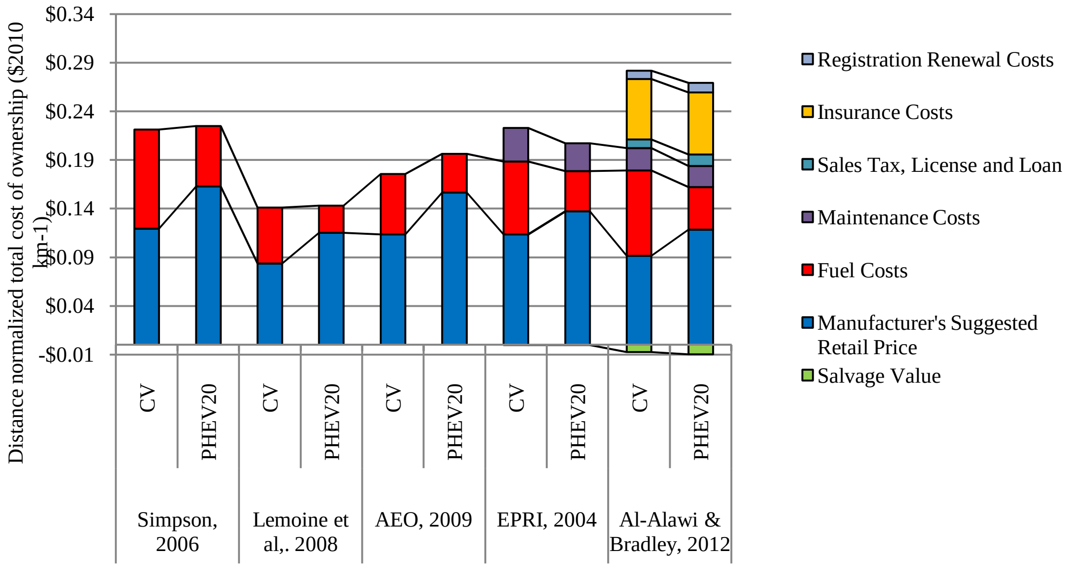

Figure 4. Total Cost in $2010 per mile Using Similar Parameters as in Base Model.

Even with this degree of scenario harmonization, there exists a great deal of discrepancy between the TCO of each model. These results show that only EPRI 2004 [104] and this model predict TCO savings for the PHEV 20. Each study predicts that PHEVs are more expensive to purchase than CVs, but the assumptions regarding PHEV fuel usage are a primary source of differences among these studies. For example, with the same vehicle type, lifetime, distance travelled, and fuel costs, the studies vary in their fuel costs predictions by 195%.

Overall, these results show that harmonizing these TCO studies requires harmonization of TCO modeling scope, and TCO model parameters.

4.4.2 PHEV Payback Period Comparison Among Previous Studies

Payback period is a common means for calculating the value of the investment in the purchase of a PHEV (or other fuel economy technology) [12,13]. In all of the studies surveyed, PHEVs have higher retail price equivalent compared to the CV due to their higher costs for the electric traction and battery system. Figure 6 shows the cumulative TCO of a PHEV20 midsize passenger car and CV midsize passenger car for each study (except in Lemoine et al., 2006 [12] which only considers the compact car). The TCO is calculated by replicating each study's assumptions and scope as defined in Table 11. Only Simpson, 2006 [10], and this study's TCO model show a net TCO benefit to the PHEV20, compared to the CV. This study's TCO model shows a significantly different behavior than the other models because it includes the concept of net present value and the mechanism of monthly payments of an automobile loan. In this study's comprehensive baseline TCO model (as in the reality of financed automobile purchases) the consumer does not pay for the incremental costs of the PHEV in year 1. Rather, the comprehensive baseline TCO model accounts for the actual payments made by the vehicle purchaser.

It is also evident from these graphs that the payback period published with each of these studies is very sensitive to assumptions implicit in each model. Slight changes to the slope (operating costs) or intercept (PHEV incremental costs) of any of these TCO curves can dramatically change the reported value of payback period.

Based on these analyses of previous studies, we can understand that there is little consensus on the TCO value or payback period of PHEVs relative to CVs. Previous studies and this work differ in scope, assumptions and results, making a synthesis of policy and economic recommendation difficult to achieve without a more detailed understanding of the scope and parameters of a comprehensive PHEV TCO model.

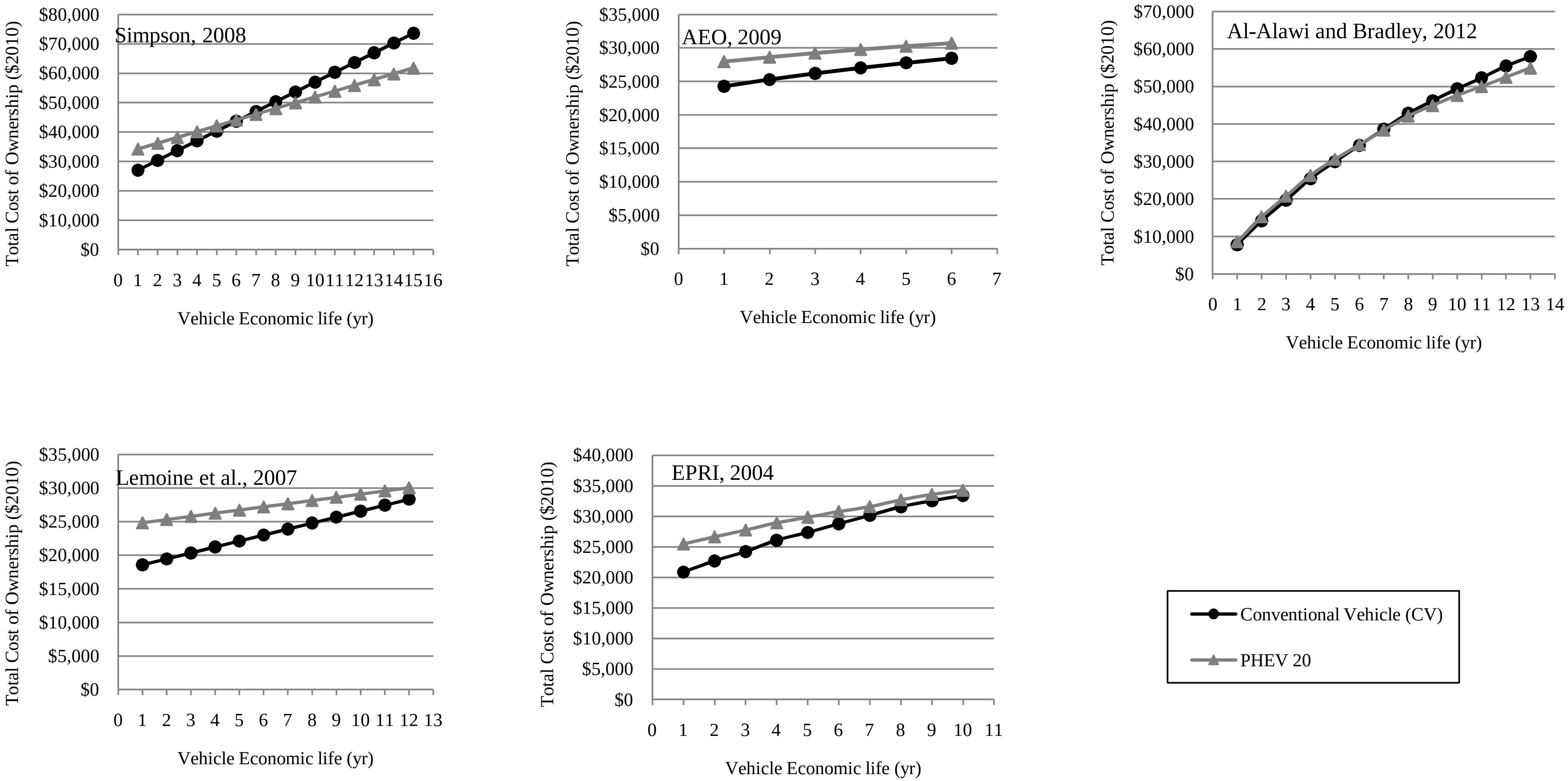

Figure 5. TCO for the PHEV 20 as Calculated Using Each Study's Parameters and Assumptions as Presented in Table 11

Based on these analysis of previous studies, we can understand that there is little consensus on the TCO value of PHEVs relative to CVs. Previous studies and this work differ in scope, assumptions and results, making a synthesis of policy and economic recommendation difficult to achieve without a more detailed understanding of the scope and parameters of a comprehensive PHEV TCO model.

4.5 Analysis and Discussion

To provide this more informative discussion of the TCO costs and benefits of PHEVs, this paper now analyzes the results of this study's baseline TCO model. These analyses include sensitivity analyses for the metric of payback period including 1) an investigation of the payback period of PHEVs across the breadth of PHEV designs, 2) a sensitivity analysis of the baseline comprehensive TCO model to discover which parameters are significantly important to PHEV payback period, and 3) a parametric study of the components of the baseline comprehensive TCO model to discover which components of the model are important to PHEV payback period. Finally, this paper considers the metrics of consumer market preference as an output of TCO modeling.

The results of these analyses allow for the rigorous defense of the included parameters, scope, and outputs of the proposed PHEV TCO model.

4.5.1 Payback Period Modeling and Analysis

4.5.1.1 Sensitivity to PHEV Types

As illustrated in Figure 6, the baseline TCO model shows that the PHEV 20 can have benefits to the consumer relative to a CV. To more completely understand the payback period of PHEVs under the assumptions of the baseline TCO model, we now calculate the payback period for a variety of vehicles. The analysis is performed using the model parameters and assumptions as listed in Table 11.

This payback analysis compares the TCO of PHEV 0-60 to CVs and of PHEV 5-60 to HEVs over the vehicles' lifetime. The TCO for each vehicle is evaluated during each year of its operation by summing its salvage value at that year, minus the cumulative total cost of operation (fuel, maintenance, insurance, registration renewal, down payment and loan payments with tax and new vehicle registration), minus the loan payments left if TCO is evaluated before the end of the loan period.

Figure 6 shows the payback period of the PHEV 0-60 relative to a CV evaluated using the baseline comprehensive TCO model. The payback period of the PHEVs ranges from 6 to 10 years in the midsize car class and from 3.5 to 5 years in the large SUV class. Only for compact cars is the payback period longer than 14 years due to the PHEV's higher incremental costs and the high CV fuel economy. For a majority of PHEV designs and vehicle classes, PHEVs show a payback period of less than 7 years.

Figure 6 also shows the payback period of the PHEV 5-60 relative to an HEV. The payback period for a PHEV compared to a HEV0 is 2 to 10 years in the midsize car class, and is 3 to 7 years in the large SUV class. Only at very large values of all electric range (AER) might some PHEVs not achieve payback over the vehicle lifetime, relative to the HEV.

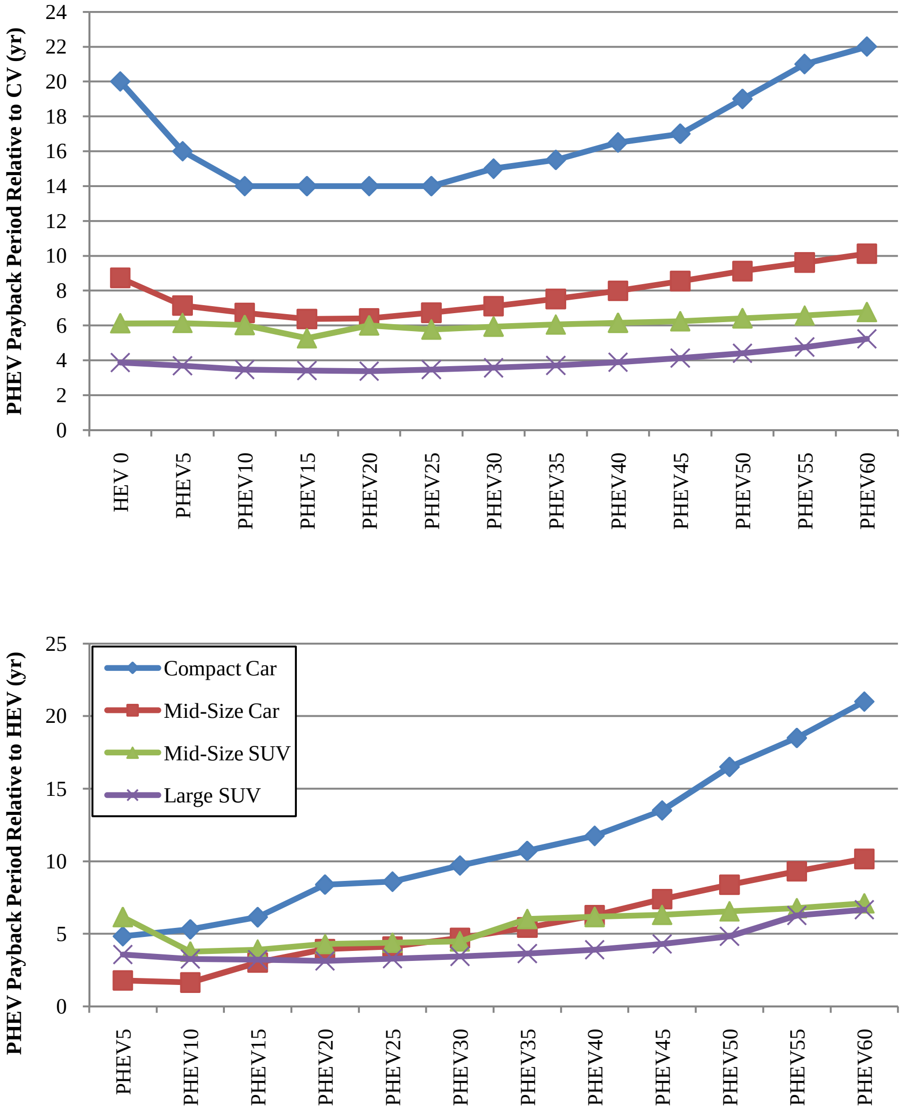

Figure 6. Payback Period of HEV0-60 Compared to CVs and HEVs

These results show that PHEVs are not only economically beneficial or only economically detrimental relative to conventional and hybridized vehicles. The payback period of these vehicles are dependent on the types of vehicle under comparison.

4.5.1.2 Sensitivity to Modeling Parameters

To quantify the sensitivity of a comprehensive TCO model to its input parameters, a sensitivity analysis is performed with sensitivity 11 factors. The analysis is performed on the TCO model of the PHEV20 in the midsized car class and in the large SUV class. Each CV and PHEV20 TCO variable is from its baseline value to 120% of baseline. The resulting percent change in payback period is shown in Figure 7 for the midsized car PHEV 20 and the large SUV PHEV20. For example, increasing the value of the incremental retail price equivalent by 20% results in a 34.7% increase in midsized car PHEV 20 payback period, and a 15% increase in the large SUV PHEV 20 payback period.

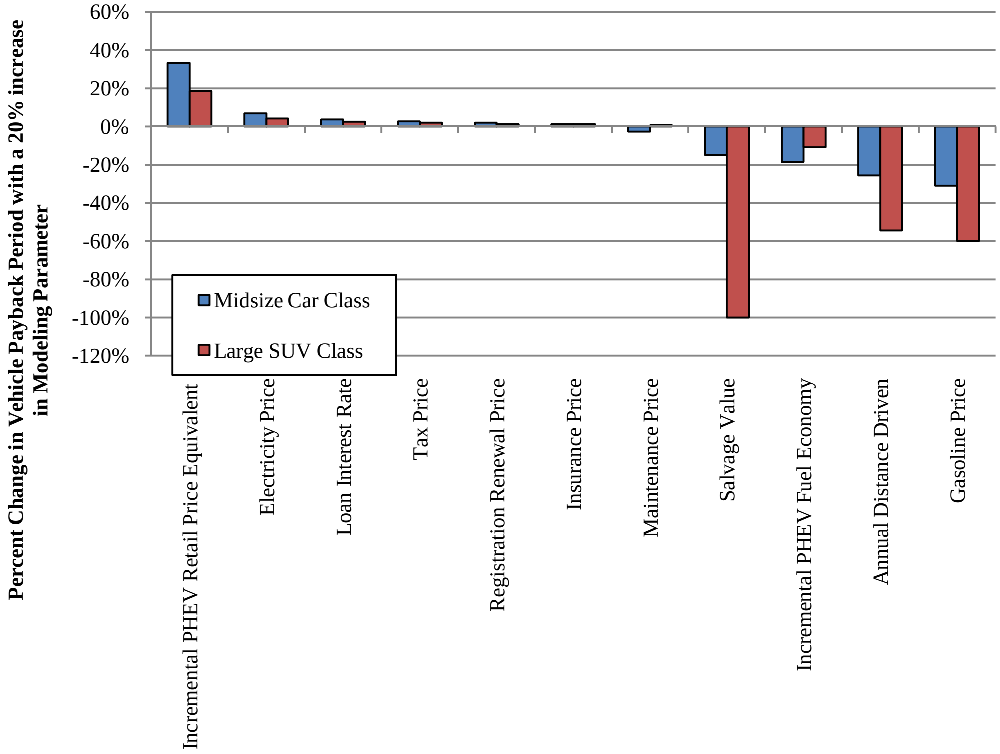

Figure 7. Sensitivity of the PHEV20 Economic Payback Period to TCO Model Parameters in the Mid-size Car and Large SUV Classes Compared to CV

We can use these results to understand that the most significant parameters to the TCO model are the parameters of annual distance travelled (VMT), fuel economy, gasoline prices, incremental costs, and salvage value. To reduce the uncertainty in the TCO model, the uncertainty regarding these parameters must be minimized. Uncertainty in the parameters of the TCO model which are less significant (i.e. insurance costs), will have less impact on uncertainty in the metric of payback period.

4.5.1.3 Sensitivity to Model Scope

Although the sensitivity analysis can help the designer of a TCO model to understand where reductions in parameter uncertainty can affect the uncertainty in the metric of payback period, it does not provide guidance regarding whether any particular portion of the model is necessary to differentiate PHEV TCO from CV TCO. In this section we will investigate the effects of the portions of PHEV TCO which have been considered insignificant in previous literature. This is performed by removing components of the TCO model from the baseline TCO model to see what effect each model component has on PHEV payback, relative to the CV.

Major TCO model components including the effects of VMT, vehicle life, fuel cost, FE and incremental costs included in each TCO model surveyed in literature and are therefore considered indispensable components of a PHEV TCO model. Instead the comprehensive TCO model is run under the following 7 conditions.

1) Tax Model Removed
2) Registration Renewal Model Removed
3) Insurance Model Removed
4) Loan Model Removed
5) Baseline Model Using all Model Components (Al-Alawi and Bradley, 2012)
6) Maintenance Model Removed
7) Salvage Model Removed

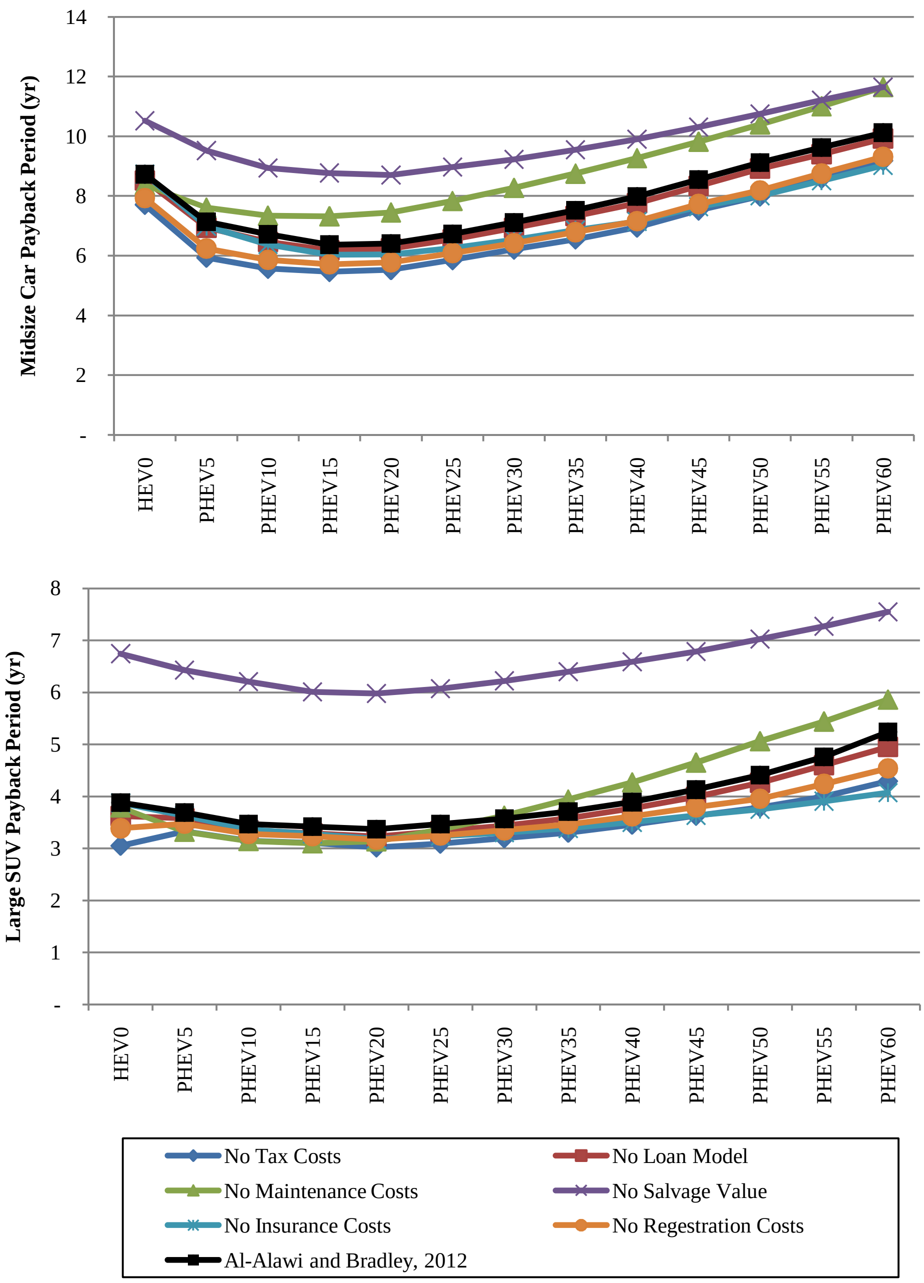

Figure 8. Sensitivity of the PHEV20 Economic Payback Period to TCO Model Scope in the Mid-size Car and Large SUV Classes Compared to CV

Figure 8 shows that the payback period is indeed quite sensitive to the presence of many of these components of TCO. In the midsized car class, inclusion of the maintenance and salvage model are shown to decrease the modeled payback period by up to 3 years; inclusion of the tax, registration, insurance and loan are shown to increase the modeled payback period by more than 2 years.

4.5.1.4 Payback Period Discussion

Overall, these analyses of payback period can help TCO modeling studies to understand the most rigorous way to construct and interpret TCO modeling studies. A number of recommendations can be formed on the bases of these analyses.

First, the breadth of possible PHEV designs and PHEV usage conditions leads to a breadth of payback period results. The economic case for purchasing a PHEV depends on the PHEV type and vehicle class under consideration. Using the baseline model, PHEV payback period can vary from less than 2 years to more than 20 years. TCO modeling results for PHEVs must be qualified as representative of only a particular class of vehicle, PHEV type, or consumer. There are no generalizations available regarding PHEV payback results, or PHEV economic incentives. Instead, PHEV payback periods are shown to be particular to a vehicle type and scenario.

Second, the quantification of the sensitivity of PHEV payback period to the input parameters and to the modeling scope shows that the PHEV TCO model must be carefully constructed. Uncertainty in some key parameters can result in unacceptable uncertainty in payback period results. For example, uncertainty in the vehicle fuel economy is shown to be a primary driver of payback period uncertainty, but the uncertainty in fuel economy simulation has been estimated at 10-12% [112,113], which corresponds to an uncertainty in payback period of 11-14%. The modeling and differentiation of vehicles by their payback period must consider the sensitivity of the metric of payback period in order to craft valid comparisons and conclusions.

Finally, these results show that the inclusion of the maintenance costs, and the salvage value of vehicles in the PHEV TCO model scope significantly decreases the PHEV payback period relative to ignoring their contribution to TCO. For instance, including the salvage value of the vehicle increases payback period by more than 3 years for each vehicle studied here. These proper but previously discounted components of a comprehensive PHEV TCO model should be considered in future work on PHEV costs and benefits.

4.5.1.5 Surveyed Market Preference Modeling and Analysis

To this point, this study has quantified the costs and benefits of PHEV ownership to consumers, with the goal of understanding the sensitivity of payback periods to the parameter values and cost components of TCO. In the literature on vehicle TCO to date, there is a large philosophical interest in the metric of vehicle payback period, informed by the assumption that a rational PHEV consumer will insist on recouping his/her investment in the costs of PHEV components with equivalent or greater benefits [10,12,13]. Although economic rationality is an important indicator of the value of a product, it is not clear that consumers are actually performing NPV calculations to determine their preference for a particular vehicle type. From the results of this TCO modeling exercise, we can test the economic "rationality" and price tolerance of consumers as measured through PHEV market preference surveys.

4.5.1.6 Consumer Preference Surveys

There are many factors that affect consumer's willingness to pay more for PHEVs, these have been studied both qualitatively and quantitatively. Qualitatively, consumers have been documented to display a preference for PHEVs because of their reduced fueling costs, reduced maintenance requirements, fewer trips to the gas station, the convenience of home refueling, lower CO_2 and GHG emissions, less petroleum use, less noise/vibration, improved acceleration, cabin preconditioning, the powering of 120 V appliances, better handling due to balanced weight distribution, and other benefits due to lower center of gravity [113]. Quantitatively, there have been a number of studies that survey consumers regarding their preference for PHEVs at certain price points, but none that present consumers with quantitative costs or benefits of the technology. For example, a 2006 survey by US Department of Energy claims that 42% of consumers are willing to pay an additional $2000 for a HEV with a fuel economy improvement of 40%, and 26% are willing to pay an additional $4000 for a PHEV20. [33] Curtin et al., [114] found that 46% of consumers were willing to purchase a PHEV at a $2500 price increment with a 75% fuel economy improvement. EPRI has surveyed consumer's willingness to pay for the purchase of PHEVs but the results were not integrated with PHEV cost/benefit modeling [4,5].

4.5.1.7 Consumer Preference for PHEVs

For this study, we would like to engage the new understanding of PHEV costs and benefits that comes from the development of the comprehensive TCO model so as to understand the relative rationality of PHEV consumers' willingness to pay. As an example dataset, we will enroll the EPRI 2001-2002 [4,5] studies as they are the most complete dataset made available to the authors. That the dataset is somewhat dated is inconsequential as it will serve merely as an exemplar of the methodology, and we will confine the discussion to the implications for TCO modeling.

These surveys recorded consumers' willingness to pay for each PHEV design (HEV0, PHEV20 and PHEV60) within each vehicle class (compact car, midsize car, midsize SUV and large SUV) at two values of vehicle incremental cost [4,5]. [34] We can use this data to calculate how consumers' preferences compare to a strict total ownership cost versus total ownership benefit analysis. Ownership costs and benefits are calculated using a vehicle economic life of 5 years [115,116]. TCO for the base model is based on the default

[33] Opinion Research Corporation International, "Would You Buy a Hybrid Vehicle?" #715238, 2006, available at http://www1.eere.energy.gov/vehiclesandfuels/facts/2006_fcvt_fotw431.html

[34] Only survey data at a fuel cost of $3.00/gallon is used here, except the midsize cars where the survey was constructed assuming only a gasoline price of $1.69/gallon [4,5].

characteristics of the base model (as shown in Table 11), where TCO for EPRI model is based on fuel and maintenance costs only. Each TCO model uses the harmonized values of vehicle lifetime, lifetime distance travelled, gasoline prices and electricity price. These parameters are chosen to be equal to the Al-Alawi & Bradley 2012 column of Table 11. The benefits are calculated relative to the CV within each model. All costs and benefits are represented in $2010.

Results are shown in Figure 9. In each subplot of Figure 9, the EPRI vehicles' costs and benefits are plotted along with lines of constant surveyed consumer preference. These survey datasets describe how consumer's preferences change with changing costs and benefits. For example the survey data shown in midsize car class of Figure 9 illustrates that consumer preference generally increases with decreasing costs and increases with increasing benefits. Also, it shows consumer's sensitivity to incremental purchase price in that the slope of the line at 35% willingness to pay decreases at high incremental costs; in other words, the consumer is less willing to accept the same ratio of costs to benefits at higher incremental cost. The consumer preference data also shows that consumer preferences is not well-aligned with a rational model of economically-motivated consumers (represented by the dashed line at discounted cost = discounted benefits).

These survey datasets can then be compared to the total ownership costs and benefits of the suite of PHEVs whose TCO is modeled in this study. In Figure 9, the costs of the PHEVs as modeled using the base TCO model are generally comparable to the costs presented in the surveys, and the benefits of the vehicles are generally larger than the benefits presented in the surveys.

4.5.1.8 Consumer Preference Discussion

This analysis leads to two primary discussion points. First, modeling consumer preference is generally more complicated than has been acknowledged in previous TCO models. Simple cost-benefit analysis cannot capture the richness of the consumer preference data that exists in the survey literature, and consideration of consumer preference can lead to an improved understanding of the design constraints that exist for incremental costs (and benefits) of PHEVs. Second, according to the comprehensive TCO modeling performed for this work, PHEVs of all types can exhibit substantial consumer preference. For example, in the midsize car class, more than 55% of consumers are willing to pay the incremental costs of PHEVs with low AER. These results challenge the consensus view that PHEVs are not economically viable and are not capable of inciting consumer preference without significant component cost reductions and/or gasoline price increases.

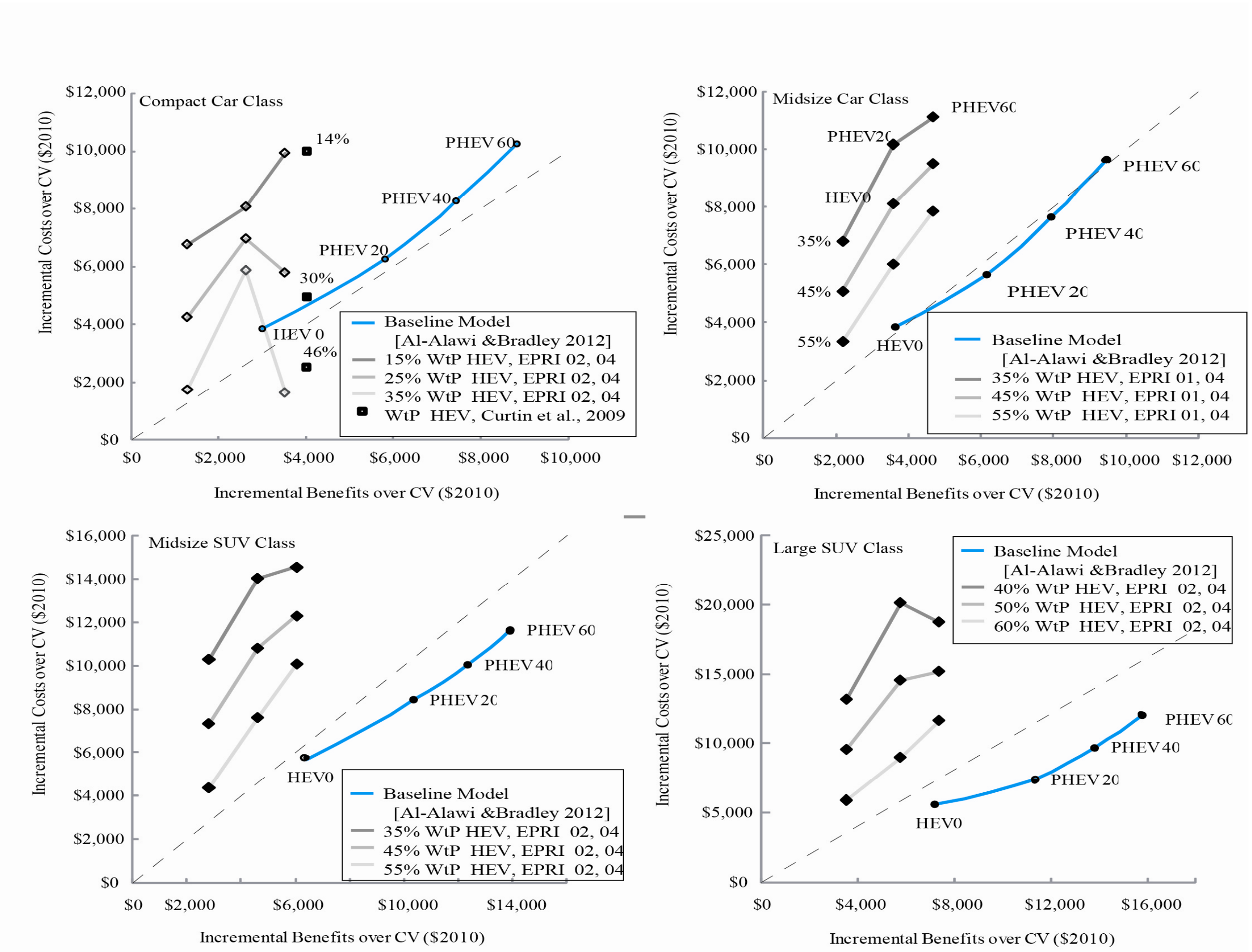

Figure 9. Consumer's Willingness to Pay (WtP) for a Large SUV HEV0-60 Plotted with the PHEV Cost/Benefit Curve Calculated Using the Baseline TCO Model [4,5,104,114].

4.6 Chapter Conclusions

The objective of this study was to define the parameters and assumptions that constitute a comprehensive TCO model of PHEVs. In this study we have developed a comprehensive ownership cost model to calculate the consumer's purchase and use of CV, HEV and PHEV5-60. The model was compared to the most cited PHEV TCO models in literature to measure the effects of model assumptions and parameters on the total cost and benefit of each vehicle. PHEV TCO modeling parameters and assumptions are found to be quite variable among studies, resulting in widely varying PHEV TCO results.

To rigorously inform and defend the components and assumptions of the comprehensive TCO model, a sensitivity analysis was performed to determine which parameters and components of TCO are most influential. This analysis shows that TCO and payback period are sensitive to parameters that have been well-modeled in literature including incremental cost, gasoline prices, and annual driving distance. This analysis also showed that TCO and payback period are sensitive to relatively understudied components of TCO modeling including salvage value, maintenance costs, and fuel economy. Finally, this study shows that the output of TCO modeling should be more than just a modeled PHEV payback period. Instead, the value of PHEVs can be presented in terms of total costs and total benefits or can be presented in terms of survey-based consumer preference.

Ideally, the technology improvements associated with high fuel economy vehicles are preferred by consumers at the same time as they enable improvements in consumer and economy-wide economic efficiencies. The type of consumer-centric TCO modeling that is presented in this study allows for consideration of the consumer's role as an enabler of any economic or environmental improvements that might result from the development of PHEVs. Only when consumers, researchers, and automakers are presented with the comprehensive costs and values of PHEVs can they consider the role that PHEVs can play in a more economically and environmentally sustainable personal transportation system.

Chapter 5-Review of Hybrid and Electric Vehicle Market Modeling Studies

5. Chapter Summary

Plug-in hybrid electric vehicles (PHEVs) are an emerging automotive technology that have the capability to increase vehicle fuel economy but at an increased cost. PHEVs can draw and store energy from an electric grid to provide propulsive power to the vehicle. Their reduced petroleum consumption and improved efficiency provides lifecycle value to consumers, society, automakers, and policymakers, but with an incremental cost. These stakeholders have sought to understand the role of PHEVs in the future vehicle fleet by estimating the diffusion rate of PHEV technologies into the automotive marketplace. This review presents a comprehensive literature review of HEV and PHEV penetration rate studies, their methods, and their recommendations. These studies have applied a suite of analytical and computational modeling tools to a wide variety of policy and macroeconomic scenarios. The results of these studies are compared and synthesized to understand the strengths and weaknesses of the field and to propose further means for improvement of PHEV market modeling exercises.

5.1 Introduction

Plug-in hybrid electric vehicles (PHEVs) are an emerging automotive technology that has the capability to increase vehicle performance and fuel economy, and to reduce the environmental impacts of personal transportation. PHEVs can be powered by both a gasoline and electricity. PHEVs were introduced to limited production in 2004 and to mass production in 2011 [3].

Many studies have forecasted that PHEVs will be a growing component of the US vehicle fleet in the future. These forecasts have served the needs of society, automakers, electric utilities, and policy makers in understanding what the impact of PHEVs will be on their sphere of influence. Society seeks to understand the benefits that it will accrue from more efficient vehicles [4,5,23,94,95,104]. Automakers seek to understand the market potential of each vehicle technology with the goals of designing salable products and of meeting regulatory fuel economy and CO_2 emissions standards [2,23]. The Utility industry seeks to model and forecast the new electricity infrastructure demand under different transportation technology scenarios [4,5,23,94,95,104]. Policymakers seek to be able to adjust and understand the impact of present and future regulatory standards, and to understand domestic and foreign energy demand [2,4,5,19,23,45,52,53,81,95,104,117,118].

Market forecasting is a well-developed field of study with practitioners in the fields of economics, business, finance and systems engineering, but forecasting of PHEV market share in the light-duty passenger vehicle fleet is complicated by factors that are difficult to model using the classical tools of market forecasting. First, PHEVs are a new automotive technology that has only just been introduced in the last years [3]. Only sales data since model year 2011 is available for validation of any market model. Second, PHEVs require consumers to shift their behavior away from fueling at a gasoline station (the normal mode of fueling for conventional hybrid electric vehicles (HEV)) towards plugging in their personal vehicle. Only a few studies have attempted to quantify consumers' preference towards this change in behavior, and the behavior change makes questionable the use of historical HEV and conventional vehicle (CV) sales data. Third, PHEV fuel consumption is measured in terms of both fuel consumption (L $(100km)^{-1}$) and energy consumption (ACW-h $(km)^{-1}$). Consumers' evaluation of PHEV ownership costs will require a weighting of these energy consumption and their costs based on consumers' driving habit. Fourth, the makeup of an automotive industry vehicle fleet is highly regulated within the US. The pricing (and therefore consumer preference) for high-fuel efficiency vehicles is presently influenced by factors such as fleet fuel economy requirements [2,81], and low carbon fuel standards [2,81,95]. Fifth, the characteristics of the US automotive industry must be considered in automotive market modeling. Analysis of sales in the US automotive industry is complicated by its oligopoly, by its relatively long and relatively constant product development lifecycles, by the used car market, by automaker's finance business units, and more.

Researchers have recently been developing market forecasting models that can include these types of complications, but the methods, scope, fidelity, and results that are the outputs of these models differ greatly among studies. The objectives of this paper are to synthesize an understanding of the state of the art in PHEV market forecasting, and to develop recommendations for improving the utility of these market forecasts for decision making. To these ends, this paper first presents a review of the published forecasts of HEV, PHEV and EV market share, which includes a cataloguing and critique of the three main modeling methods that have been applied to HEV and PHEV market forecasting. Next we present a synthesis of the results from some key PHEV market forecast studies that have been performed to date. The recommendations and conclusions section provides means for improving the utility of PHEV market forecasts from the point of view of automotive and utility industries.

5.2 Review of Market Forecast Models for HEVs, PHEVs, and EVs

5.2.1 Overview

Many researchers have developed models to estimate the penetration rate of currently available HEV technologies and new PHEV and EV technologies in the US market. These models can be characterized by the modeling technique that they use to represent the interactions within the marketplace. The three major modeling techniques used in the literature on PHEV, HEV and EV market forecasting are: agent-based models, consumer choice models, and diffusion and time series models.

5.2.2 Agent Based Models

Agent-based modeling (ABM) is a computer based simulation method that creates a virtual environment to simulate the action and interaction of each agent. Agents are entities or individuals that have control over their interaction with other agents in the system model. Each agent is supplied with internal characteristics which dictate their interactions among other agents in the environment. ABM has been applied to many fields including population dynamics, epidemiology, biomedical applications, consumer behavior, vehicle traffic, and logistics simulation [119–130]. In the field of vehicle technology adoption, ABM has been applied by many practitioners [21–23,94,117,118]. These ABM vehicle technology market forecasting studies have defined three or more different agents in the modeling environment including consumers, automakers, policymakers, and fuel suppliers [21–23,94,117,118].

The demand for vehicles is represented by consumer agents. The consumer agents are characterized by their modeled demographics and preferences. These characteristics have included gender, age, income, location, social network, lifestyle, daily driving needs, transportation budget, ownership period, and preferences to vehicle class, fuel type, safety, reliability, powertrain types, and performance. The consumer agents' behavior during the ABM simulation is determined by their needs and preferences when acted upon by the exogenous vehicle supply and market conditions.

The supply for vehicles is represented by automaker agents supplying vehicles from suite of vehicles characterized by vehicle class, fuel type, safety, powertrain characteristics, performance and costs. Automaker agents have access to vehicles with improved fuel economy but vehicles with high fuel economy are modeled as requiring time to develop and may come with higher incremental cost compared to CVs. Automaker agents attempt to meet CAFE standards, and consumer demand for vehicles while maximizing profit [23,118].

Policymaker agents set many of the policies and standards under which automaker agents and consumer agents must act. Their actions are based on factors including, energy demand, oil security, and global environmental goals. Policymaker agents' actions will be to set new policies such as subsidies, tax rebates, sales tax exemptions or increasing gasoline taxes to motivate consumers' adoption of more fuel efficient vehicles[23,118].

Fuel supplier agents control fuel resources and acted on by consumer demand for fuel, policies including Clean Fuels Standards, and fuel resources availability. When there is an increase in fuel prices, consumers are going shift to more fuel efficient vehicles or adjust their driving habits while not going over their transportation budget [23,131].

5.2.2.1 Review of Key Agent Based Modeling Studies

In this section we review some key studies that have used ABM to estimate the adoption rate of HEVs, PHEVs and EVs.

Sullivan et al., (2009) developed an agent based simulation, virtual automotive marketplace (VAMMP) to define the PHEV market penetration. The simulation model considered a variety of consumers, economic situations, and policy conditions [23]. Four classes of agents are present in the simulation: consumers, government, fuel producers, and vehicle producers/dealers. Decision makers interact in every cycle (one month) where consumers choose among twelve vehicle models from three producers. In every cycle consumers will decide whether it is time to purchase a new vehicle or change their driving mileage to remain within their transportation budget limit. Vehicle dealers will monitor their sales and profits while government agents monitor fuel consumption, carbon emissions and new vehicle introductions in order to adjust/modify current policies to meet their objectives.

The model was validated under different scenarios. These scenarios included stress free market conditions, gasoline shock, vehicle pricing changes, as well as van, SUV, and HEV introductions. The results of this study showed under the current policy case the PHEV fleet penetration rate would be insignificant, less than 1% over ten years. Combinations of tax rebates, PHEV subsidies and sales tax exemptions could enable a significant increase in the penetration rate of the PHEV technology. Under this more active policy scenario PHEVs are estimated to reach 4-5% of sales by 2020 with more than 2% fleet penetration rate [23]. This same model was used in the PHEV Market Introduction Study [95] to study new technology penetrations in the US over different market and policy conditions. Four scenarios were examined and the results show that the projected PHEV fleet penetration would range from 2.5% to 4% for the period 2015-2020.

Eppstein, et al., (2010) developed an ABM to estimate the adoption rate of PHEVs using only consumer agents [117]. The consumer was assumed to consider different environmental and financial costs and benefits based on their personal behavior and knowledge of the technology. This study attempts to answer the question of how much an agent is willing to pay for a PHEV technology and its projected economic and environmental benefits. This can be used to inform policy makers and automakers about the possible set of policy and action that effect PHEV adoption rate. Consumer’s attributes considered in the study were: Annual salary, age, home location, vehicle ownership time before buying another, VMT, neighborhood radius (miles), social network radius (miles), threshold for willingness to consider PHEV, social influence, greenness, fuel operating cost years considered, current vehicle age and current vehicle fuel economy [117]. Sensitivity analysis included investigation of the assumptions regarding fuel price, PHEV price, rebate availability, and the number of agents performing fuel cost estimation. This study is notable in that it includes models of many of the barriers that might affect the introduction and acceptance of PHEVs and lead to a slow penetration rate [117]. These barriers included consumer's unfamiliarity with PHEV technology, PHEV battery life, battery replacement cost, long recharging time, future fuel prices uncertainty and short driving range. One of the recommendations stated was the need to educate consumers on the cost/benefits of PHEVs and for a web-based tool to accomplish the task [117]. The study presented the results of the model in terms of trade-off in agent selection of HEV and PHEV 40 versus mean threshold (T = 0% to 100% shifting from being an early adaptors (T <= 0%), early majority to not considering PHEV (T > = 100%)). Results show that after 10 years the penetration rate of HEV approximately will have an increase between 25% to 38% where the increase will be between 30% to 60% after 20 years. After 20 years the penetration rate of PHEV approximately will decrease from 15% to 0 at T = 0% and 38% to 1% at T = 40% [117].

Cui et al., (2010) developed PHEV adoption model called a multi agent-based simulation framework to model PHEV distribution ownership at a local residential level [94]. This study attempts to identify zones where PHEV penetration level increases quickly and then estimates the impact of PHEV penetration rate on the local electric distribution network. The model integrates the consumer choice model of Sikes et al., (2010) to estimate consumers' vehicle choice probability, a consumer transportation budget model to estimate the time when a consumer will search for a new vehicle, and a neighborhood effect model to predict consumers' vehicle choice [94,95]. Some of the factors found to affect PHEV penetration rate were gasoline prices, consumers' ability to calculate vehicle fuel saving, PHEV price, battery range, vehicle purchase options, social and media influence.

Other studies have developed a consumer behavior model using the ABM framework to estimate new vehicle technology market demand under the impact of greenhouse gas emission policies [118]. Garcia, (2007) used the individual logic model developed by Boyd and Mellman, (1980) to estimate consumers' vehicle choice probability [118,132]. The study did not report any results and it was to investigate the relationships between vehicle technology options, GHG policy and consumer behaviors [118]. A study by Zhang (2007) adopts the model developed by Struben and Sterman (2008) to estimate the adoption rate of diesel vehicles in Europe using the diesel vehicle registration historical data [45,133]. The model found to have a better fit to key patterns of the diesel vehicle registration historical data over the Bass (2004) model [133]. Zhang observed that a decrease in vehicles operating costs and an increase in its performance yield an increase in diesel vehicles adoption. Stephens (2010) used an ABM to estimate the electricity demand, fuel demand and the resulting greenhouse gas emissions [131]. In their model PHEV driver are found to be less sensitive to fuel prices compared to CV drivers [131].

ABM has been applied to many scientific and engineering fields including vehicle technology adoption. Most ABM method studies in vehicle technology market forecasting have defined consumers as the primary agent but some studies have included automakers, policymakers, and fuel suppliers in the modeling environment. The agent’s vehicle choice or actions is dependent on their utility towered each vehicle technology. The advantages of using ABM are that it uses agents’ characteristics, needs, limits, and preferences when simulating their behavior and interactions in the modeling environments. Another advantage is the ability for consumer’s agent to choose between vehicle technologies, keep his current vehicle, and change his/her transportation habits. ABM agents behave in a way that maximizes their utility and not going over there budget. The calculation of each agent utility is dependent on the elasticity value which either calculated or used from other studies. ABM studies have run different market condition scenarios while ignoring running sensitivity analysis on the modeling method and data. The disadvantages are that accuracy of model assumptions, data and elasticity values decreases the accuracy of the model results if not verified. In the ABM the market conditions simulation can be improved by including more different agents to cover different automobile market players, and more agents to cover wide ranges of US vehicle consumers. Finally the results presented for ABM shows that consumer's agents are very sensitive to vehicles MSRP and they are willing to purchase a more fuel efficient vehicles (PHEVs) when there incremental costs are lowered. Their behavior regarding the increase in fuel prices found to be different than other model results and they will decrease their miles traveled, keep their current car, or switch to smaller more efficient vehicle not necessary to be PHEV.

5.2.3 Consumer Choice Models

Discrete choice models and logit models have been used in the literature to describe individual and collective decision making. Logit models are a commonly used means for modeling the probabilistic preference of consumers, while discrete choice models calculate the probability of a specific product being chosen among alternatives under the influence of these preferences.

Numerous studies have used these consumer choice models to model vehicle purchase or holding decisions. These studies have incorporated logit models of consumer preference to vehicle technology, class, make, and characteristics. These models are most commonly derived from combinations of purchaser demographic data and past vehicle sales data. For technologies such as PHEVs, where such data does not exist, the sensitivities of purchasing decision to the attributes of PHEVs must be estimated or be derived from survey [30]. Some attributes estimated in consumer preference modeling of new vehicle technologies include the sensitivity to technology incremental cost, HEV battery replacement, refueling/charging infrastructure availability, refueling/recharging time, maintenance cost and driving range [18].

The two different logit models used in the automotive consumer preference literature are the multinomial logit model (MNL), which represents the probability of choosing an alternative over all alternatives [31–39], and the nested logit model (NMNL), which represents the probability of choosing an alternatives over the nest alternative [38,40–43,46]. For all of the HEV and PHEV market forecasting studies reviewed here, the logit model is then input to a discrete choice model which is used to represent the response of individual customers [19,24,29,44–53].

The multinomial logit model (MNL) is based on utility theory wherein each individual is trying to choose an alternative that maximize his/her personal utility (*U*) [134]. It assumes that the probability *P* that individual *n* will choose an alternative *i* from a set of alternatives *j* in *C* (where *C* is a set that includes all the potential alternatives) is given by:

$$P_{in} = P\left(U_{in} \geq U_{jn}, \forall j \in C_n, j \neq i\right) \quad (1)$$

The general multinomial logit model is defined as

$$P_{in} = \frac{e^{U_{in}}}{\sum_{j \in C_n} e^{U_{jn}}} \quad (2)$$

Where

$$\sum_{i \in C_n} P_{in} = 1 \quad (3)$$

P_{in} is the probability that an individual n chooses an alternative *i* where U_{in} is the utility function of an individual *n* chooses an alternative *i* [134]. The utility function equation is:

$$U_i = \sum_n \beta_n X_{in} + \varepsilon_i$$
$$\varepsilon_i \sim G(0, \mu) \quad (4)$$

X_{in} is an explanatory variable (measurable or observable) for alternative *i* (i.e. incremental cost or fuel economy). β_n is the slope parameter for the explanatory variable X_{in}. and ε_i is the alternative *i* random component [134]. The slope parameter β_n is calculated by knowing the elasticity $E_{X_{in}}^{P_i}$ of the probability (P_i) of an individual n choosing an alternative *i* with respect to a change in X_{in}. For example the direct elasticity $E_{X_{in}}^{P_i}$ formula can be modified to calculate the slope parameter β_n:

$$\beta_n = \frac{E_{X_{in}}^{P_i}}{(1 - P_i) X_{in}} \tag{5}$$

Each alternative's elasticity can be estimated, or derived from survey data. The slope is then used to calculate the utility function for each alternative for each individual. The final step is to use the MNL function to estimate individuals' probabilities of choosing an alternative *i*. The method is applied for each group of individuals and each group of alternatives over the forecasting period by changing the utility function parameters for each alternative as a function of time or exogenous input.

In the discrete choice model, individuals are assumed to choose a vehicle that achieves the highest score or utility value [48]. The mathematical nomenclature of the discrete choice model will follow that of the study by Greene et al., (2004). The utility function equation is:

$$u_{ij} = b(A_i + \sum_{l=1}^{K} w_l x_{il} + \varepsilon_{ij}) \tag{6}$$

The utility function is defined as the weighted sum of the relevant vehicle attributes considered such as fuel economy, price, range performance and safety [48]. Because there will also be unquantified attributes for each individual, a random component is added to the utility function. So u_{ij} is the ranking score for *ith* vehicle for the *jth* individual, w_l is the weight of the *lth* attribute, x_{ij} and ε_{ij} is *jth* individual's random component for the *ith* make and model. A_i, is a constant that represent the value, in dollars, of the unmeasured attributes of vehicle *i* and *b* is the price coefficient [48].

The probability of an individual *n* will choose alternative *i* from *k* alternatives is the exponential of the utility of the alternative divided by the sum of all of the exponential utilities [48]. The probability that an individual will choose the *ith* make and model from the *kth* vehicle class is

$$p_{i|k} = \frac{\exp(bu_i)}{\sum_{l=1}^{L} \exp(bu_l)} \qquad (7)$$

The NMNL has been used in the context of vehicle choice modeling to estimate the probability of a consumer choosing a vehicle class and then choosing among vehicle make and model as a nested decision [48]. The utility function for each class is modeled as the probability weighted average of the utility scores of vehicles within the class. For each class *k* the expected utility U_k is:

$$U_k = \frac{1}{b} \ln\left(\sum_{i=1}^{n_k} \exp(u_{lk})\right) \qquad (8)$$

The probability that a consumer will choose a vehicle from class *k* is:

$$p_k = \frac{\exp(A_k + BU_{ki})}{\sum_{K=1}^{n} \exp(A_K + BU_{Ki})} \qquad (9)$$

Where *K* is the summation of all vehicle classes and *n* is the number of vehicle classes. A_k is a constant that represent the value, in dollars, of the unmeasured attributes of vehicle class *k*. *B* is a slope parameter that measures the sensitivity of vehicle classes choices to the change in their expected value [48]. The probability of the consumer choosing vehicle *i* from class *k* is the product of equation (7) and (9):

$$p_{ik} = p_{i|k} * p_k$$

5.2.3.1 Review of Key Consumer Choice Based Modeling Studies

In this section we review some key studies that have used consumer choice modeling to estimate the adoption rate of HEVs, PHEVs and EVs.

The Advanced Vehicle Introduction Decision (AVID) model was developed by Argonne National Laboratory (ANL) to predict consumer's vehicle purchase decision [18]. The model was developed using multinomial logit model to predict consumer's preferences using weighted score for individual vehicle technologies and vehicle share. In this model, consumers are divided into early adopter (15%) and majority buyer (85%) groupings [18]. The study considered four multinomial logit models based on the four permutations of these consumer groupings and vehicle production being either constrained or unconstrained. Some of the factors considered were the change in consumer market preference, vehicle attributes, fuel prices, and technology production decisions [18]. There were 13 vehicle attributes in the model including vehicle price, fuel cost, range, battery replacement cost, acceleration, home refueling, maintenance cost, luggage space, fuel availability and top speed. The base case scenario used a gasoline price of \$1.50 gal^{-1} and a 7% HEV incremental price increase relative to the CV. Under these base case assumptions, the estimated HEV share under the unconstrained vehicle production decision was estimated to be ~17% on 2020, ~23% on 2035 to 2050. Vehicle adoption rate was found to be sensitive to gasoline price and HEV technology incremental cost. In the case of a gasoline price increase from \$1.50 gal^{-1} to \$3.00 gal^{-1} , HEV sales share increased to 56% in 2020 and to 64% from 2030 to 2050 [18].

In the case of an 18% increase in HEV incremental cost and gasoline price at \$3.00 gal^{-1}, HEV sales share is estimated to be between 5% and 8% from 2020 to 2050 [18].

The PHEV Market Introduction Study by Sikes K et al., 2010 developed consumer choice modeling to study the diffusion of new technologies in the US automotive market under different market and policy conditions [95]. The Market Adoption of Advanced Automotive technology (MA3T) is based on nested multinomial logit (NMNL) model. MA3T projects HEV demand and its impact on energy demand and the environment. The model estimates the penetration rates of 26 vehicle technologies including HEVs and PHEVs for the passenger car fleet and light truck fleet over the period from 2005 to 2050. The model has four decision makers: consumers, government, fuel producers and vehicle produces/dealers. Three consumer types were considered: early adopters, early majority and late majority. The US was divided into nine divisions and each division into urban, suburban and rural statistical areas. Some of the factors included in the model were: vehicle attributes such as: MSRP, performance, fuel economy, capacity, battery cost, vehicle range and fuel price. Other factors considered in the model are home refueling value, refueling infrastructure availability, subsidies, tax credits, housing type, consumers' attitude, driving behavior, technology cost reduction , vehicle and components supply constraint and vehicle makes and model availability and variations. Two scenarios that were considered are the base case and the PHEV success case [95]. Each scenario was examined in terms of different geographical regions, driver types, technology attitudes, recharge availability and vehicle technologies. HEV sales were estimated to range from 13 to 17 million in 2020 and PHEV sales to range from 332,975 current policy case to 3,569,400 in 2020 over different cases considered [95].

Diamond (2009), developed a model of consumer demand based on consumer's behavior utility function for pre state market share of HEV [19]. The goal of this study was to examine the effect of tax incentives and gasoline price on HEVs sales in the U.S so as to communicate their effectiveness to policy makers. The primary model developed for this study was a cross-sectional model of hybrid vehicle market share derived from a behavioral utility function for automobile demand [19]. In this model Diamond accounts for consumer's income, average vehicle mileage and car dealership availability. The primary data used in his analysis was HEV registration data for U.S states [19]. He observed that when supply is constrained the sales will be determined by automakers internal distribution policies and there is a strong relationship between gasoline prices and hybrid adoption. He concluded that incentives will be effective only if they are provided upfront [19].

Social influences have been shown to play a role in determining consumer's openness to adoption of new vehicles and technologies, and consumer choice modeling has been used to model these effects. Axsen (2010) explored the role of social influences on the adoption of plug-in hybrid electric vehicles [50]. The author used a discrete rational choice framework that models an individual's personal utility for a particular vehicle to choose among different alternative vehicle technologies [50]. In the work of Sturben, and Struben, and Sterman, (2006), (2008), the adoption rate of alternative fuel vehicles was estimated by integrating diffusion models with discrete consumer choice theory [45,52,53]. In this model, the consumer's preference to a specific vehicle platform was defined through the multinomial logit choice framework as the expected utility of the vehicle, including the dynamics of social influences, infrastructure, supply and vehicle demand [45,52,53]. Work by Bandivadekar, (2008) uses a discrete choice modeling approach to estimate the market penetration rates of new vehicle technology sales [24]. The model was an extended version of the Heywood et al., (2004) model and it included consideration of light-duty vehicle fleet sales, market share, age, scrappage rate, travel, fuel consumption and greenhouse gas emissions [24,135]. Four different scenarios were considered and it was estimated that in 2035 the HEV sales will range from 15% to 40% and PHEV sales will range from 0% to 15% [24]. Greene et al., (2004) developed a nested multinomial logit model to estimate diesel and hybrid vehicles rate would be 7-10% by 2008 and 15-20% by 2012 [48].

Some studies have used the consumer choice model to predict the penetration rate of new technology vehicles outside the US Bolduc et al., (2008) have used a hybrid choice modeling framework to estimate the adoption rate of HEVs in Canada [49]. The model was based on a multinomial logit model with consumer's utility function and contains latent psychometric variables [49]. Mau, (2005) research developed a discrete choice model that uses Canada national survey to estimate HEV adoption rate in Canada [29]. Feeney, (2009) has developed a vehicle choice model to predict the penetration rate of HEVs over 5-10 years, PHEVs over 5-20 years and EVs over 20 or more years in the NSW metropolitan region of Australia [47]. Three different charging infrastructure availability scenarios were considered to measure the adoption rate of the vehicles [47].

Consumer choice methods have been used by many studies to model vehicle purchase or holding decisions. They have been used to estimate the probability of consumers' choosing a vehicle within a fleet or a vehicle class and then choosing among vehicle make and model. Consumer choice model is consumer's utility dependent where the utility function for each vehicle is the probability weighted average of the utility scores of vehicles. The discrete choice model estimates the market penetration rate of new vehicle technologies based on consumers preferences and vehicle attributes. The validity of the model is dependent on the parameters considered and their estimated values. The intercepts, slopes and attributes coefficients must be estimated using data on the market share of preexisting vehicles, actual vehicle attributes and vehicle attributes elasticity. Consumer choice model studies simulated different scenario of market conditions without testing the model data, parameters or assumptions. The model advantages are that it uses and simulates consumer preference to vehicle technology, class, make, and characteristics. It also integrates consumer's attributes and sensitivity to technology characteristics. The disadvantages are that the models are derived from combinations of purchaser demographic data and past vehicle sales data which are not available or does not exists. For technologies such as PHEVs, where such data does not exist, the sensitivities of purchasing decision to the attributes of PHEVs must be estimated or be derived from survey. Results presented show that an increase in fuel prices or a decrease in technology incremental costs by applying tax credits or subsidy will lead to a fast increase in HEV and PHEV penetration rate. It is found that the successful diffusion of HEVs may saturate the market and led to low PHEVs sales.

5.2.4 Diffusion Rate and Time Series Models

Diffusion is defined as the process of acceptance of a new invention or product by the market. The speed with which a new product spreads through the market is called the rate of diffusion. The sales of new products in the market are influenced by internal and external factors which may be controllable or not [13]. There are many parameters that influence the rate of diffusion including metrics of innovation, communication, time, and the surrounding social system.[58] Diffusion rate and time series models seek to capture the life cycle of new products over time. Classical theories on diffusion include the concepts of classification of adopters, the role of social influence in adoption, and the S-shaped curve associated with the rate of an innovation's adoption. The diffusion of innovation is often modeled as a normal distribution over time, as shown in Figure 10 [58]. This normal distribution is divided into five categories: innovators, early adopters, early majority, late majority and laggards [58]. Innovators are the first adopters who are willing to take risks by purchasing new and innovative products. Early adopters are individuals who adopt an innovation following innovators. Early adopters are influenced by their social connections to innovators and other adopters. The rest of the categories will have slower adoption rate due to their lower level of social influence and lower financial status. According to Mahajan et al., (2000) Some of the best-known diffusion models in the marketing field are those of Fourt and Woodback, (1960), Mansfield, (1961), and Bass, (1969) [54–57,136].

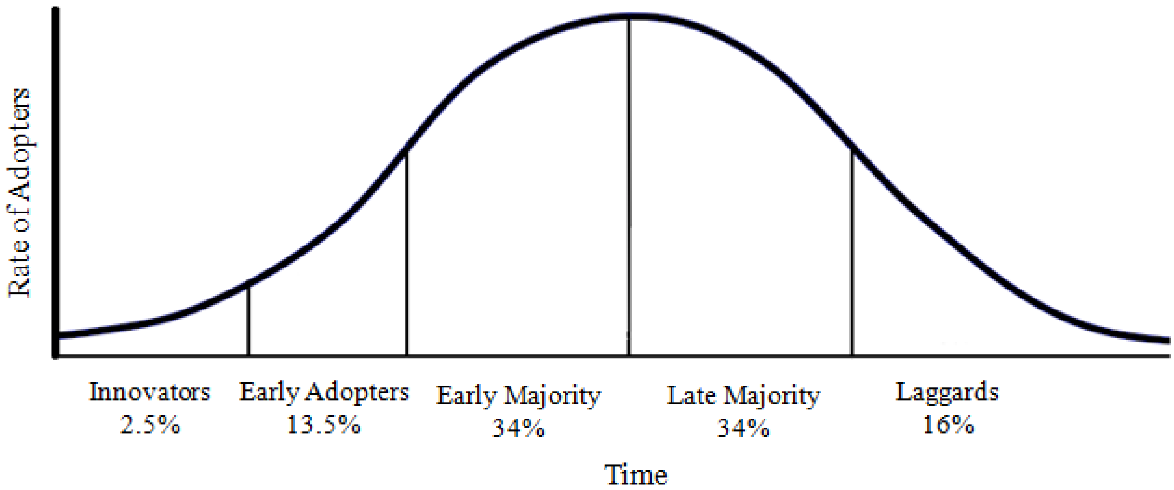

Figure 10. Categories of Consumers in a Diffusion of Innovation Framework [58].

Time series and diffusion rate models have been applied to the prediction of diffusion in a variety of different markets including telecommunication, electronics, energy and transportation. The most widely used models are the Bass model, Gompertz model and Logistic model. These models have been used extensively to model innovation diffusion in automotive markets [37,41,54,55,60–70,72–77,79,80].

The Bass model is used for forecasting the adoption rate of a new technology under the assumption that no competing alternative technology will exists in the marketplace [55]. Bass divided consumers into two groups: innovators and imitators, as shown in Figure 11. Innovators are defined as adopters due to a mass-media effect, whereas imitators are defined as adopters due to a word-of-mouth effect.

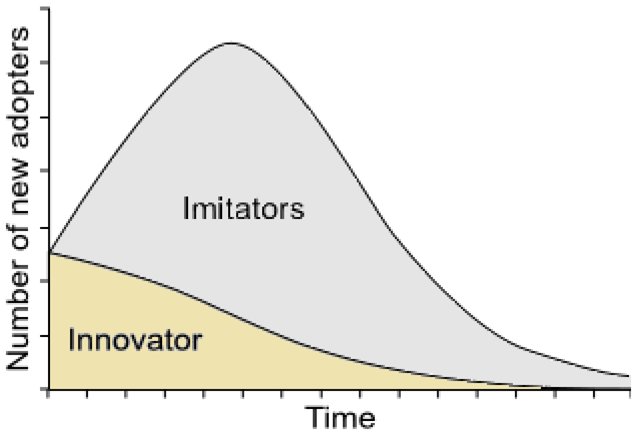

Figure 11. Categories of Consumers in a Bass Framework [55]

According to Bass there are two conditions at which the Bass model is appropriate for use in forecasting the long-term sales pattern of the new technology [55].

1) The new technology has been introduced to the market for which the time period sales are observed.

2) The new technology has not been introduced yet but it could have a market behavior similar to some existing technology with known adoption parameters.

In modeling the automotive market, the Bass model can be used to predict the adoption time and rate of new vehicles. For vehicles where sales data already exists, the parameters of the Bass model can be regressed. For vehicles where there is no historical sales data, analogs or surveys must be used to determine consumer's product adoption characteristics. These assumptions cause a higher degree of uncertainty and require more extensive model calibration and/or the inclusion of more variables such as price and advertising affects.

The Bass model formulation presented here includes the capability to perform both methods of model construction and follows the notation of [55]. The fraction of the available market that will adopt a product at time *t* can be defined as,

$f(t)/[1 - F(t)] = p + q*F(t)$ (10)

where the adoption at time *t* takes the form,

$a(t) = M*p + (q - p)*A(t) - (q/M)*[A(t)]^2$ (11)

M: market potential, (total number of customers in the adopting target segment)

p: coefficient of innovation, (external influence)

q: coefficient of imitation, (internal influence)

f(t): the portion of M that adopts at time t

F(t): the portion of M that have adopted by time t

a(t): adoption at time t

A(t): cumulative adoption at time t

The equation of the generalized Bass model can be fit existing sales data using the following equations:

$$F(t) = \frac{1 - e^{-(p+q)t}}{1 + \frac{q}{p} e^{-(p+q)t}} \quad (12)$$

where

$$f(t) = \begin{cases} F(t), & t = 1 \\ F(t) - F(t-1), & t > 1 \end{cases}$$
$$A(t) = M * F(t),$$
$$a(t) = M * f(t) \quad (13)$$

The time of the peak sales can be calculated as

$$t = 1/(p+q)*Ln(q/p) \tag{14}$$

In addition, price and advertising affects can be incorporated into the Bass model through the inclusion of the function *x(t),* where *x(t)* can be a time dependent function of price or other variables.

$$f(t)/[1-F(t)] = [p + q*F(t)]*x(t) \tag{15}$$

A function *x(t)* which includes consideration of price and advertizing can be calculated from

$$x(t) = 1 + \alpha * \frac{[P(t) - P(t-1)]}{P(t-1)} + \beta * Max\left\{0, \frac{[Ad(t) - Ad(t-1)]}{Ad(t-1)}\right\} \tag{16}$$

α: Coefficient capturing the percentage increases in diffusion speed resulting from a 1% decrease in price

P(t): price in period t

β : Coefficient capturing the percentage increases in diffusion speed resulting from a 1% decrease in advertising

$Ad(t)$: Advertising in period t

Time series and diffusion models assume that products are redesigned, remodeled or updated and marketed in successive generations. Although the period between generations is different for different products and technology, each generation will follow the diffusion process. The ultimate diffusion rate for the product family will be the summation of the diffusion for each generation. In the diffusion modeling of automotive products, automotive product generations have been variously defined as a new generation of a current carline (Toyota Prius generation II) [28], as the introduction of a new technology within a current carline (Toyota Camry HEV) [28], or as an entirely new car line in the market (Chevrolet Volt) [28].

The Bass formula for the first seven generations of a product line is:

$$G_{1,t} = F(t_1)M_1[1-F(t_2)] \quad (17)$$

$$G_{2,t} = F(t_2)[M_2+F(t_1)M_1][1-F(t_3)]$$

$$G_{3,t} = F(t_3)\{M_3+F(t_2)[M_2+F(t_1)M_1]\}[1-F(t_4)]$$

$$G_{4,t} = F(t_4)\{M_4+F(t_3)[M_3+F(t_2)[M_2+F(t_1)M_1]]\}[1-F(t_5)]$$

$$G_{5,t} = F(t_5)\{M_5+F(t_4)[M_4+F(t_3)[M_3+F(t_2)[M_2+F(t_1)M_1]]]\}[1-F(t_6)]$$

$$G_{6,t} = F(t_6)\{M_6+F(t_5)[M_5+F(t_4)[M_4+F(t_3)[M_3+F(t_2)[M_2+F(t_1)M_1]]]]\}[1-F(t_7)]$$

$$G_{7,t} = F(t_7)\{M_7+F(t_6)[M_6+F(t_5)[M_5+F(t_4)[M_4+F(t_3)[M_3+F(t_2)[M_2+F(t_1)M_1]]]]]\}$$

M_i: incremental market potential for generation i

t_i : time since introduction of *ith* generation and $F(t_i)$ is Bass Model cumulative function where p and q are the same for each generation

Estimating the market potential (M_i) is a critical part of the formulation of a diffusion model. The market potential need to be estimated for each technology as it will be the upper market bound for that technology. This has proven to be a complicating factor in automotive technology market diffusion modeling because of the need to understand the market potential for each vehicle class, the market preference for each technology within each vehicle class, and the share of manufacturers who will actually integrate a given technology into each vehicle class. The market potential must often change over the period of the analysis by integrating fleet expansion, vehicle class volume change, manufacturer performance and the availability of carline and technology. An example of a market potential for the passenger car HEV within the midsize class will be:

$$M_i = S*P_{rf}*S_h \tag{18}$$

M_i :market potential over i year.

S: Total number of new US vehicle class sales.

P_{rf}: Consumer's preference toward the technology vs. its incremental cost.

S_h: Market share of the manufacturers selling HEVs or announced to have introduce HEV carline.

In addition to the Bass model, some HEV adoption studies have used the Gompertz and Logistic models to model HEV market diffusion. The Gompertz model is a time series mathematical model developed to describe human mortality age dynamics [137]. The Gompertz model equation is

$$f(t) = ke^{-bt}e^{-le^{-bt}} \tag{19}$$

Where

$$\begin{aligned} F(t_n) &= \sum_{i=1}^{n} f(t_i) \\ A(t) &= M * F(t), \\ a(t) &= M * f(t) \end{aligned} \tag{20}$$

k :long run market potential

b: delay factor

l: inflection point (time where 36.8% of the market potential is expected to be reached)

The Logistic model is a sigmoid curve used as an S-shaped curve to model population growth. The simple Logistic Model equation is

$$f(t) = \frac{1}{1 + \exp(-t)} \qquad (21)$$

The logistic model used to model the diffusion of innovation is:

$$f(t) = \frac{S}{1 + B * \exp(-A * t)} \qquad (22)$$

Where

S: Long run market potential

T: time index

A: Delay factor (between 0 and 1)

I: Inflection point (time at 50% market potential to be reached)

*B = exp(I*A)*

In general, the frameworks for using the Gompertz and Logistic models are similar to the framework of the Bass models in that all require the fitting of preexisting data, the concept of generations, and a detailed estimation of market potential.

Diffusion and time series models have been applied to the prediction of diffusion in a variety of different markets including transportation. Diffusion models are based on the process of acceptance of a new invention or product by the market over time. The models seek to capture the life cycle of new products over time. The adoption rate of a new technology can be forecasted only under the assumption that no competing alternative technology will exists in the marketplace. The disadvantages are that assumptions used cause a higher degree of uncertainty and require more extensive model calibration and/or the inclusion of more variables such as price and advertising affects. Also the time of peak need to be known in advanced, it cannot simulate the diffusion of technology where there an existing competing technology, the market potential for each technology need to be estimated which has proven to be a complicating factor in automotive technology. The advantages are that it is easy to implement and use by known the historical trend of the technology or similar technology. It simulates consumers' adoption using classical theories on diffusion and like in Bass generalize model it can model different generations of vehicle technology over time. Results show that using only Bass model can lead to very inconsistent results within and between studies. Some studies show that a decrease in PHEVs MSRP will lead to an increase in there diffusion. A study by Jeon presented the results of HEVs, PHEVs, and EVs using Bass model with successful generation and with a very rich market potential estimation. His result show that HEVs will lead the market but with successful PHEVs and EVs reaching 5 million, 1 million and 2 million by 2030 of new vehicle sales respectively.

5.2.4.1 Review of Key Diffusion and Time Series Modeling Studies

In this section we review some key studies that have used diffusion and time series modeling to estimate the adoption rate of HEVs, PHEVs and EVs.

Lamberson, (2009) examined the adoption rate of HEVs using the Bass and Gompertz models [25]. The study compared diffusion of HEV technologies to that of other automotive innovations and extrapolated results to the US fleet. Each model gave a different result though the Gompertz model was found to perform more favorably than Bass model [25]. He concluded that government incentives and regulation will play a major rule in HEV adoption. He uses a nonlinear least squares method to estimate the parameters of the Bass and Gompertz model on the monthly US HEV sales. The total market penetration is estimated to be 1.6 million for the Bass model and 25.7 million for the Gompertz model [25]. The Bass model estimated that HEV sales will peak out on summer 2008 and then decline whereas the Gompertz model estimate it to increase until 2015 and then decline. It is estimated that on 2015 the annual HEV sales will be 2636 and 1,296,310 from Bass and Gompertz models, respectively [25]. In 2020 the HEV sales will be 33 and 1,208,039 from Bass and Gompertz models, respectively [25].

McManus and Senter, (2010) studied market models for predicting PHEV adoption [96]. Two scenarios were considered, without fixed saturation level and another with a fixed saturation level. In the fixed saturation scenario, Bass, Generalized Bass, Logistic and Gompertz models were used. The market potential was estimated to be around 1.8 million for the Bass, Generalized Bass and Logistic models where it was 4.4 million in the Gompertz model [96]. PHEV sales were estimated to peak at 350,000 after 7 to 8 years from introduction [96]. In the without fixed scenario, a model presented in Centrone et al., (2007) and consideration-purchase model were used [26,96]. The consideration-purchase model accounts for vehicle sales, stock and scrappage. For different PHEV incremental cost $2,500 to $10,000, on 2015 the PHEV penetration rate is estimated to be 118,793 to 4,726 units and on 2025 it is estimated to be 1,891,576 to 84,341 units and on 2035 it is estimated to be 6,021,141 to 379,615 units [96].

Cao, (2004) used an extended Bass model with variable market potential to model HEV market diffusion [27]. He included forecasted gasoline prices 2003-2025 and prediction of consumer's evolving awareness of HEV technology. Some of the assumptions considered are that the coefficients of the Bass model do not change over time, there exists no interaction among vehicle technologies, vehicle technology supply always equals or exceeds their demand and the diffusion rate is not effected by government policies or marketing strategies. The model was tested under different scenarios of; HEV awareness influence, gasoline price change, and market potential scenarios. In the scenario analysis the market potential was assumed to be around 10% of the total US registered vehicles in 2000, and consumers awareness to increase by 2% per year. There were two peaks due to first HEV purchases (2013) and replacement sales (2023). Those HEV sales are estimated to reach 510,000 in 2008 and 2 million in 2013. In the two gasoline price scenarios considered, gasoline price is assumed to increase by 25 cents and 50 cents per gallon per year from 2007 on. The average annual HEV sales are estimated to be 2.2 million and 2.8 million from 2011 to 2025 for these two scenarios, respectively.

Jeon (2010) examined the penetration rate of HEVs, PHEVs and EVs until 2030 based on the Bass diffusion model [28]. He analyzed the problem by using a successful generations to overcome the limitations and fixed saturation problems of the Bass model. The generations were defined by either a start of new technology carline or a new generation of current carline technology. The market potential was estimated for each generation as the approximate average sales of the US vehicle fleet or class in which the technology exist multiplied by the generation period. His model estimated the US annual sales of HEVs, PHEVs and EVs to reach 5 million, 1 million and 2.1 million respectively.

Becker, (2009) reports the rate of electric vehicle adoption using the Bass model under two gasoline price scenarios and accounting for vehicle purchase price and operating costs [138]. In the baseline scenario the EV will have a penetration rate of 3% in 2015, 18% in 2020, 45% in 2025 and 64% in 2030 of the total US light vehicles sales [138]. Trappey and Wu, (2007) evaluated three forecasting methods on large and small data sets [139]. An extended logistic model fit large and small datasets better than a simple logistic or Gompertz model and was well suited to predict market growth with limited historical data [139].

Other studies have used diffusion models to estimate the diffusion rate of HEV in countries other than the US. In a study by Won et al., (2009) a Bass diffusion model was used to estimate the adoption rate of PHEV in Korea by using US HEV sales data [140]. The study did not test or use any historical vehicle sales data in Korea but they only considered the total vehicles registered and the year vehicle sales. They limit their analysis to small sized HEV cars excluding light trucks and other larger vehicles [140]. In their estimation of Bass model parameters they assume that the market potential for HEVs are estimated from US HEV sales data [140]. By 2032 the adoption rate of PHEV was estimated to reach its maximum where in 2052 the Korean market would be saturated with PHEV [140].

Muraleedharakurup et al., (2010) used Gompertz growth and Logistic models to forecast the adoption rate of HEV in the UK up to 2030 [141]. The Bass model was not used due to the absence of past vehicle sales data. The study considered technology life cycle net cost in the predicting of HEV adoption rates although they did not explain how they integrated the life cycle cost in the penetration rate curve fit [141]. The analysis was performed by specifying the market segment, estimating the market potential, estimating the economic cost and estimating the technology penetration rate. The study considered the UK fleet and results show that the penetration rate will achieve 7.5% by 2020 and 16% of the UK vehicle market by 2030 [141]. Some of the factors found to affect HEV penetration rate are the oil prices and increase in diesel vehicle penetration [141].

5.2.5 Other Models

Some studies have examined the penetration rate of HEVs using existing forecast, survey data, or supplier's capabilities. A study by Balducci, (2008) examines the market potential for PHEVs in the US [142]. Three scenarios were examined for PHEV market penetrations from 2013 to 2045. The first scenario was based on existing forecast of hybrid technology and the estimated PHEV shares as derived from EPRI and NRDC estimates [142]. The second scenario was based on asking domain experts for the best judgment under a given set of PHEV conditions that range from marginal cost to tax incentives. The last scenario was based on estimates of the supply capabilities of automakers and battery manufacturers. The study found that in 2045, the PHEV market penetration is estimated to reach 11.9% using the first scenario, 30.0% using the second scenario and 73.0% using the third scenario [142].

In another example of unconventional Curtin et al., (2009) examined the purchasing probability of HEVs and PHEVs [114]. The analysis was based on the results of interviewing a nationally representative sample of 2,513 adults from July to November 2008 in US [114]. The data showed social factors to affect consumers purchasing decisions, but that economic incentives dominate consumers' automobile purchasing decisions [114].

5.3 Penetration Rate Modeling Results and Discussion

In this section, we present the results of each reviewed study where the authors performed a market penetration rate study for the US that used a model of the US vehicle fleet, and that attempted to predict HEV, PHEV or EV market share as a function of time. Whereas the review of the literature presented above relies on studies of HEV, PHEV and EV market modeling, these results are restricted to only PHEV market studies. The results for each modeling type are presented together.

5.3.1 Agent Based Models

Using agent based models, only Sullivan et al. (2009) estimated HEV, PHEV or EV market penetration according to the above requirements. Eppstein et al., (2010) predicted the adoption rate of PHEVs as a function of time but without specifying initial start date [117]. Sullivan et al., (2009) estimated fleet penetration and new PHEV sales for 2015, 2020 and 2040 using two fuel price scenarios [23]. The four cases considered in each fuel price scenario are, 1) a base case, 2) a case under which automobile manufacturers subsidize the incremental cost of PHEVs, 3) a case under which sales tax for PHEVs is exempted, and 4) a case under which both 2 and 3 are combined. The results presented in Figure. 4 show that subsidy and sales tax exemption are required for PHEV adoption. The increase of PHEV sales over the base case is estimated to be 4% to 5% in 2020 and 17% to 24% in 2040. It is estimated that changes in fuel price are more significant than the considered policies in increasing PHEV sales. An increase in fueling costs to $4 per gallon will increase PHEV adoption by 1% in 2020 and 8% in 2040 [23].

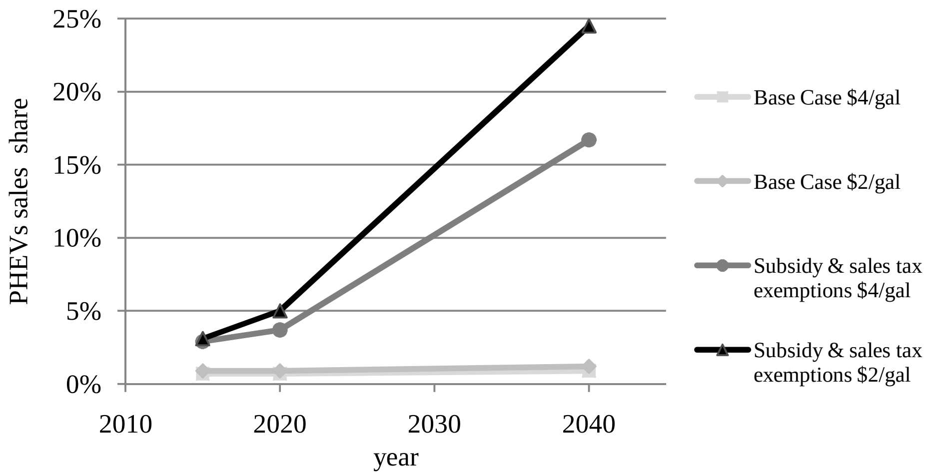

Figure 12. PHEV sales penetration rate fleet share as estimated using agent based methods. [23]

5.3.2 Consumer Choice Model

Using consumer choice models, a few studies have estimated HEV, PHEV or EV market penetration according to the above requirements. The HEV sales rate was most completely estimated by Santini and Vyas, by the PHEV Market Introduction Study and by Bandivadekar [18,24,95]. A comparison of these results is shown in Figure 13.

The differences between the results of these studies are due to the variation in modeling, model parameters, and assumptions as discussed in previous sections. The variations of HEVs penetration rate estimated by each study are ~ 82% on 2020 and 46% on 2045. The variation within the AVID model is due to the fuel price scenarios of $1.5/gal and $3/gal. HEV adoption rate is estimated to increase by ~ 41% for an increase of the fuel price by $1.5/gal. PHEV Market Introduction Study results show higher HEV adoption rate where the variation between scenarios considered are estimated to be ~ 14% on 2020 due to the change in HEV ownership cost. The variation between scenarios results are ~ 4% on 2020, ~ 19% on 2030 and ~ 30% on 2045. Ignoring studies parameters, assumption and data dissimilarity the variation on HEV penetration rate estimated by each study are due to either a decrease in HEV purchase cost or a decrease in its operation cost due to an increase in fuel price when compared to similar gasoline operated conventional vehicle.

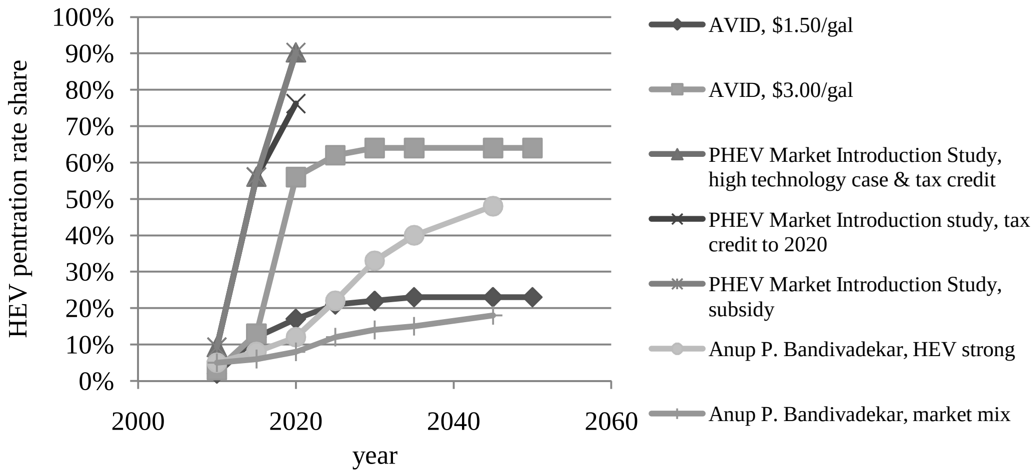

Figure 13. HEV Fleet Penetration Rate Estimated Using Consumer Choice Method [18,24,95].

Figure 14 show the results of the PHEV Market Introduction Study and Bandivadekar model study for PHEV penetration rate [24,95]. The successful PHEV scenario at the Market Introduction Study of tax credit to 2020 show that the adoption rate will reach ~18% by 2020 but this will be by taking some of HEV market share. At Bandivadekar model the variation between scenarios results are ~ 2% on 2020, 5% on 2030 and 9% on 2045.

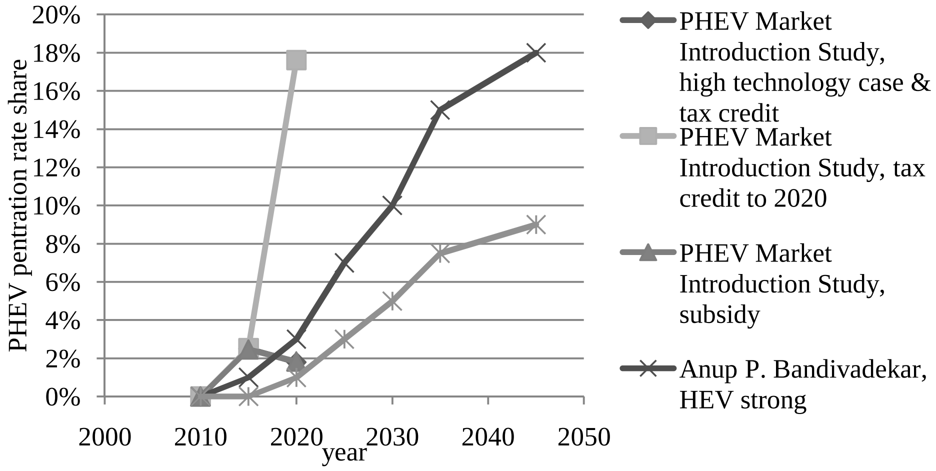

Figure 14. PHEV Fleet Penetration Rate Estimated Using Consumer Choice Method [24,95].

5.3.3 Diffusion Rate and Time Series Models

Lamberson used the Bass and Gompertz model to estimate HEV and PHEV new vehicle sales. He used the US monthly vehicle registration data [25]. Xinyu used an extended Bass model with variable market potential where Jeon used the Bass model with successful generation; results are presented in Figure 15 [25,27,28].

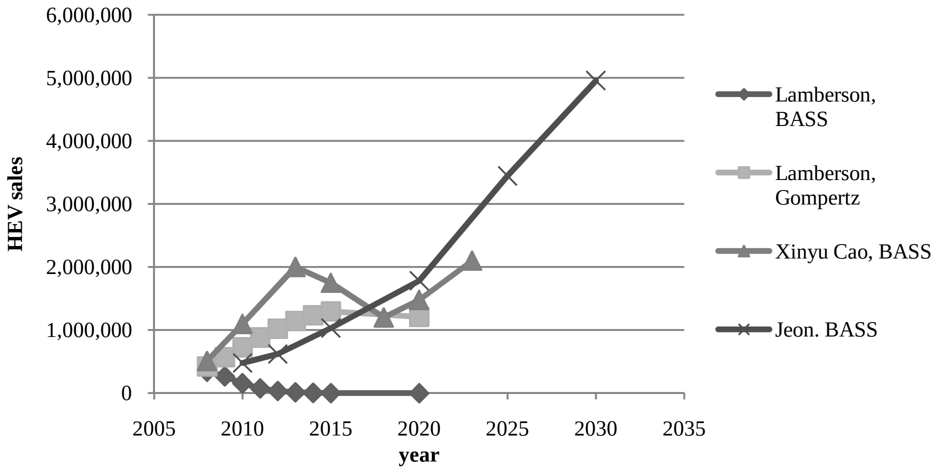

Figure 15. HEV Penetration Rate Estimated Using Bass and Gompertz Methods [25,27,28].

The PHEV penetration rate was estimated by McManus and Senter for two PHEV incremental cost scenarios [96]. The increase in PHEV sales is estimated to be ~100,000 vehicles on 2015, 1.8 million on 2025 and 5.6 million on 2035 this was due to a decrease in PHEV cost by $7,500 [96]. Jeon results show that PHEV sales will slowly increase to reach 1 million vehicles by 2030 due to fast increase in HEV market share, results are presented in Figure 16 [28].

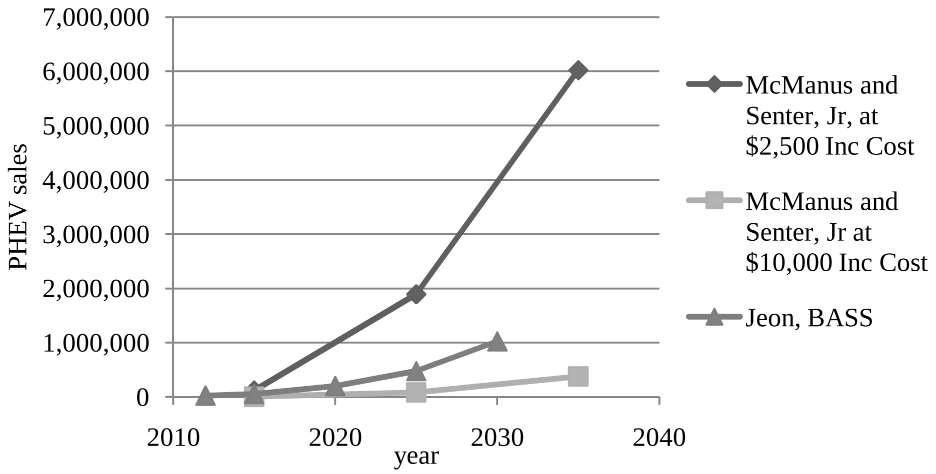

Figure 16. PHEV Penetration Rate Estimated Using Diffusion Method [28,96].

The adoption rate of Electric vehicle was estimated by Becker using two scenarios [138]. The variation in electric vehicle adoption rate scenarios will increase to 256,000 on 2020, 480,000 on 2025 and decrease to 336,000 on 2035 [138]. Jeon estimated that EVs will have a high market share compared to PHEVs and vehicle sales will increase to reach ~ 2 million by 2030, results are presented in Figure 17 [28].

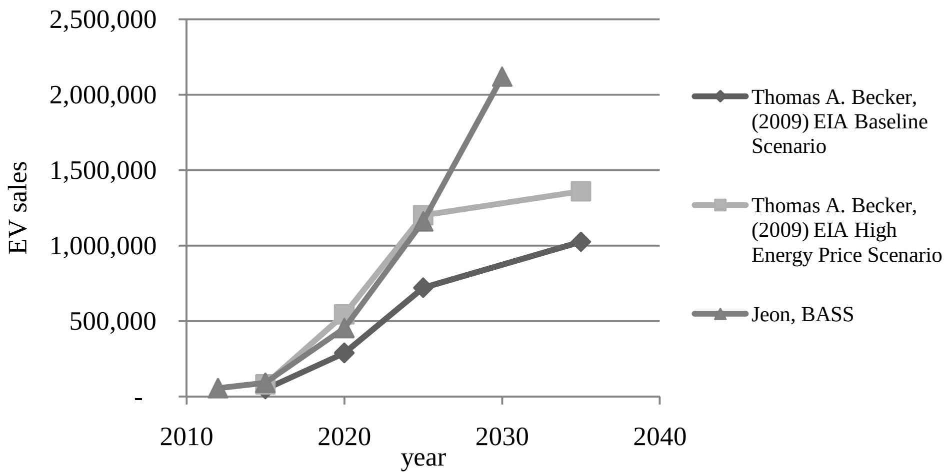

Figure 17. EV Penetration Rate Estimated Using Diffusion Method [28,138].

Results presented show there is a large variation between models, studies and within each study scenarios. Simulation of PHEV market penetration rate is very difficult but needed for researches and policy makers as part of larger analysis. In the next section the recommendations will provide an essential guidance to enhance the PHEV market penetration models.

5.4 Recommendations and Conclusions

This study has reviewed and analyzed the primary purposes, methods, and results of studies of PHEV market penetration. The purposes of performing vehicle technology market diffusion studies are to 1) determine the future number of PHEVs for planning purposes, 2) understand whether PHEVs will be present in the US vehicle fleet, and 3) understand the role of policy in encouraging PHEV market diffusion. The primary methods used in literature are agent-based behavior models, consumer choice models and market diffusion models. Each method is analyzed to understand its strengths and weaknesses. The results of these studies have been shown to be highly variable due to differences within and among studies in terms of the methods used (agent-based methods, consumer choice methods, and diffusion rate models), the values of important parameters (including total available market), assumptions (including fuel costs), and uncertainty in policy and market condition scenarios.

On the basis of these findings, we can synthesize recommendations for improving the utility of these studies for decision making by society and in the vehicle and utility industries.

An improved interface between modeling and surveys needs to be developed. Most studies do use consumer survey data to inform their adoption rate modeling, but the fidelity with which the consumer is modeled does not match the richness of data that could be derived from survey. For instance, many adoption rate models divide consumers into categories of innovation including: innovators, early adopters, early majority, late majority and laggards as defined by Rogers [58,95,114]. First, is unclear whether the innovation categorizations developed for low-operation cost consumer products are applicable to the high operations costs associated with vehicle fuel economy preference. Second, none of the PHEV market preference surveys performed to date poll consumers on their openness to automotive innovation, so as to identify surveyed preferences with these categories.

Include modeling of vehicle supply and the actions of automakers. None of the reviewed studies have attempted to measure and model automakers actions and plans for PHEVs. Automakers represent the supplier of the technology under consideration and they are constrained by factors including budget, technology availability, brand preference, and preexisting product plans. The primary assumption for most of these studies is that manufacturers are able to meet the proposed demands for PHEVs. This assumption has not been strongly challenged, but numerous studies have shown that policy demands and consumer demands for fuel economy can be met in ways that do not require the mass-production and mass-marketing of PHEVs [2,81].

Include modeling of competition among technologies. Most of the models assumed that consumers will consider the discrete choice between the new purchase of an HEV and a CV. Most of the studies reviewed here did not consider how consumers will understand competition among the other technologies that will be available. The majority of models assume that one technology (HEV, PHEV or EV) will dominate for the next 10-30 years and the market of these vehicles will not be lost to a new technology. Most models did not consider automakers' rate of adoption of improved and fuel efficient CV technologies [2,81]. Most models did not consider the presence of HEVs or other advanced technologies in the used car market.

Improve modeling of market volume and vehicle classifications. A majority of the models reviewed here consider the vehicle fleet to be monolithic; only a few of the studies consider the effect of variation in consumer preference for HEV, PHEV and EV technologies among vehicle classes and types, and those use EPA-type vehicle classifications. The market share of vehicle fleets, classes and makes must be estimated and integrated in the modeling to set the correct market potential for every vehicle technology.

Improved sensitivity analysis will support and verify the model results and provide a guideline to future improvement in the model, parameters and assumptions. Studies have considered different scenario analyses but were based on parameters that affect vehicle technology cost. Studies are lacking sensitivity analysis within the model assumptions, parameters, market condition such as elasticity, slops, utility functions, and change in market or consumers economy. Studies run their models under different scenarios assuming the validity of the model! There are four measures of uncertainty, model components, model data, market potential, and technology cost/benefits. There is a need to measure how the final model results are sensitive to the model components and assumptions used. Validation of the data needs to be followed by validation of the model, parameters, data, and assumptions used. This will measure the performance and accuracy of the model and model results.

5.4.1 Conclusions

This literature review is focused on PHEV penetration rate model studies. PHEV technology is a critical technology due to their reduced petroleum consumption and consequent value to consumers, society, automakers, and policymakers. PHEVs can reduce greenhouse gas (GHG) emissions and increase US energy security. This paper presented the available research study in PHEV penetration rate model. These studies are relevant and defensible within their scope, but many researchers and policy makers will be using these types of studies as components within larger analysis. The large and unquantified sources of uncertainty and the large variability among studies makes synthesis of the state of the art simulation of PHEV market penetration very difficult. By following the recommendations of this literature review, it is hoped that the field can expand its impact and relevance to decision making entities in the government, utility and automakers.

Chapter 6- Multi-Criteria Modeling System of the U.S. New Vehicle Fleet

6. Chapter Summary

Policymakers, analysts, society, and consumers are interested in understanding various vehicle types and technologies under different fleet penetration scenarios so as to understand the trajectory of various sustainability indicators of the personal transportation fleet including fuel economy, total cost of ownership, air emissions reduction, and imported oil reduction. These long-term studies have concentrated on describing the effect of technological advancement on these indicators without considering the policy context in which these technological advances occur.

For this example, we consider the effect of the long-term trajectory of US Corporate Average Fuel Economy (CAFE) standards, which are proposed to double by 2025. CAFE policy provides an aggressive baseline model of fleet performance against which any advanced vehicle technology must compete. In order to understand the costs and benefits of vehicle electrification (through PHEV technology) this study has constructed a multi-criteria modeling system to simulate the fuel economy, total cost of ownership, air emission and fuel displacement of the US vehicle fleet over the period 2010-2030. Various HEV and PHEV penetration scenarios are simulated to understand the economic, environmental and policy effects of the technologies. Results show that only a very high PHEV penetration scenario can meet the proposed CAFE regulations, and that vehicle electrification is one of only a few technology paths that can realize long-term economic and petroleum reduction benefits.

6.1 Introduction

This study presents a multi-criteria modeling system that simulates the sales of US new light-duty vehicles over the period 2010-2030. The system model is based on the CAFE and TCO models developed and discussed earlier but updated and upgraded to include all of the vehicles sold in the US, and an assessment of oil displacement and emissions cost/benefits.

In 2008, The US National Academy of Engineering developed a study to review PHEVs projection, factors affecting PHEVs diffusion, PHEVs maximum practical penetration rate, and estimating PHEVs costs and impacts on petroleum consumption and well-to-wheel CO_2 emissions under different PHEV penetration scenarios. In their study the used mid-size car PHEV 10 similar to Toyota Prius (parallel) and PHEV 40 similar to Chevrolet Volt (series). The fuel economy and electric use were similar to results from Simpson (2006). PHEVs costs to manufacturer relative to CVs were estimated using Li-ion battery under two incremental costs scenario, optimistic and probable. Some of the weaknesses of the US National Academy of Engineering study are

- Applying the technology to only mid-size car class.
- The cash flow analysis considered technology costs and fuel costs only.
- Not including the fleet CAFE achieved for each technology scenario.
- The model used is simple and missing a level of detail needed for the analysis; it was based on NRC, 2008 model (STM (Simple Transition Model)) with some modification.
- Electricity prices are kept constant at $0.08/kWh.

- The estimated cash flow was not discounted but estimated to be the required costs to make PHEVs.
- Fleet have the same total number of vehicles over the period 2005-2050.
- The total technology incremental price charged to the customers was overestimated and it is 140% of the PHEVs incremental costs.
- PHEVs emissions calculated do not account for battery manufacturing emissions
- Air emission assessment was for GHG emissions only.

Overall the US National Academy of Engineering study results and conclusions are

- Costs of Lithium-ion battery is high and it is expected to have a limited price reduction in the future
- PHEVs costs are very high and this without including homes electric system upgrades that might be needed. Incremental costs of HEV is estimated to be ~ 56% of PHEV 10 and ~ 21% of PHEV 40
- The benefits of PHEVs are very sensitive to their incremental costs and gasoline prices. PHEV 10 will achieve cost-effectiveness faster than PHEV 40 because of its lower incremental costs.
- Maximum Practical rate of PHEVs are unlikely to occur due to market, consumer and automakers behavior
- The impact of PHEVs on oil consumptions will be limited before 2030 due to their low penetration rate

- PHEVs with large battery capacity will emits less GHG but this benefits is driven by how clean is the electric power used
- PHEVs will not harm the electric grid for next decades if they are charged at night
- More research are needed

The primary goal of this analysis is to calculate and evaluate the achievable CAFE of US fleets, and the net value of reduced costs, air emissions, and oil consumption over the period 2010-2030. The vehicle technologies that are available in this study are conventional vehicles (CVs), hybrid electric vehicles (HEVs), and plug-in hybrid-electric vehicles (PHEVs). The CAFE model evaluates the fuel economy of all US new vehicle sales where the TCO, oil displacement and emission assessment is calculated for a set of vehicles representing ~95% of U.S. new vehicle sales.

6.2 Model Development

6.2.1 Data Collection and Modeling

This multi-criteria modeling system is based on the CAFE and TCO models described in Chapter 3 and Chapter 4 with the addition of an oil displacement and air emission assessment. The CAFE model was upgraded to include all of the new US carlines, carline sales, carlines MSRP, carlines footprint, carlines weight and fleet actual and forecasted sales over the period 2010-2030. Vehicles were classified into passenger car and light truck fleets. In the light truck fleet, SUVs and Pickups were divided into small, medium and large classes based on their footprints as shown in Table 13. The HEV and PHEV5-60 technologies are applied to four vehicle classes within each fleet to cover 95% of the total vehicle sales. In the passenger car fleet, the four vehicle classes that are subject to electrification are the subcompact car, compact car, midsize car and large car. In the light truck fleet the four vehicle classes that are subject to electrification are the midsize SUV, large SUV, minivan, and large pickup. As proposed by NHTSA [2] the required footprint CAFE standard for each vehicle footprint category within each fleet were calculated for the 2010-2030 using vehicles forecasted sales and reference year footprints [2]. Vehicle classes and carline shares are kept the same but their volume changes with respect to NHTSA forecasted fleet volumes over the period 2010-2030.

The TCO model was upgraded the same way and by adding two more vehicle classes to each fleet to cover 95% of the fleet's vehicles. The TCO model calculates the total cost of owning and operating each CV, HEV and PHEV5-60 vehicle sold in the period 2010-2030. The model was updated with forecasts of vehicles sales [2], fuel economy [102], MSRP [102], registration renewal and fuel prices [2,143]. The source for the nation forecasted fuel prices were NHTSA and EIA [2,143]. All costs are in 2010$ and discounted at 6%.

The reference (baseline) case has the same vehicle types as the 2008 MY vehicle sales but with forecasted 2010-2030 fleet volumes.

Finally, a model of air emissions and oil displacement valuation is included. Oil displacement and emissions costs assessment data, assumptions and method were based on the methods reported in [144]. The oil displacement valuation costs used are presented in Table 14 well-to-wheel GHG and other emission components are presented in Table 15. The complete emission quantity and costs are presented in appendix C.

Table 13. Additional classification of SUVs and Pickups in the Light truck fleet

	Minimum	Maximum
Small SUV	41.0	42.5
Mid-Size SUV	43.1	47.0
Large SUV	47.1	61.0
Small Pickup	44.8	47.9
Mid-size Pickup	53.4	60.0
Large Pickup	63.8	75.2
Minivan	45.3	55.6
Van	63.5	65.2

Table 14. Oil displacement valuation, [144].

Military	Monopsony	Supply disruption
$0.03/gal	$0.22/gal	$0.09/gal

Table 15. Air emission components evaluated [144].

Gasoline US refineries Emissions	Direct emissions	CO_2	CH_4	N_2O	CO_{2e}	NO_x	PM_{10}	PM_{25}	SO_2	VOC	CO
	Upstream emissions	CO_2	CH_4	N_2O	CO_{2e}	NO_x	PM_{10}	$PM_{2.5}$	SO_2	VOC	CO
Power Generation	Direct emissions	GHG	NO_x	PM_{10}	$PM_{2.5}$	SO_2					
	Upstream emissions	GHG	CO	NO_x	PM_{10}	$PM_{2.5}$	SO_2	VOC			
Tailpipe emissions	GHG emission	CO_2	CO4	N_2O	GHG						
	Air Pollution emissions	CO	NO_x	PM_{10}	$PM_{2.5}$	VOC					
Battery emission	Battery Assembly	CO_2	CH_4	N_2O	CO_{2e}	VOC	CO	NO_x	PM_{10}	$PM_{2.5}$	SO_x
	Battery upstream	CO_2	CH_4	N_2O	CO_{2e}	VOC	CO	NO_x	PM_{10}	$PM_{2.5}$	SO_x

6.2.2 System Model Interaction, Input and Outputs

The function of the multi-criteria modeling system process is shown in Figure 18. The inputs to the model are derived from an input/output (I/O) graphical user interface (GUI), and from the database of information pertaining to each year and each vehicle fleet. The inputs to the model for each vehicle class within each fleet and over the period 2010-2030 are:

- Technology scenario penetration rates
- CVs MSRP

- HEVs and PHEVs technology incremental costs
- CVs, HEV and PHEV5-60 fuel economy
- Fuel prices
- Fleet volume
- Discount rate
- Technology incremental costs learning curve coefficient
- CVs and technology fuel economy learning curve coefficients
- Air emission and oil displacement valuation costs

The multi-criteria modeling system has a base case scenario and works by updating each CAFE, TCO and air emission model

The system model has 20 CAFE models for the passenger car fleet and 20 CAFE models for the light truck fleet, one for each year modeled. The CAFE models results for each fleet are collected and sorted by the CAFE interaction model to be presented at the main I/O GUI. There are 20 TCO models (one for each year modeled) for each vehicle class. Each TCO model calculates the TCO of each new vehicle sold. The results of each TCO model are collected and sorted by the TCO interaction model and then presented at the main I/O GUI. The air emission and oil displacement model uses both emission and TCO interaction models to assess the emission and oil displacement quantity and value.

The outputs from the model for each fleet, vehicle class, and reference and scenario case over the period 2010-2030 are:

- Achieved fleet CAFE
- CAFE costs
- Total cost of ownership (fuel costs, maintenance costs, salvage value, insurance costs, purchase costs, and registration renewal costs)
- Annual and cumulative cash flow
- Air emission (GHG, CO_2, CH_4, N_2O, NO_x, SO_2, PM_{10}, $PM_{2.5}$, VOC and CO) quantity and valuation
- Gasoline consumption, electricity consumption and Oil displacement valuation
- Gasoline fuel displaced and gasoline fuel tax lost

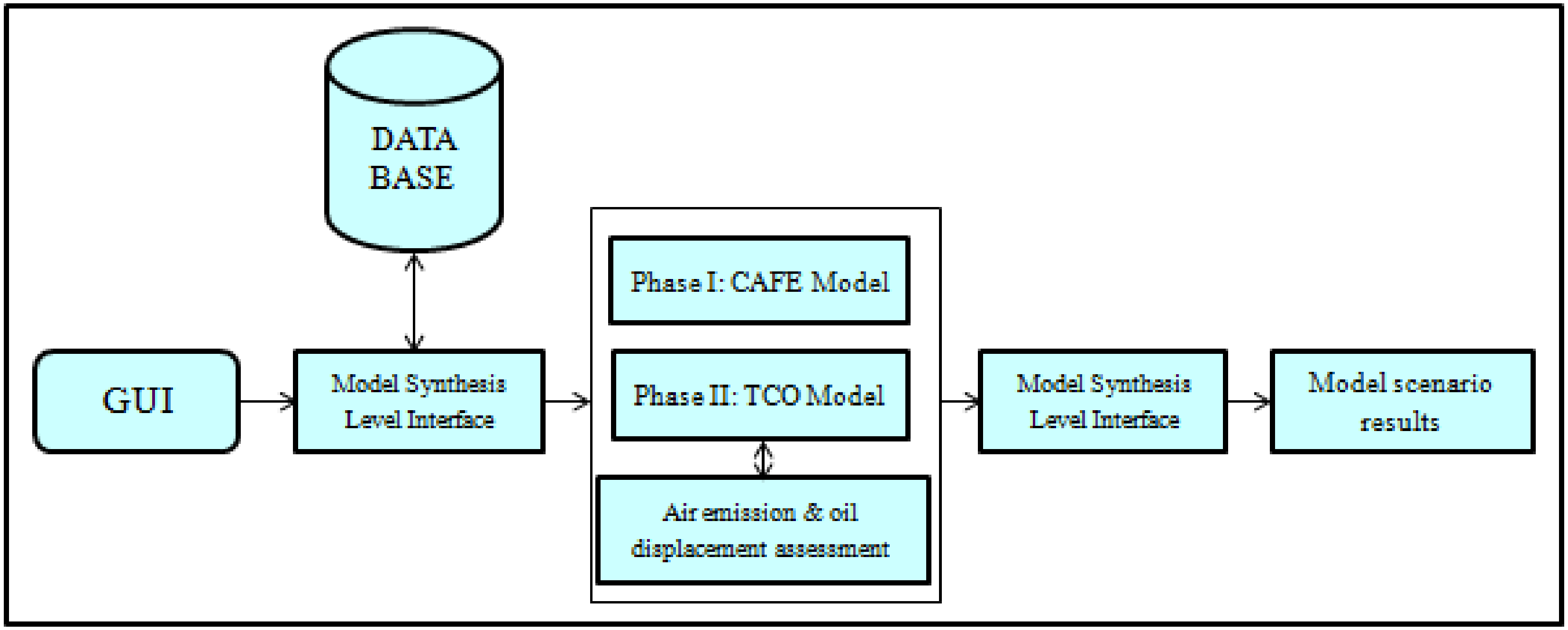

Figure 18. Multi-criteria modeling system flow chart

6.2.2.1 Scenario Definitions

Penetration rates for HEVs and PHEVs are presented in four scenarios and compared to a reference case that assumes a fleet with no HEV or PHEV technology. The four scenarios are labeled

1. *Low HEV*,
2. *High HEV*,
3. *Medium HEV/PHEV*, and
4. *High PHEV*.

The low HEV scenario assumes HEVs to reach 41% of new vehicle sales by 2030 in both passenger car and light truck fleets. HEV sales reach 100% of the new vehicle sales in the high HEV scenario by 2030. In the medium HEV/PHEV scenario, HEVs reach 42% of the new vehicle sales by 2030 in both fleets whereas PHEVs reach 32% of sales in the passenger car fleet and 45% of sales in the light truck fleet. The high PHEV scenario is designed to meet the proposed footprint CAFE standards each year over the period 2010-2030. The high PHEV scenario also includes HEV sales. In the high PHEV scenario, HEV sales make up 7% of vehicle sales by 2030 and PHEV make up 66% of the passenger car fleet and 75% of the light truck fleet by 2030. The three PHEV technologies used for each scenario were PHEV 30, PHEV 40 and PHEV 60.

Figure 19 and Figure 20 shows the modeled cumulative vehicle sales of PHEV and HEV technologies under the four considered scenarios. The penetration rate of each vehicle technology is presented in Figure 21 through Figure 24 for the passenger car fleet, and in Figure 25 through Figure 28 for the light truck fleet. In scenarios 1 through 3, HEVs and PHEVs gradually replace CVs with monotonically increasing market share. In scenario 4 (the high

PHEV penetration scenario, PHEVs become the majority technology by 2025 and HEV share decreases between 2017 and 2030.

In each scenario of the multi-criteria modeling system, the following assumptions apply:

- Gasoline fuel and electricity prices are based on EIA projections, 2009 [2,143].
- Fleet fuel economy efficiency improvements and technology incremental cost decrease followed ANL average rates [102].
- The estimated cash flow was discounted at 6% rate.
- The base scenario used was a fleet without HEV or PHEV technology.
- Fleet volumes are forecasted with reference to NHTSA but carlines have the same share over period 2010-2030 [2].
- Vehicle miles traveled are similar to the VMT used in TCO model
- Technologies incremental costs are the manufactured cost as in CAFE and TCO models

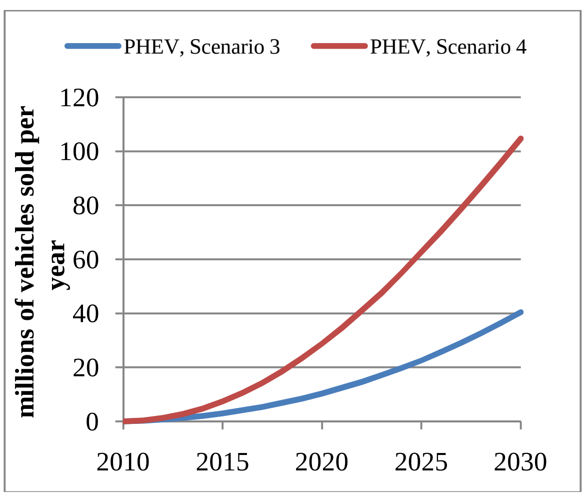

Figure 19. Market Penetration (Cumulative Sales) for PHEVs Under Scenarios 3 and 4.

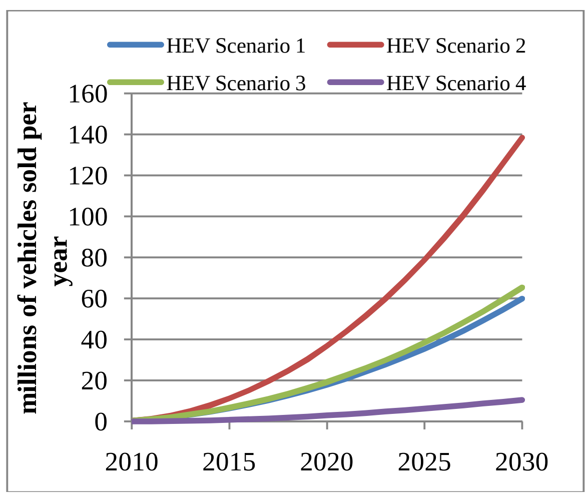

Figure 20. Market Penetration (Cumulative Sales) for HEVs Under Scenarios 1 Through 4.

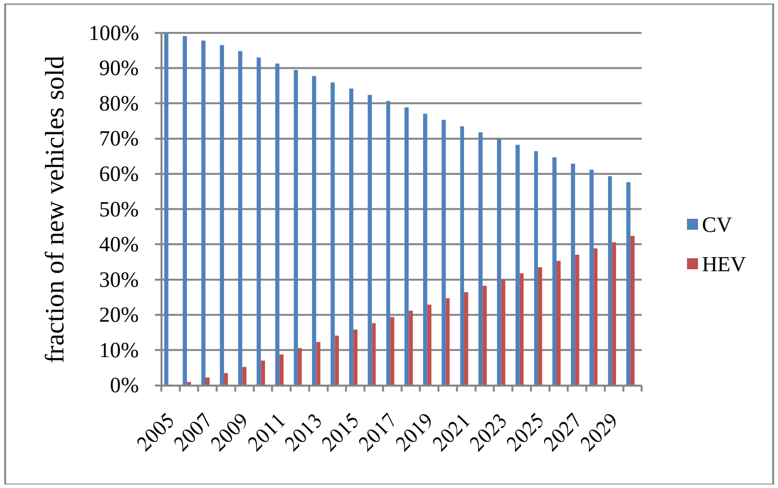

Figure 21. Technology Penetration for the *Low HEV* Scenario in the Passenger Car Fleet

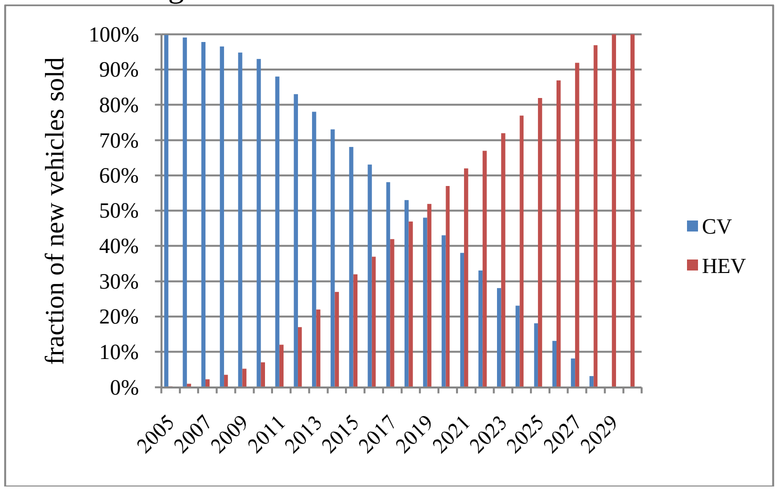

Figure 22. Technology Penetration for the *High HEV* Scenario in the Passenger Car Fleet

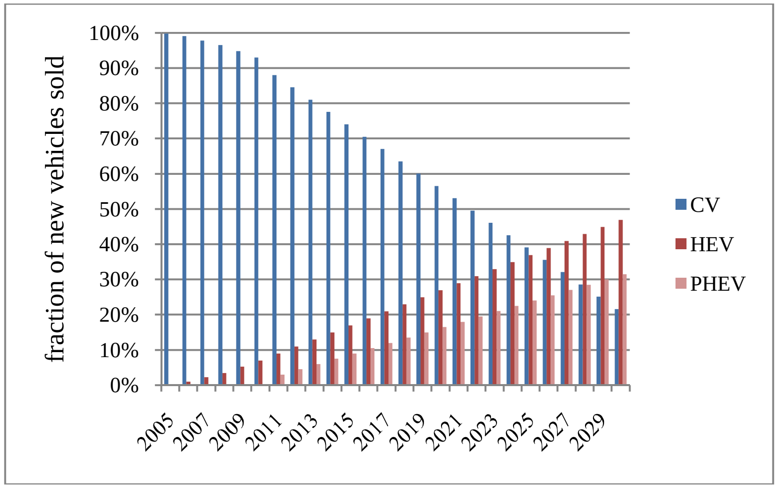

Figure 23. Technology Penetration for the *Medium HEV/PHEV* Scenario in the Passenger Car Fleet

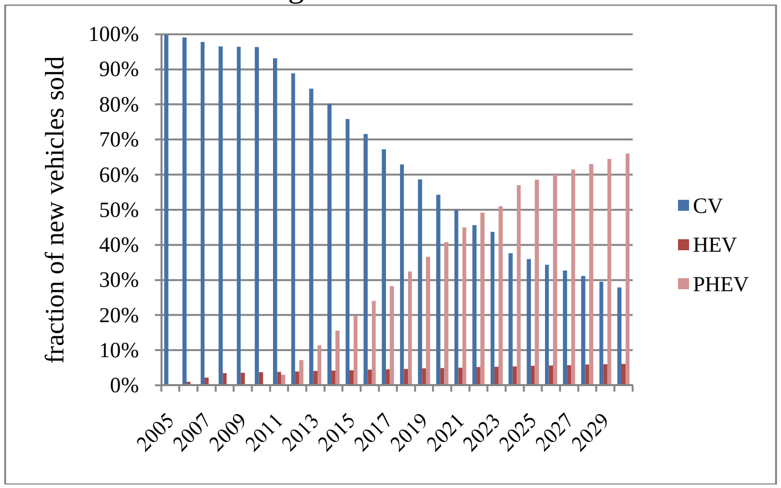

Figure 24. Technology Penetration for the *High PHEV* Scenario in the Passenger Car Fleet

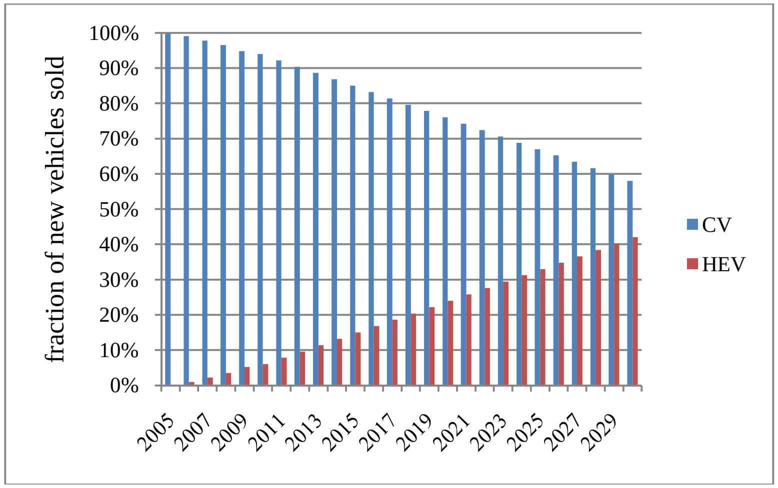

Figure 25. Technology Penetration for the *Low HEV* Scenario in the Light Truck Fleet

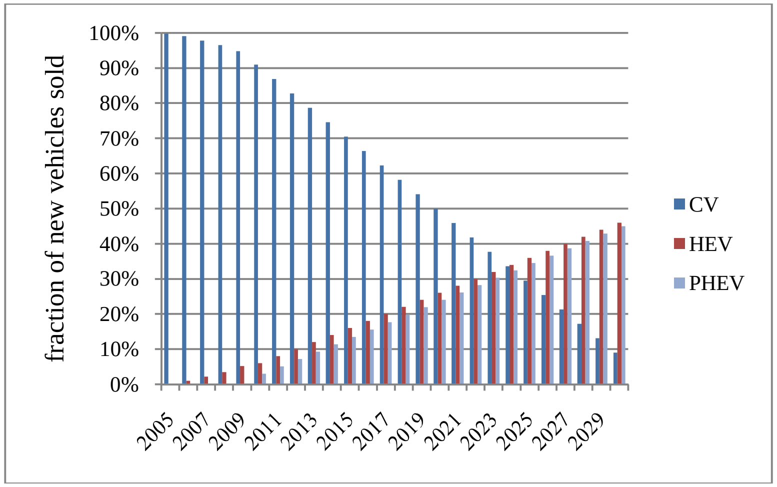

Figure 27. Technology Penetration for the M*edium HEV/PHEV* Scenario in the Light Truck Fleet

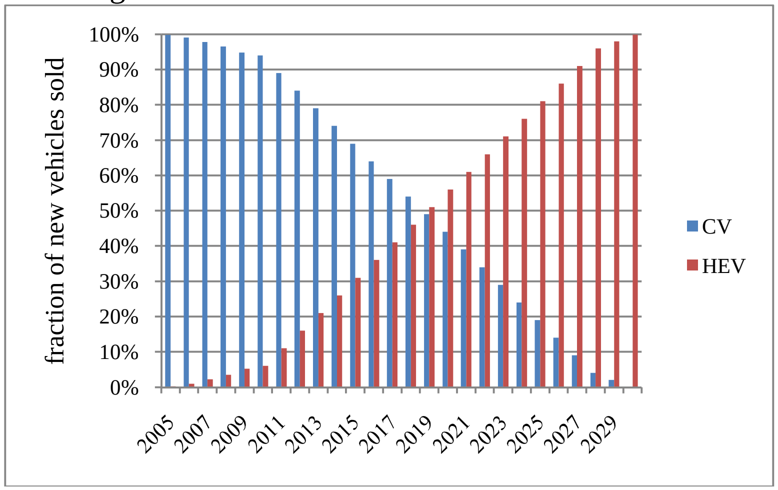

Figure 26. Technology Penetration for the *High HEV* Scenario in the Light Truck Fleet

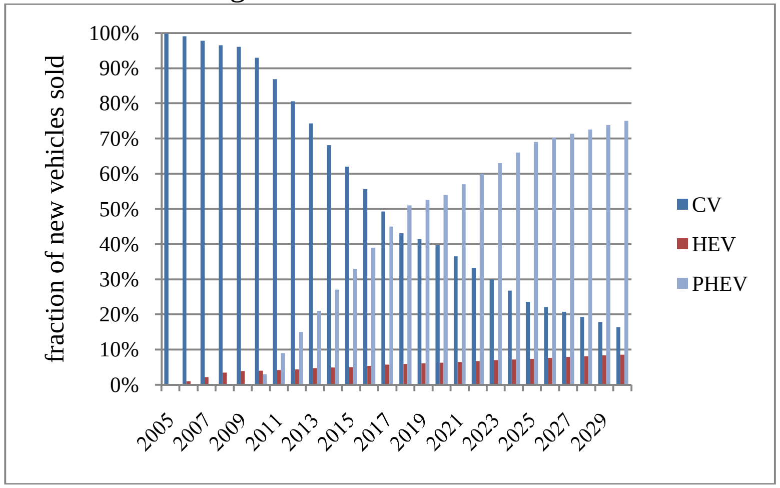

Figure 28. Technology Penetration for the *High PHEV* Scenario in the Light Truck Fleet

6.2.2.2 CAFE and Cash Flow Results and Discussion

Based on the technology penetration scenarios above, we can define the fleet CAFE and economic cash flow for the US vehicle fleets. Figure 29 and Figure 30 shows the fleet CAFE for the reference case, and shows the footprint and the calculated achievable CAFE of the passenger car and light truck fleet for each scenario. Only the High-PHEV scenario is able to meet CAFE regulations. Under all other scenarios, the automotive OEM will face economic penalties for not meeting the required CAFE.

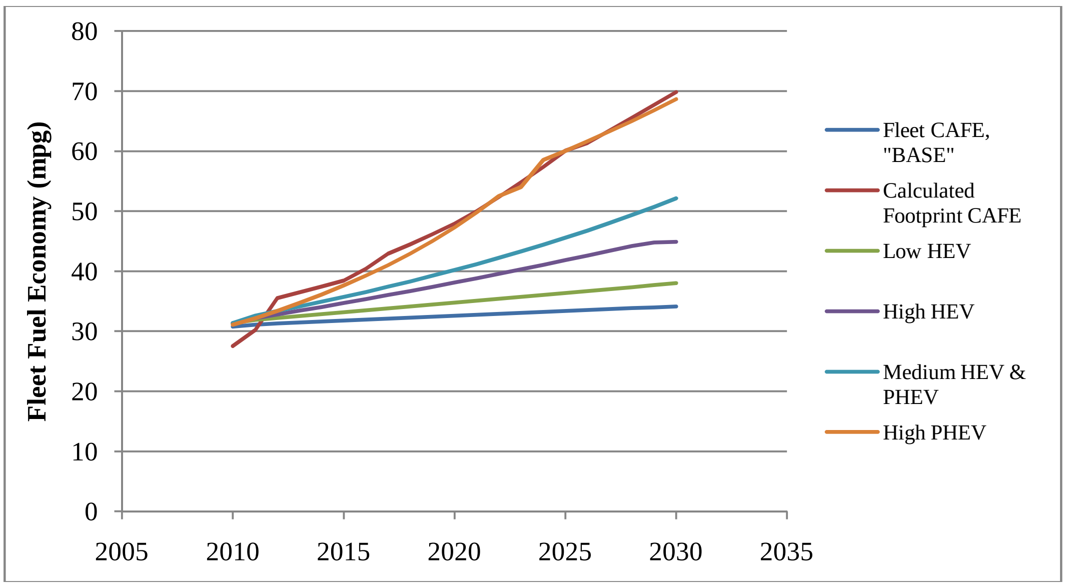

Figure 29. Achieved Passenger Car CAFE for Each of the Considered Technology Penetration Scenarios

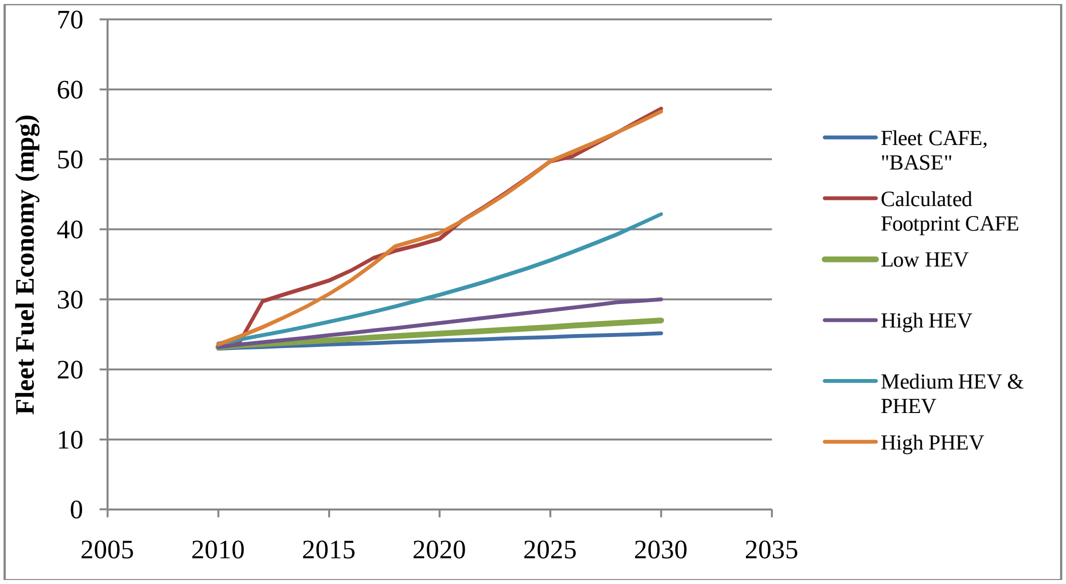

Figure 30. Light Truck Fleet CAFE for Each of the Considered Technology Penetration Scenarios

The economic results of this analysis are shown in Figure 31 through Figure 34 for the passenger car fleet and Figure 35 through Figure 38 for the light truck fleet. Figure 31 and Figure 32 presents the cash flow and cumulative cash flow for each scenario using the vehicles' total cost of ownership as the only source of cost or benefit. Figure 33 and Figure 34 presents the cash flow and cumulative cash flow for each scenario using the vehicles' total cost of ownership, oil displacement and emissions as the sources of cost or benefit.

In each case, the cash flow starts negative because it represents the cost difference of scenario technology to the base case. The negative cash flow increases over time as more HEVs or PHEVs sold since the prices of HEVs or PHEVs are more than that of CVs. and the net cash flow then increases due to the economic benefits of HEVs or PHEVs over CVs. The year at which the cash flow crosses the X-Axis is the break-even year at which the benefits of a technology scenario exceed their costs. The cumulative cash flow is the summation of year-by-year cash flow over the life of vehicles and when it is minimum (negative peak at the break-even year) it represents the amount of funds required to implement each technology scenario.

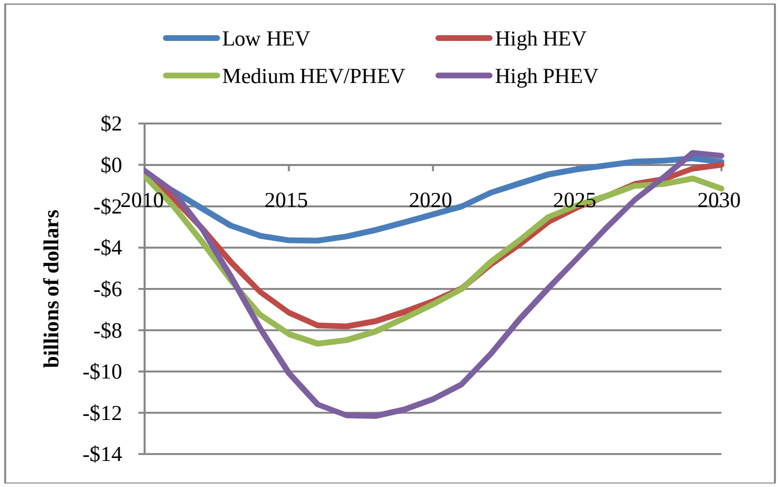

Figure 31. Passenger Car Fleet Cash Flow (Only TCO)

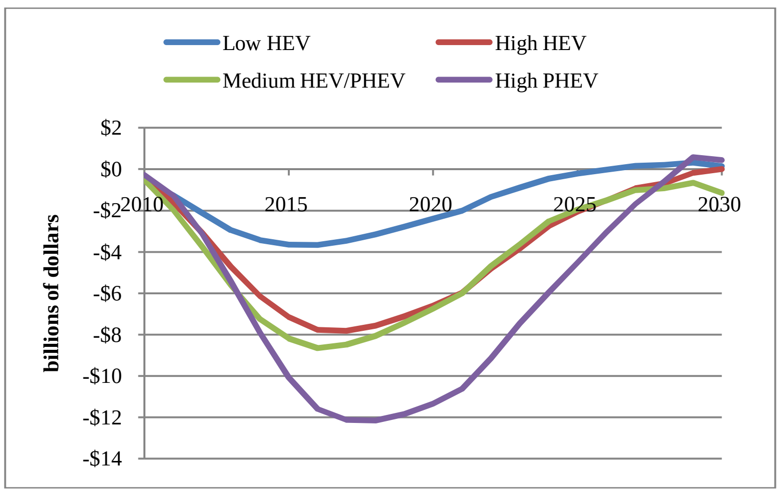

Figure 32. Passenger Car Fleet Cumulative Cash Flow (Only TCO)

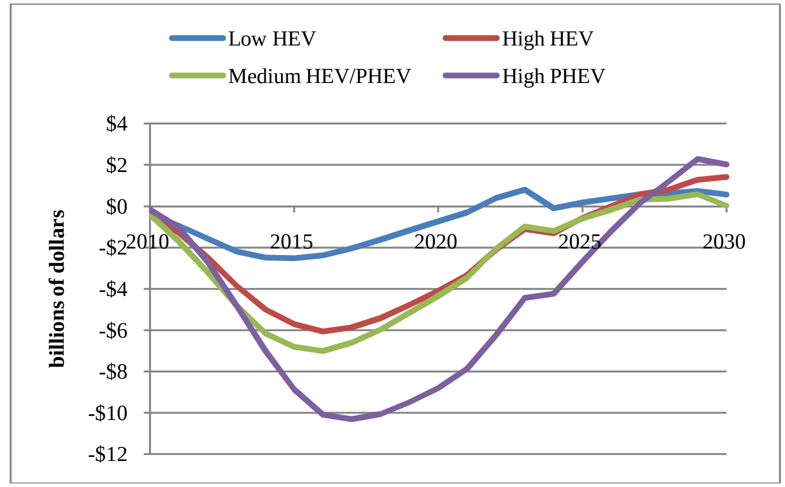

Figure 33. Passenger Car Fleet Cash Flow (TCO, Air Emission and Oil Displacement Valuation)

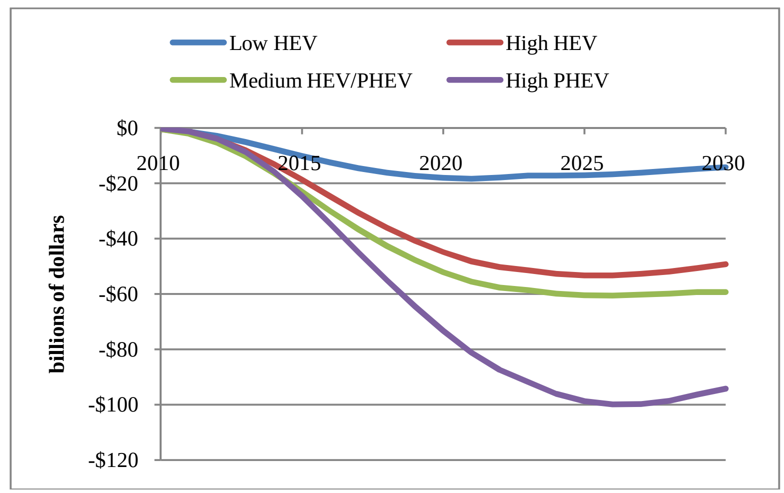

Figure 34. Passenger Car Fleet Cumulative Cash Flow (TCO, Air Emission and Oil Displacement Valuation)

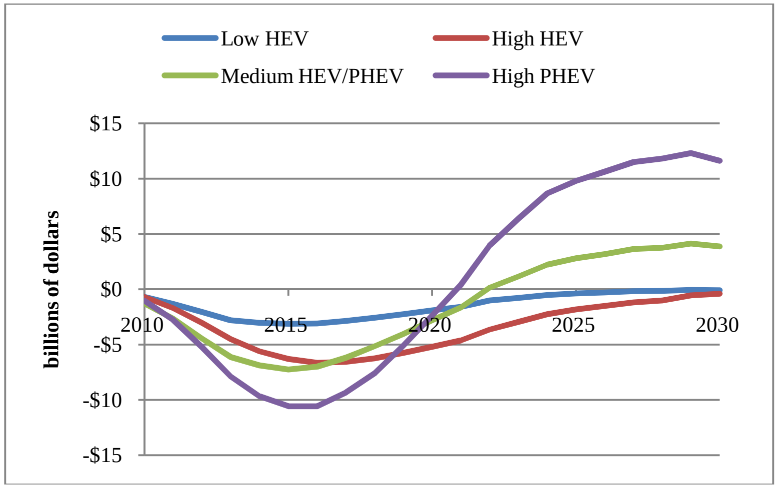

Figure 35. Light Truck Fleet Cash Flow (Only TCO)

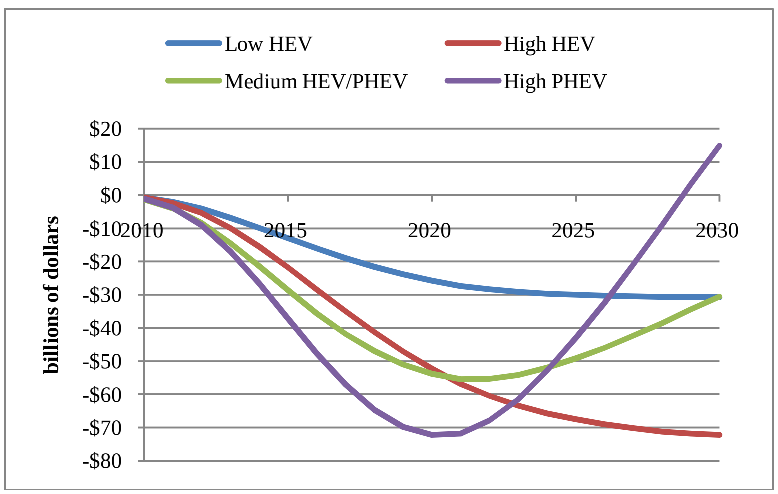

Figure 36. Light Truck Fleet Cumulative Cash Flow (Only TCO)

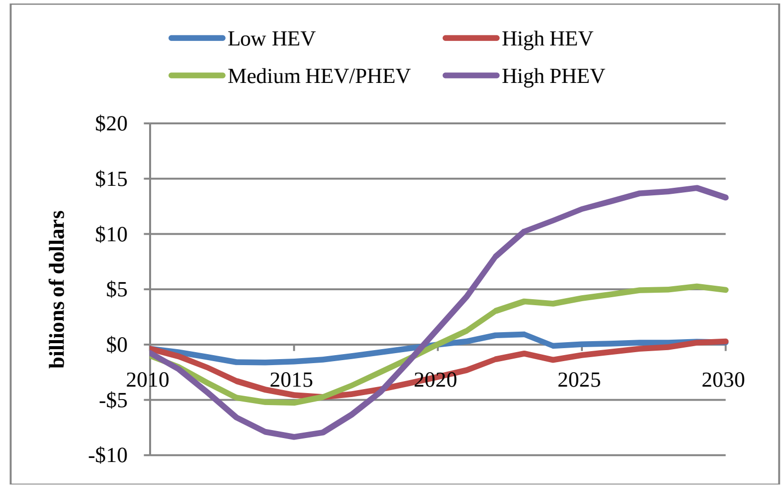

Figure 37. Light Truck Fleet Cash Flow (TCO, Air Emission and Oil Displacement Valuation)

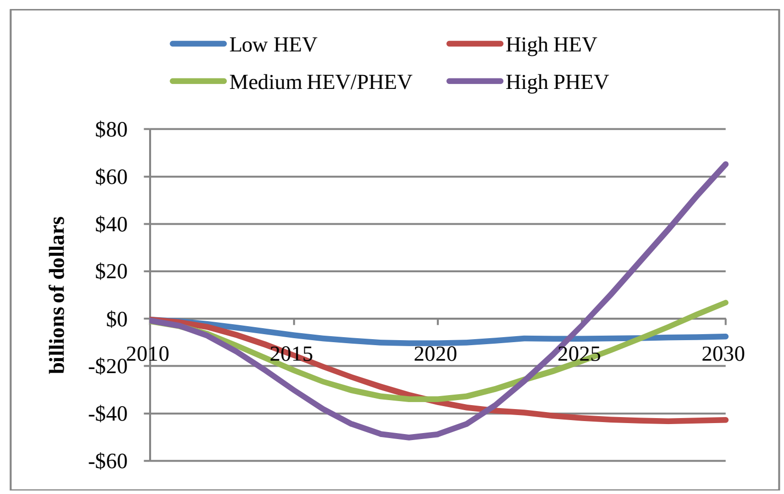

Figure 38. Light truck Fleet Cumulative Cash Flow (TCO, Air Emission and Oil Displacement Valuation)

Table 16. Cash Flow Analysis Results for Each Technology Scenario

Study	Fleet	Vehicle Class	Scenario	Technology	Break-Even Year	Buy-down Cost in $Billions
National Academy of Engineering	Passenger Car	Midsize Car	PHEV 40, Maximum Practical	PHEV 40	2040	$408
			PHEV 40, Maximum Practical, DOE Goal	PHEV 40	2024	$24
			PHEV 40, Maximum Practical, High Oil	PHEV 40	2025	$41
			PHEV 40, Probable case	PHEV 40	2047	$303
			PHEV 10, Maximum Practical	PHEV 10	2028	$33
			PHEV 10, Probable case	PHEV 10	2028	$15
			Mixed case, Maximum Practical	70% PHEV 10, 30% PHEV 40	2032	$94
			Mixed case, Probable case	70% PHEV 10, 30% PHEV 40	2034	$47
Multi-criteria Modeling system	Passenger Car	Subcompact Car, Compact Car, Midsize Car, Large Car	Low HEV	HEV	2026	$34
			High HEV	HEV	2029	$83
			Medium HEV/PHEV	HEV, PHEV 30, 40, 60	2030	$91
			High PHEV	HEV, PHEV 30, 40, 60	2027	$130
Multi-criteria Modeling system	Light Truck	Midsize SUV, Large SUV, Minivan, Large Pickup	Low HEV	HEV	2030	$31
			High HEV	HEV	2030	$72
			Medium HEV/PHEV	HEV, PHEV 30, 40, 60	2021	$55
			High PHEV	HEV, PHEV 30, 40, 60	2020	$73

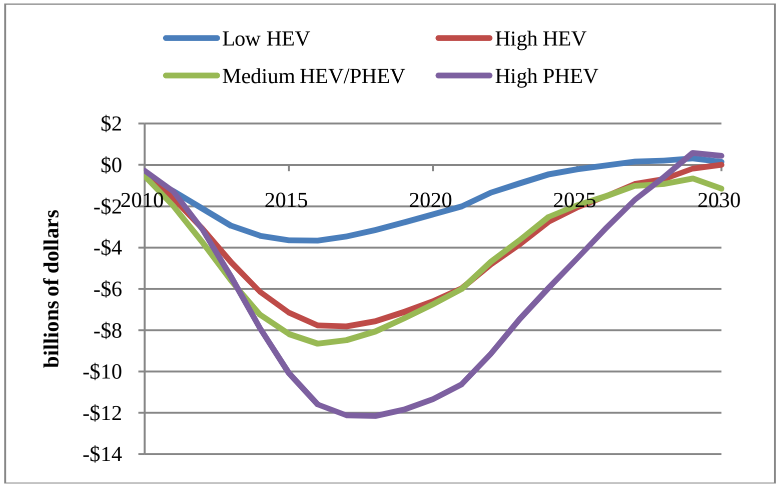

Figure 31. Passenger Car Fleet Cash Flow (Only TCO)

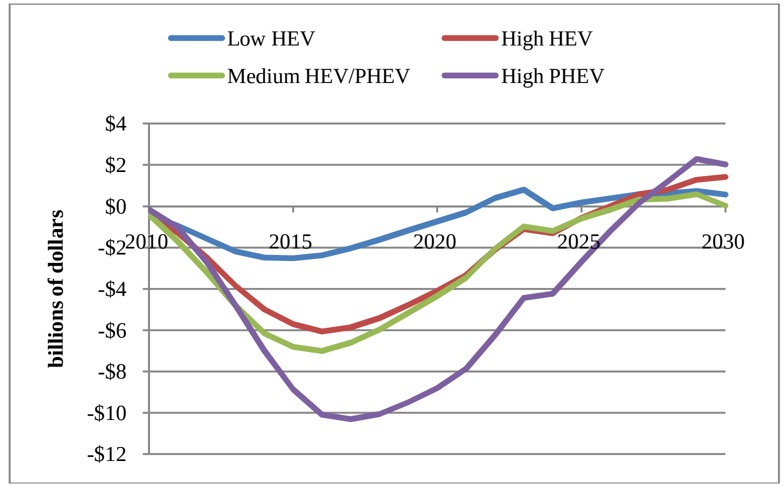

Figure 33. Passenger Car Fleet Cash Flow (TCO, Air Emission and Oil Displacement Valuation)

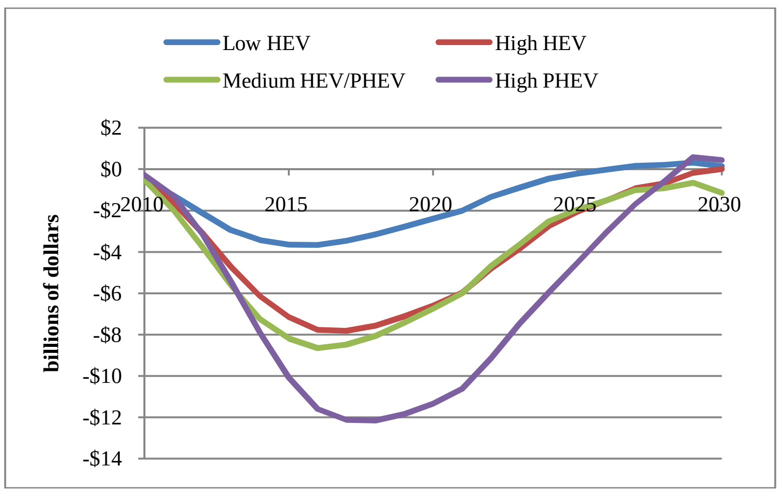

Figure 32. Passenger Car Fleet Cumulative Cash Flow (Only TCO)

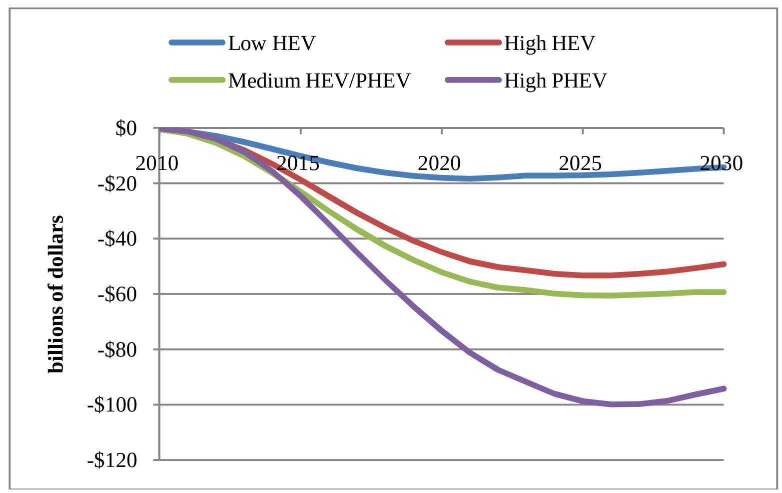

Figure 34. Passenger Car Fleet Cumulative Cash Flow (TCO, Air Emission and Oil Displacement Valuation)

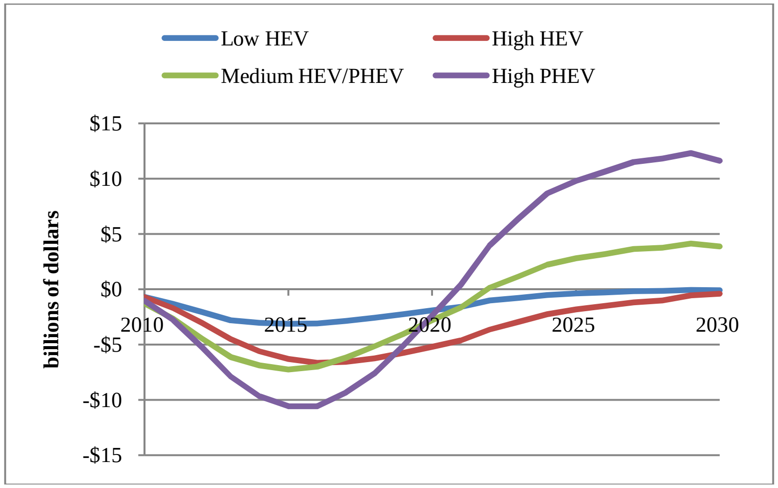

Figure 35. Light Truck Fleet Cash Flow (Only TCO)

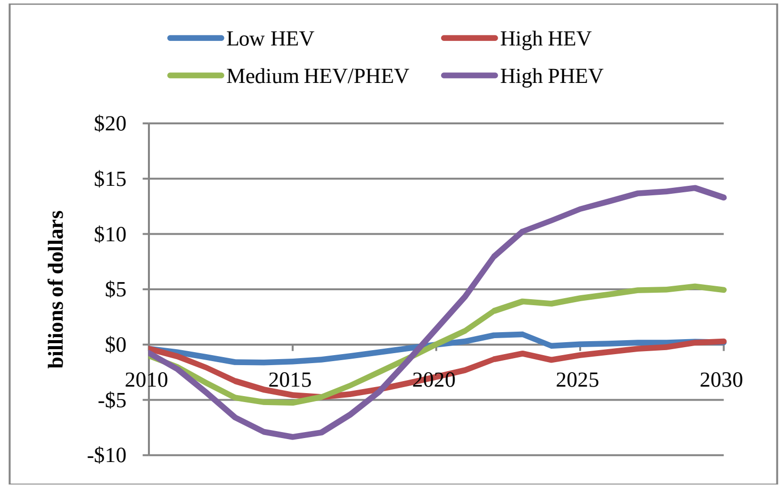

Figure 37. Light Truck Fleet Cash Flow (TCO, Air Emission and Oil Displacement Valuation)

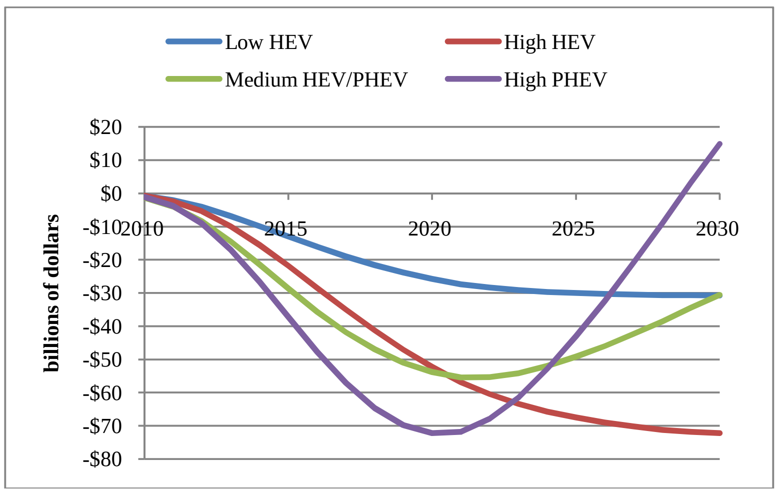

Figure 36. Light Truck Fleet Cumulative Cash Flow (Only TCO)

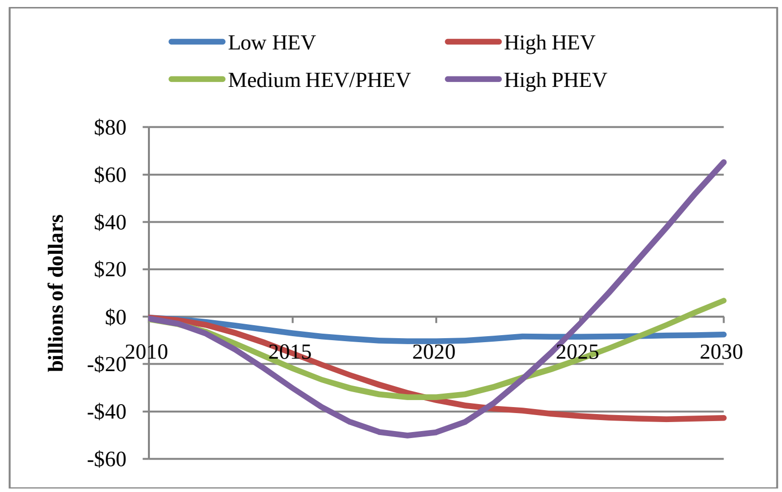

Figure 38. Light truck Fleet Cumulative Cash Flow (TCO, Air Emission and Oil Displacement Valuation)

Table 16 summarizes the findings of the economic analysis and compares the results to the results of the National Academy of Engineering study. In addition, some key comparators are graphed in Figure 39. The US National Academy of Engineering scenarios of PHEV 40 are found to have higher buy-down costs and a longer break-even time than this study. This is due to the higher technology costs used in the analysis and the NAE's not including other costs or benefits components for HEV/PHEVs.

In each scenario of the NAE model the following assumptions apply:

- Study was based on NRC, 2008 model with some modification [145].
- Gasoline fuel prices are based on EIA projections, 2008 (gasoline price, high) .
- Electricity prices are kept constant at $0.08/kWh.
- Fleet fuel economy efficiency assumed to have improvements in engines and other vehicle technologies. CVs and HEV fuel economy proposed to increase by 2.7%/year from 2010 to 2025, 1.5%/year from 2026 to 2035, and 0.5%/year from 2036 to 2050.
- The estimated cash flow was not discounted but estimated to be the required costs to make PHEVs.
- The base scenario used was a fleet without HEV or PHEV technology.
- Fleet will have the same total number of vehicles with the same vehicle miles traveled
- PHEVs costs to manufacturer relative to CVs were estimated using Li-ion battery under two incremental costs scenario, optimistic and probable and it is estimated to decline over time as shown in Figure 40.

- The total technology incremental price charged to the customers is 140% of the PHEVs incremental costs.
- The PHEV market penetration probable scenario uses the probable incremental PHEV costs and assumes new PHEVs sales rise to 3% by 2020, 15% by 2035 and assumes the continuance of current policy incentives.
- The PHEV market penetration maximum practical scenario uses the same Hydrogen Case for HFCVs annual rate but starts in 2010. It uses the optimistic incremental PHEV costs and assumes new PHEVs sales rise to ~ 45% by 2035 and requires strong policy intervention.

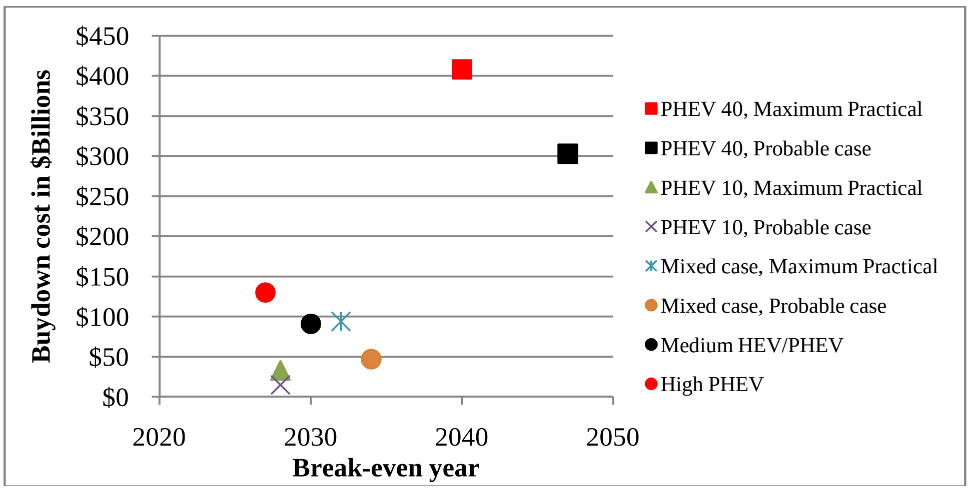

Figure 39. Cash Flow Analysis Results for Some of the Technology Scenarios

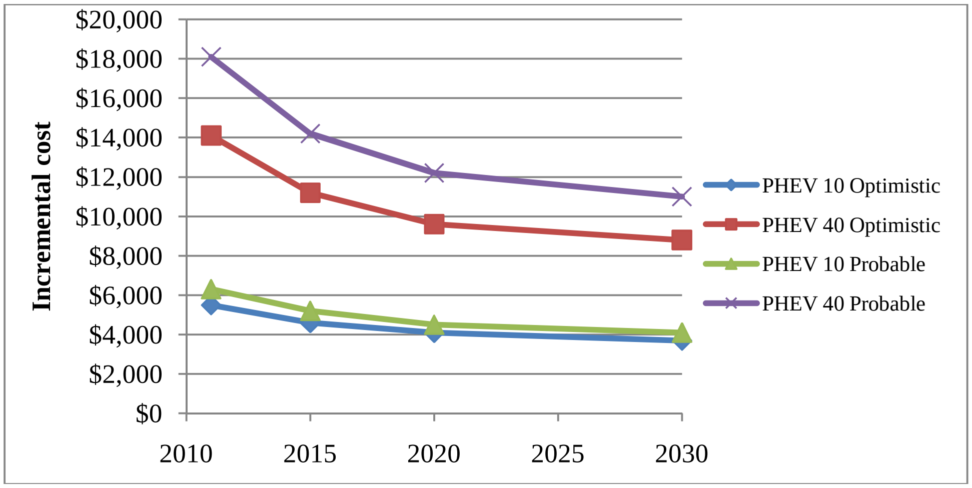

Figure 40. PHEVs Incremental Costs with no Engineering, Overhead, or Other Costs, or Profit

6.2.2.3 Air Emission, Oil Displacement and Total Cost of Ownership Results and Discussion

The GHG and other emissions quantity resulted from well-to-wheels, battery upstream and assembly emissions of this analysis are shown in Figure 41 and Figure 42 for the passenger car fleet and Figure 43 and Figure 44 for the light truck fleet. In each case, the air emission increases as the cumulative number of vehicles increases and then decline when vehicles retired. A scenario with HEV or PHEV technology found to have a lower GHG emission in both passenger car and light truck fleets. For the other emissions, results are varies but the reference case scenario found to have a lower other emission when compared to the high PHEV scenario and this is mainly because of PHEVs battery assembly emissions.

The valuation of air emission and oil displacement is presented in Figure 45 for the passenger car fleet and Figure 47 for the light truck fleet. In both fleets technology scenarios will impose a lower air emission costs compared to the reference case scenario.

Figure 47 presents the oil displacement, air emissions and total cost of ownership for the passenger car fleet and Figure 48 for the light truck fleet for each scenario and compared to the reference case. In each scenario the total costs are greater than the reference case and this is mainly due to technology incremental costs.

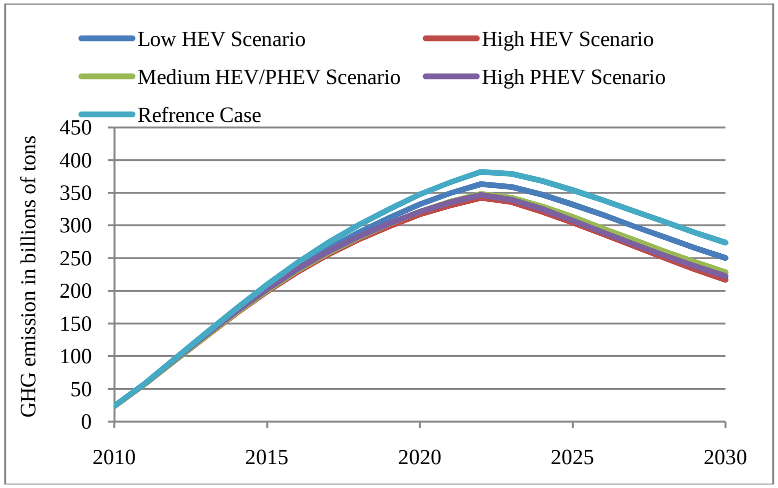

Figure 41. Passenger Car Fleet GHG Emission

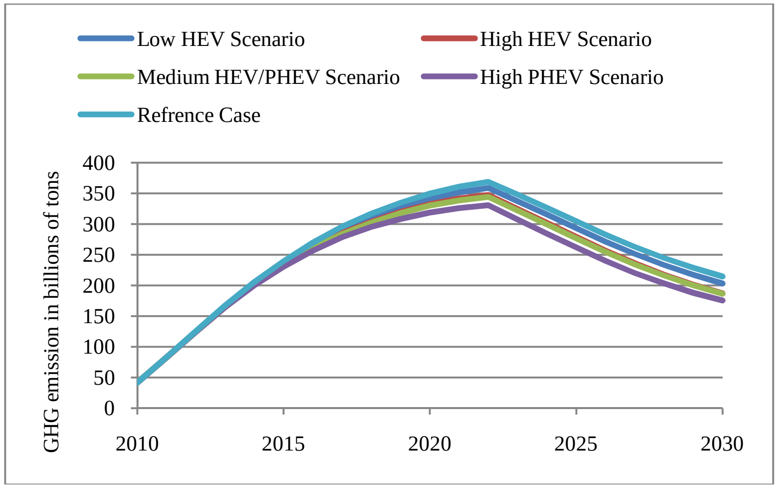

Figure 43. Light Truck Fleet GHG Emission

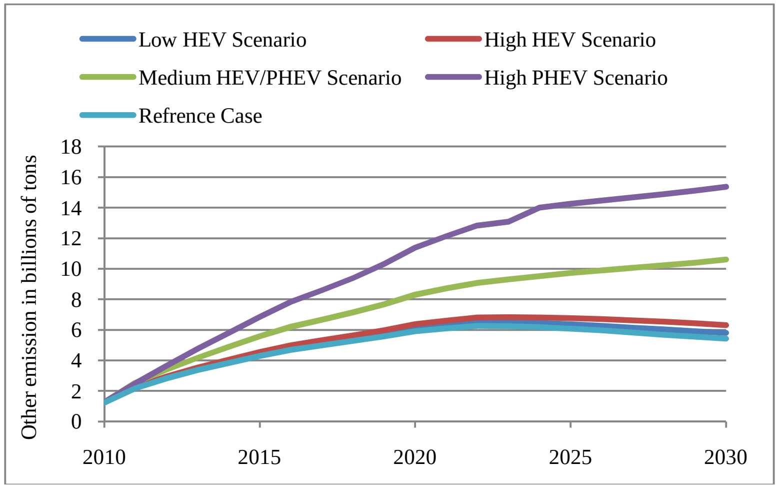

Figure 42. Passenger Car Fleet Other Emission

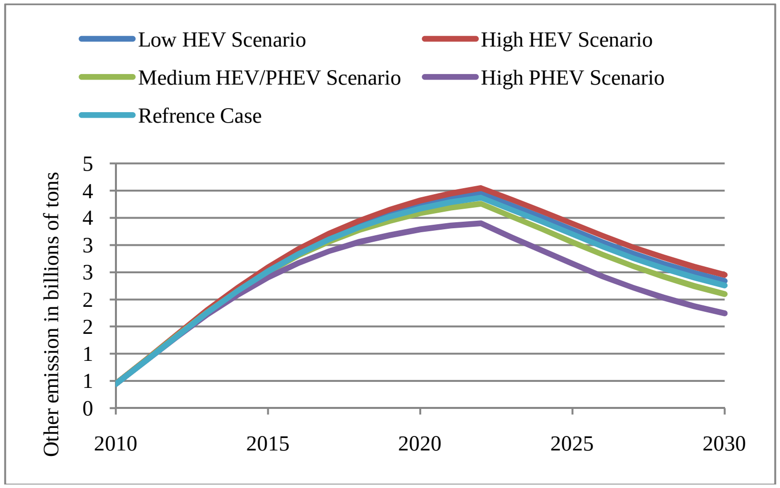

Figure 44. Light Truck Fleet Other Emission

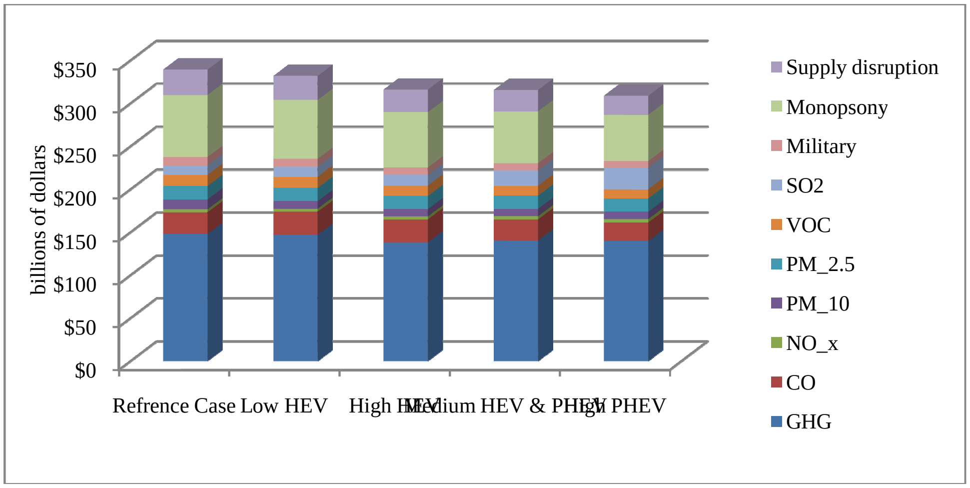

Figure 45. Oil Displacement and Emissions Costs at the Passenger Car Fleet

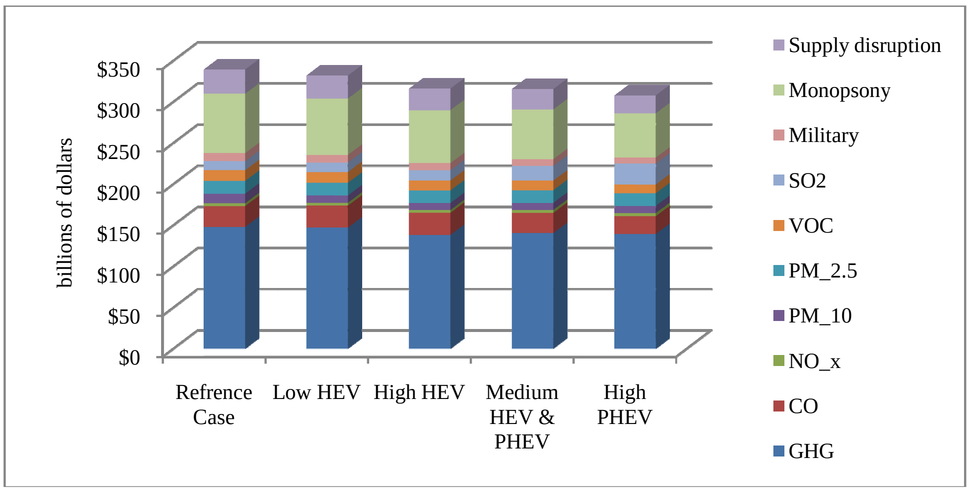

Figure 46. Oil Displacement and Emission Costs at the Light Truck Fleet

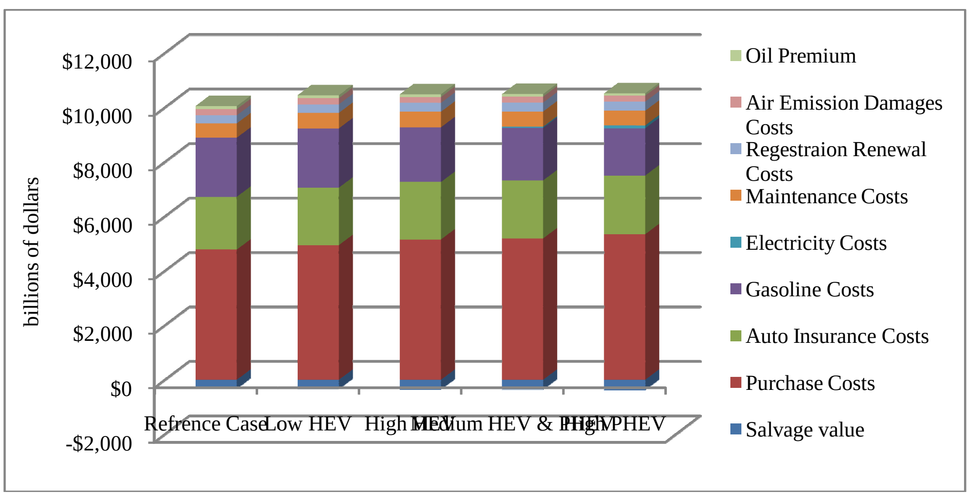

Figure 47. TCO, Oil Displacement and Emissions Costs at the Passenger Car Fleet

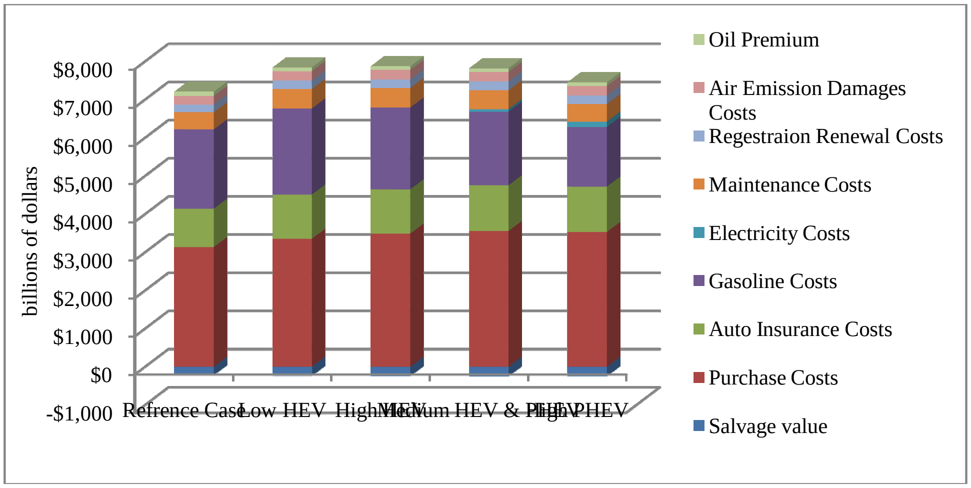

Figure 48. TCO, Oil Displacement and Emission Costs at the Light Truck Fleet

Figure 49 and Figure 50 presents the quantity of gasoline reduction after using each scenario and the amount of gasoline tax lost for the passenger car fleet and Figure 51 and Figure 52 for the light truck fleet.

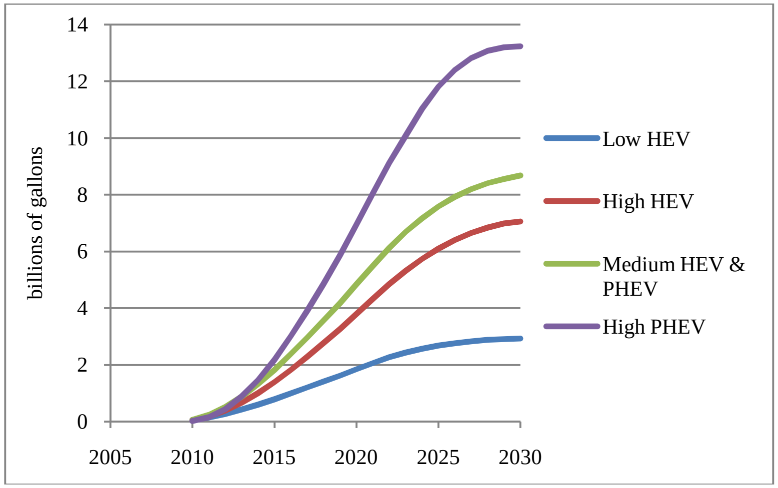

Figure 49. Quantity of Gasoline Reduced at Each Scenario in the Passenger Car Fleet

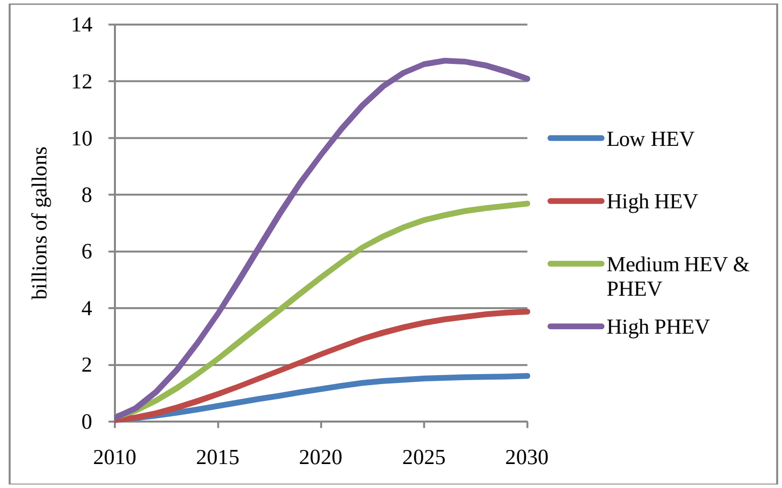

Figure 51. Quantity of Gasoline Reduced at Each Scenario, in the Light Truck Fleet

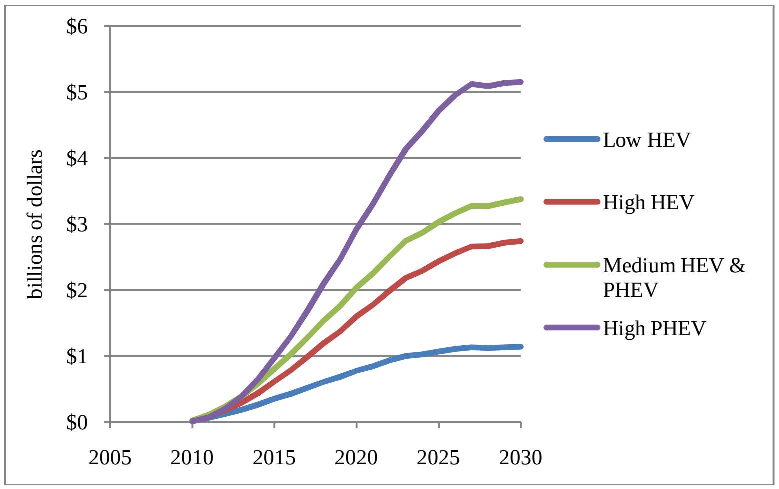

Figure 50. Cost of Gasoline Tax Lost at Each Scenario in the Passenger Car Fleet

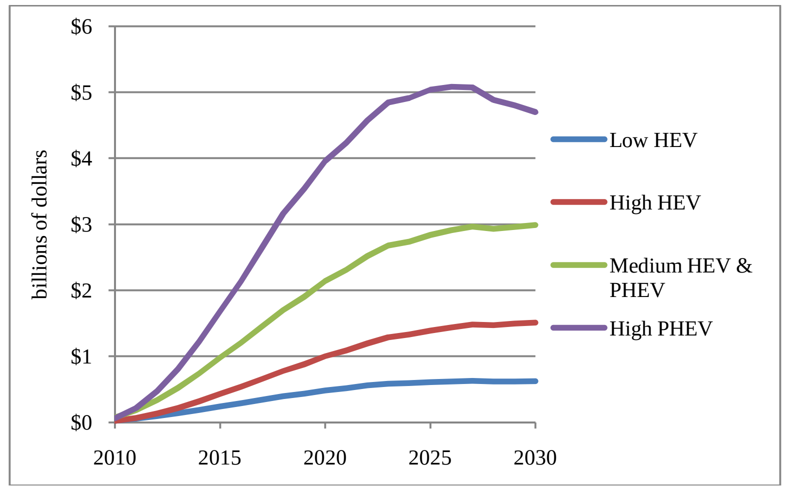

Figure 52. Cost of Gasoline Tax Lost at Each Scenario, in the Light Truck Fleet

6.3 Chapter Conclusions

Plug-in hybrid electric vehicle are found to be the most successful technology to be able to meet the proposed footprint CAFE standards over the next few years. A scenario without high PHEV technology cannot increase the US fleets fuel economy to meet the required footprint CAFE standards. To double the average fuel economy of new US cars and light trucks by 2030, PHEV must be considered as a forth technology options in addition to the three technology options considered by Cheah et al., 2007 [146]. The three technology options considered by Cheah et al., 2007, to double the U.S. fleet fuel economy are: (1) Improving vehicles fuel efficiency rather than technology, (2) increasing the penetration rate of diesel, turbocharged and hybrid gasoline vehicles, (3) reduction in vehicles weight and size [146]. Our analysis show that low HEV, high HEV and medium HEV/PHEV scenario will increase the U.S. new vehicles sales CAFE but cannot double the U.S. fleet fuel economy to meet the proposed footprint CAFE over the period of 2010 to 2030.

In our multi-criteria modeling system the cash flows at different vehicle technology penetration rates is the total cost of owning and operating the new sales vehicles rather than only the price and fuel costs of vehicles as considered by the National academies study "Transition to Alternative Transportation Technologies—Plug-in Hybrid Electric Vehicles." At this analysis we have extended the cash flow valuation by adding air emission and oil displacement costs. As explained at chapter five the total cost of ownership need not to restrict the costs and benefits of vehicle technology to its purchase and fuel costs. Vehicles might have benefits due to their lower gasoline consumptions and maintenance costs but with an increased purchase price and associated insurance, sales tax and registration renewal costs.

PHEVs are found to be successful in increasing the fleets' fuel economy that break-even within 20 years. This comes with lower air emission damages but at increased incremental costs. The benefits of PHEVs will increase under high oil prices, clean electric energy and lower battery manufacturing emissions.

Chapter 7-Conclusions

The final chapter of this thesis will give a brief summary of the results and list the major conclusions achieved from each chapter.

7. Chapter Summary

The objective of this research was to build a framework that can model and optimize the costs and benefits of PHEVs to a variety of stakeholders.

Chapter Three focused on the economic value of PHEVs in allowing an automobile manufacturer to meet increasing CAFE standards for the years 2012-2016. This analysis compared the effects of 3 designs of PHEV and HEV to estimate the cost of CAFE compliance with PHEVs as a component of the domestic passenger car fleet and as a component of the domestic light truck fleet. The model describes the costs of CAFE compliance of a major US automaker for model years 2012-2016. Novel models of HEV and PHEV fuel economy and incremental costs have been used to quantify the relative costs and benefits of these vehicle technologies. Results and discussion sections compared the costs of CAFE compliance among HEV technologies, and vehicle types, and proposed that PHEVs can be an important component of auto manufacturer's CAFE compliance strategy.

The goal of Chapter Four was to more systematically synthesize a PHEV total cost of ownership (TCO) and consumer acceptability model. It presented a novel TCO model and compared it to those in similar studies in the primary literature so as to understand the effects of TCO study scope, methods and assumptions. The TCO model proposed for this study included models of various vehicle types, various PHEV types, vehicle purchase cost, loan cost, tax cost, insurance cost, annual registration cost, fuel cost, maintenance cost and salvage value. The more comprehensive PHEV ownership cost model developed for this study showed a lower cost of ownership than previous work, which resulted in a shorter payback period and higher consumer preference. This study asserted that the most effective means to gauge the market potential and consumer acceptability of PHEVs is through a TCO model connected to a survey-derived consumer preference model. The consumer preference model used the cost and benefits derived from the comprehensive ownership model to determine consumer preference for each vehicle type and PHEV type. It presented the sensitivity of TCO, payback period, and consumer preference results to vehicle characteristics, economic assumptions and model scope.

Chapter Five presented a comprehensive literature review of PHEV and HEV penetration rate studies. This study reviewed and analyzed the primary purposes, methods, and results of studies of PHEV market penetration. The purposes of performing vehicle technology market diffusion studies were to 1) determine the future number of PHEVs for planning purposes, 2) understand whether PHEVs will be present in the U.S. vehicle fleet, and 3) understand the role of policy in encouraging PHEV market penetration rates. The primary methods used in literature were agent-based behavior models, consumer choice models, and market diffusion and time-series models. Each method was analyzed to understand its strengths and weaknesses. The results of these studies were highly variable due to differences within and among studies in terms of models used, parameters, assumptions, and uncertainty in future scenarios of policy and market conditions. The findings provided recommendations for researchers to understand and define model components and parameters that need to be integrated into estimation of HEV and PHEV adoption rates.

Chapter Six developed a multi-criteria modeling system that used and interacted with phase I and II models. The comprehensive model gave a deeper understanding of hybrid vehicle costs and benefits over the next twenty years using different hybrid vehicles penetration rate scenarios. The model estimated the achieved U.S. fleet CAFE, fleet total cost of ownership, fleet air emissions damages, air emission costs, and society costs. The model was used as the basis for a decision support system with negotiation process presented in Appendix D. The results show that PHEVs have a net benefit to society under a variety of market penetration scenarios and that PHEVs can be an important component of an aggressive program for improving the sustainability of the US transportation sector.

7.1 Conclusions

A list of conclusions drawn from this work are as follows:

- The results of phase I analysis (Chapter Three) showed that in many vehicle classes, PHEVs with 20 miles of electric vehicle range have a lower cost of CAFE compliance than both grid-independent HEVs and PHEVs with 60 miles of electric vehicle range. The baseline results show that in both the passenger car and light truck fleets, PHEVs have a lower cost of compliance with CAFE regulations than conventional HEVs. Passenger car PHEVs were shown to provide reduced costs of CAFE compliance than the suite of conventional technologies used to benchmark CAFE compliance costs. The more detailed scenario analysis showed that passenger car PHEVs can enable a lower CAFE cost of compliance than the suite of more conventional technologies considered in NHTSA’s preferred alternative scenario. The reduction in CAFE compliance costs to the automakers is approximately 50% of the average incremental PHEV retail price in the passenger car fleet, thereby potentially reducing the incremental cost to the automaker of PHEV production and sale. These results can be used by automakers and regulators to understand that incentives for PHEV production that are preexisting in the CAFE regulations. The methods that will be used to reap these incentives will be specific to each automaker’s market, regulatory, financial and consumer position. Overall, results show that PHEVs can contribute to a reduction in the costs of CAFE compliance for domestic automakers and should be considered in near-term regulatory and industrial analyses of CAFE compliance strategies.

- The results of the phase II study (Chapter Four) show that a comprehensive TCO model requires significant increase in scope over previous models in literature. The TCO model scope presented in this work is shown to represent the costs to own and operate vehicles in the U.S. The analysis showed that TCO and payback period are sensitive to parameters that have been well-modeled in literature including incremental cost, gasoline prices, and annual driving distance. It also showed that TCO and payback period are sensitive to relatively understudied parameters of TCO modeling. Such parameters include models of various vehicle types, various PHEV types, vehicle purchase cost, loan cost, tax cost, insurance cost, annual registration cost, fuel cost, maintenance cost and salvage value.
- An additional result of Chapter 4 is to show that consumer preferences toward the purchase of PHEV must be modeled considering more than only PHEVs cost or benefits. There are a many factors that influence consumers in their vehicle purchase decision and some are quantitative and others are qualitative. The highest fidelity means for assessing consumers' willingness to pay for PHEVs incremental costs is the combination of TCO modeling and consumer survey data.
- An additional result of Chapter 4 is that consumers are found to be willing to pay for more incremental costs at fewer benefits than would be assumed from a requirement for 5 year payback period. This leads us to the conclusion that consumers should have a tool to evaluate PHEV design based on their needs and preferences in which the tool has to include all of the cost/benefits parameters for different PHEV designs within different vehicle classes.
- In Chapter Five, a literature review of HEV and PHEV market penetration studies shows that the large and unquantified sources of uncertainty and the large variability among

PHEV penetration rate studies makes synthesis of the state of the art in simulation of PHEV market penetration infeasible. In order to test and estimate the economic feasibility of PHEV technology, there is a need for models that consider manufacturers' supply capacity, energy cost uncertainty, air emission policy, CAFE policy, market conditions, consumer characteristics, consumer preference, and technology improvements over time. A set of recommendations for improving the utility of these studies for decision making in the vehicle and utility industries are:

    - Develop an improved interface between modeling and surveys within each adoption rate model.
    - Develop and integrate an improved model of vehicle development and supply
    - Integrate competition among vehicle technologies.
    - Improve vehicle classification modeling to support and provide a level of detail to the adoption rate model.
    - Construct an improved sensitivity analysis to support and verify the model results and provide a guideline to future improvement in the model, parameters and assumptions.

- In Chapter Six, results show that PHEVs can reduce long-term societal costs relative to conventional and hybrid vehicles but at higher incremental costs. Plug-in hybrid electric vehicles combine a reduction in air emission damages and oil dependency with economic benefits to consumers. HEVs can increase the fleet fuel economy but PHEVs are the most economically efficient vehicle to meet the proposed footprint CAFE standards for both passenger car and light truck fleets. Plug-in hybrid electric vehicle are found to be the most successful technology to be able to meet the proposed footprint CAFE standards over the next few years. A scenario without high PHEV technology cannot increase the US fleets fuel economy to meet the required footprint CAFE standards. To double the average fuel economy of new US cars and light trucks by 2030, PHEV technology must be considered. Our analysis show that low HEV, high HEV and medium HEV/PHEV scenario will increase the U.S. new vehicles sales CAFE but cannot double the U.S. fleet fuel economy to meet the proposed footprint CAFE over the period of 2010 to 2030. Results of the cash flow analysis show that in the passenger car fleet, the break-even year is 2028 where it is 2021 in the light truck fleet for the high PHEV scenario. After this payback date, the total societal cost of PHEVs will be lower than the total societal cost of CVs. PHEVs are found to be successful in increasing the fleets' fuel economy that break-even within 20 years. This comes with lower air emission damages but at increased incremental costs. The benefits of PHEVs will increase under high oil prices, clean electric energy and lower battery manufacturing emissions

7.2 Research Contributions of this Dissertation

The primary contributions of this dissertation are presented below:

- A quantitative and general mathematical assessment of HEV/PHEV technology incremental cost, fuel economy and fleet CAFE improvement.
- A set of hybrid vehicle valuation sub-system models including vehicle physical, energetic, economic, and consumer preference characteristics that can be assembled into a comprehensive system model. These sub-models are application integrated, scalable, parametric, optimizeable, validated and usable in the final comprehensive system model of U.S. fleet new sales technology assessment.
- A comprehensive total cost of ownership model of CV, HEV and PHEV with assessment systematic defense of the model scope and sensitivity.
- A literature survey and synthesis of recommendations for the existing hybrid vehicles penetration rate literature.

- A comprehensive personal transportation system model that can calculate and evaluate the U.S. fleet achievable CAFE, total cost of ownership, air emission damages, and societal quantitative and qualitative cost and benefits using different technology penetration scenario of HEVs and PHEVs over the period of 2010 to 2030.

7.3 Recommendations for Future Research

This dissertation involves the valuation and assessment of PHEV technology cost/benefits to consumers, automakers, and society. The models and methods developed for this research effort are widely applicable to efforts other than PHEVs. In general, the models and methods constructed for this research effort will be useable to answer other relevant questions regarding the sustainability and commercial viability of the US vehicle fleet.

For example, this research has assumed the domination of HEV/PHEV vehicles technology in the next few years. As an upgrade to the model, the next stage of this research will be to consider additional vehicle technologies such as diesel engine, electric vehicle, fuel cell, and other alternative fuel vehicles. This research has performed a survey on the existing hybrid vehicles technology penetration rates and used some of the results as input to the system model and as a next step a penetration rate model will be constructed and integrated with this research models. In this research we used EPA vehicle classification which is based on vehicles interior volume and weight but different vehicle classification that classifies vehicles using more of the vehicle characteristics such as fuel economy, horse power, engine displacement, axle ratio, emissions and dynamometers can be developed and used. This will group vehicles with similar design and performance characteristics into clusters that represent the U.S. fleet and can be used to apply and measure the effect of any technology advancement. This will lower the computational time and simplify the modeling of the vehicle fleet.

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Appendix A- Supporting Material for Chapter 3

Table 17: Ford Motor Company 2008 Model Year Vehicles Unit Sales and Price, 2010$

Vehicle	Quantity	MSRP ($)	Fuel Economy (mpg)
Mustang	91,251	$19,901	23.14
Crown Victoria	48,557	$24,935	19.87
Focus	195,823	$14,579	36.78
Fusion	147,569	$18,367	28.75
Taurus (new)	52,667	$23,937	26.44
Edge	110,798	$26,064	24.56
Escape	156,544	$20,398	30.58
Expedition	55,123	$31,746	18.51
Explorer	78,439	$26,834	20.41
F-series	515,513	$23,294	19.83
Ranger	65,872	$14,675	21.7
Taurus X	23,112	$27,376	24.56
MKS	12,982	$41,393	24.56
MKZ	30,117	$31,376	28.01
Town Car	15,653	$45,874	22.8
MKX	29,076	$39,413	24.87
Mark LT	4,631	$49,368	17.47
Navigator	14,836	$25,760	18.51
Grand Marquis	29,766	$19,339	19.87
Milan	31,393	$19,339	28.75
Sable	16,187	$24,241	26.44
Mariner	32,306	$21,815	29.25
Mountaineer	10,596	$27,143	20.41
S-Type	742	$48,953	25.89
X-Type	382	$35,508	23.6
XF	3,457		23.47
Xj	1,133	$64,651	24.94
Xk	1,307	$75,792	23.9
LR2 (I)	2,919	$34,420	22.51
LR3 (I)	2,158	$49,146	18.2
Range Rover (I)	3,681	$78,162	18.14
Range Rover Sport (I)	5,534	$58,463	18.26
Volvo 30 (I)	4,299	$26,029	29.71
Volvo 40 (I)	9,687	$24,677	29.14
Volvo 50 (I)	1,856	$27,158	29.14
Volvo 60 (I)	8,966	$31,371	27.09
Volvo 70 (I)	18,276	$39,742	24.05
Volvo 80 (I)	11,038	$39,200	23.66
Volvo truck XC90 (I)	18,980	$36,673	20.96
Mazda3 (I)	49,129	$14,073	33.36
Mazda6	29,378	$19,385	28.67
MX-5 Miata (I)	6,085	$20,899	31.21
RX-8 (I)	1,548	$26,773	24.04
B series	709	$15,734	21.83
CX-7 (I)	13,999	$24,054	24.89
CX-9 (I)	11,393	$29,776	23.54
Mazda5 (I)	10,561	$18,225	31.13
Tribute	6,568	$19,380	30.58

Table 18: Domestic and Imported (I) Vehicles Allocated to each Ford Motor Company Vehicle Class for 2008

Class	Vehicle Type
Two Seater	Mazda MX-5 (I)
Minicompact Cars	Jaguar XK (I)
Subcompact Cars	Mazda RX-8 (I), Ford Mustang, Volvo C70 (I)
Compact Cars	Mazda MAZDA3 (I), Jaguar X-Type (I), V50 (I), FOCUS, C30 (I), S40 (I), S60 (I)
Midsize Cars	V70 (I), Mazdaspeed3 (I), Jaguar S-Type (I), Jaguar X-Type (I), Fusion, Milan, MKZ, Mazda 6
Large Cars	Jaguar XJ (I), Crown Victoria, Taurus, Grand Marquis, Sable
Luxury Large	MKS, S80 (I), Town Car
Minivan	Mazda 5 (I)
SUV Mid-Size	CX-7 (I), Tribute, Escape, Mariner, MKX, LR2 (I), Range Rover Sport (I)
SUV Large	Edge, Taurus X, XC90 (I), CX-9 (I), LR3 (I) ,Range Rover (I), Mountaineer, Expedition, Navigator, Explorer
Pickup	Mazda B, Ranger, Explorer Sport, F150, Mark LT

Table 19: Comparison Between NHTSA and Modified Ford Motor Company Passenger Car Fleet for 2012-2016, (the Fuel Economy is the Median of the Carlines FE)

Modified Passenger Car Fleet				NHTSA Passenger Car Fleet			
Nameplate	Median Fuel Economy	MY2011 Sales	Number of Carlines	Nameplate	Median Fuel Economy	MY2011 Sales	Number of Carlines
MUSTANG	22.93	118,844	5	MUSTANG	22.93	118,844	5
SHELBY MUSTANG GT	22.60	4,081	3	SHELBY MUSTANG GT	22.60	4,081	3
FOCUS	36.62	223,804	2	FOCUS	36.62	223,804	2
FUSION	28.86	204,111	4	FUSION	28.86	204,111	4
MILAN	28.86	48,303	4	MILAN	28.86	48,303	4
TAURUS	26.42	108,869	2	TAURUS	26.42	108,869	2
MKZ	26.42	42,690	2	MKZ	26.42	42,690	2
TOWN CAR	22.42	16,178	2	TOWN CAR	22.42	16,178	2
GRAND MARQUIS	22.80	59,165	1	GRAND MARQUIS	22.80	59,165	1
CROWN VICTORIA	22.80	12,484	1	CROWN VICTORIA	22.80	12,484	1
SABLE	26.42	35,431	2	SABLE	26.42	35,431	2
				Generic Mini Car	36.34	48,284	1
				TAURUS X	23.57	58,028	2
				MKX	24.20	17,202	1
				C30	29.02	7,378	2
				C70 CONVERTIBLE	27.71	9,082	2
				S40	29.25	15,458	4
				S60	27.05	17,877	4
				S80	23.25	15,037	3
				V50	28.56	2,466	3
				V70	24.05	5,080	1
				XC 90	20.95	9,960	1
				EDGE	24.20	77,684	1
				ESCAPE	28.95	138,290	3
				ESCAPE HYBRID	43.41	19,156	1

Modified Passenger Car Fleet				NHTSA Passenger Car Fleet			
Nameplate	Median Fuel Economy	MY2011 Sales	Number of Carlines	Nameplate	Median Fuel Economy	MY2011 Sales	Number of Carlines
				MARINER	27.57	27,016	2
				MARINER HYBRID	43.41	2,451	1

Table 20. Comparison Between NHTSA and modified Ford Motor Company Light Truck fleet for 2012-2016

Modified Light Truck Fleet				NHTSA Light Truck Fleet			
Nameplate	**Median Fuel Econom y**	**MY2011 Sales total**	**Number of Carlines**	**Nameplate**	**Median Fuel Econom y**	**MY2011 Sales total**	**Number of Carlines**
ESCAPE	28.44	250,286	5	ESCAPE	26.70	111,996	2
ESCAPE HYBRID	40.72	33,307	2	ESCAPE HYBRID	38.03	14,151	3
MARINER	27.32	55,038	4	MARINER	26.70	28,022	2
MARINER HYBRID	40.72	5,169	2	MARINER HYBRID	38.03	2,717	1
EDGE	23.57	127,468	2	EDGE	22.93	49,784	1
EXPLORER	19.81	49,803	4	EXPLORER	19.81	49,803	4
EXPLORER SPORT TRAC	19.81	14,701	4	EXPLORER SPORT TRAC	19.81	14,701	4
EXPEDITION	18.36	15,971	1	EXPEDITION	18.36	15,971	1
MKX	23.57	36,557	2	MKX	22.93	19,355	1
NAVIGATOR	18.36	3,992	1	NAVIGATOR	18.77	41,593	1
MOUNTAINEER	19.81	12,095	4	MOUNTAINEER	19.81	12,095	4
RANGER	22.11	56,217	10	RANGER	22.11	56,217	10
MARK LT	17.69	4,775	2	MARK LT	17.69	4,775	2
F150 PICKUP	18.95	363,012	11	F150 PICKUP	18.95	363,012	11
E-SERIES MDPV	14.86	2,972	12	E-SERIES MDPV	14.86	2,972	12
E-SERIES WAGON MDPV	15.63	10,472	3	E-SERIES WAGON MDPV	15.63	10,472	3
TAURUS X	23.57	58,028	2	XC 70	22.11	12,680	1
				XC 90	20.10	19,778	2

Table 21:Forecasted U.S. Sales for Ford Motor Company Passenger Car Fleet, (In Thousands)

Passenger Car	2012	2013	2014	2015	2016
NHTSA reported	1,468	1,486	1,568	1,542	1,559
Modified fleet	920	908	957	931	956

Table 22:Forecasted U.S. Sales for Ford Motor Company Light Truck Fleet, (In Thousands)

Light Truck	2012	2013	2014	2015	2016
NHTSA reported	852	940	966	937	911
Modified fleet	1,195	1,308	1,356	1,334	1,297

Appendix B- Supporting Material for Chapter 4

Table 23. Maintenance Costs, (Compact Car).

		PHEV												
Vehicle life	CV	0	5	10	15	20	25	30	35	40	45	50	55	60
1	$141	$141	$129	$129	$99	$99	$99	$99	$99	$69	$69	$69	$69	$69
2	$226	$226	$204	$117	$204	$173	$173	$173	$173	$173	$173	$173	$173	$173
3	$343	$381	$325	$314	$233	$261	$235	$235	$235	$233	$233	$233	$233	$206
4	$793	$793	$771	$834	$834	$747	$747	$747	$722	$749	$749	$722	$722	$747
5	$162	$162	$155	$78	$78	$137	$161	$78	$78	$78	$55	$81	$81	$55
6	$328	$360	$169	$242	$194	$191	$169	$225	$169	$169	$169	$169	$147	$171
7	$169	$169	$289	$289	$175	$131	$129	$129	$182	$109	$129	$109	$129	$129
8	$367	$367	$557	$535	$535	$578	$537	$535	$535	$584	$584	$535	$535	$515
9	$383	$410	$244	$163	$285	$142	$182	$144	$142	$142	$124	$189	$124	$142
10	$180	$180	$166	$109	$109	$225	$109	$147	$110	$109	$109	$91	$153	$91
11	$79	$79	$72	$55	$57	$55	$165	$55	$39	$39	$39	$55	$39	$39
12	$410	$433	$289	$391	$336	$336	$336	$320	$370	$337	$336	$320	$336	$375
13	$70	$70	$193	$210	$178	$180	$178	$276	$178	$210	$180	$178	$164	$164

Table 24. Maintenance Costs, (Mid-size Car).

		PHEV												
Vehicle life	CV	0	5	10	15	20	25	30	35	40	45	50	55	60
1	$183	$183	$168	$168	$121	$102	$102	$102	$102	$73	$73	$73	$73	$73
2	$330	$330	$264	$126	$264	$234	$234	$234	$234	$217	$217	$199	$199	$199
3	$298	$336	$323	$340	$210	$255	$213	$213	$213	$210	$210	$226	$226	$184
4	$1,317	$1,317	$1,302	$1,368	$1,368	$1,262	$1,262	$1,262	$1,222	$1,265	$1,265	$1,222	$1,222	$1,262
5	$203	$203	$194	$96	$96	$158	$196	$96	$96	$96	$58	$98	$98	$58
6	$298	$330	$176	$270	$214	$212	$176	$235	$176	$176	$176	$176	$141	$179
7	$603	$603	$657	$657	$575	$525	$523	$523	$578	$489	$523	$489	$523	$523
8	$753	$782	$722	$688	$688	$737	$690	$688	$688	$740	$740	$688	$688	$656
9	$57	$57	$192	$85	$173	$53	$99	$55	$53	$53	$23	$102	$23	$53
10	$197	$197	$188	$114	$114	$199	$114	$158	$116	$114	$114	$86	$161	$86
11	$102	$102	$94	$67	$69	$67	$147	$67	$41	$41	$41	$67	$41	$41
12	$480	$502	$319	$461	$394	$394	$394	$369	$433	$396	$394	$369	$394	$436
13	$45	$45	$462	$475	$438	$440	$438	$510	$438	$475	$440	$438	$415	$415

Table 25. Maintenance Costs, (Mid-size SUV).

		PHEV												
Vehicle life	CV	0	5	10	15	20	25	30	35	40	45	50	55	60
1	$336	$336	$267	$267	$267	$222	$222	$222	$222	$222	$222	$177	$177	$177
2	$379	$420	$338	$295	$295	$295	$295	$250	$250	$250	$250	$250	$250	$250
3	$664	$664	$1,290	$1,290	$1,290	$1,228	$1,188	$1,231	$1,191	$1,191	$1,191	$1,188	$1,188	$1,188
4	$890	$890	$323	$224	$187	$282	$282	$187	$187	$187	$187	$189	$189	$149
5	$371	$405	$353	$339	$248	$210	$210	$265	$300	$210	$175	$210	$210	$212
6	$679	$679	$1,112	$1,214	$1,164	$1,166	$1,114	$1,112	$1,078	$1,130	$1,078	$1,078	$1,045	$1,078
7	$679	$710	$228	$196	$290	$163	$212	$165	$163	$163	$211	$211	$163	$163
8	$273	$273	$223	$178	$180	$268	$148	$194	$150	$148	$148	$118	$194	$118
9	$598	$625	$578	$547	$504	$504	$617	$504	$548	$506	$504	$504	$476	$547
10	$103	$103	$478	$520	$519	$480	$452	$532	$452	$493	$453	$452	$452	$425
11	$550	$550	$225	$151	$124	$124	$126	$124	$200	$124	$163	$126	$124	$124
12	$382	$405	$321	$391	$358	$332	$295	$295	$295	$272	$272	$272	$272	$295
13	$408	$408	$400	$378	$378	$378	$378	$379	$378	$445	$378	$412	$379	$355

Table 26. Maintenance Costs, (Large SUV).

		PHEV												
Vehicle life	CV	0	5	10	15	20	25	30	35	40	45	50	55	60
1	$374	$374	$318	$318	$318	$275	$275	$276	$276	$276	$276	$232	$232	$232
2	$465	$505	$388	$347	$347	$347	$347	$299	$299	$299	$299	$300	$300	$300
3	$617	$617	$1,355	$1,355	$1,355	$1,265	$1,227	$1,271	$1,232	$1,232	$1,232	$1,227	$1,227	$1,227
4	$995	$995	$442	$267	$231	$352	$352	$231	$231	$231	$231	$236	$236	$194
5	$494	$528	$467	$451	$291	$252	$252	$332	$366	$252	$218	$252	$252	$257
6	$670	$670	$1,176	$1,347	$1,294	$1,299	$1,181	$1,176	$1,143	$1,219	$1,143	$1,143	$1,111	$1,143
7	$751	$781	$262	$231	$388	$196	$307	$201	$196	$196	$267	$267	$196	$196
8	$351	$351	$279	$212	$216	$364	$183	$288	$187	$183	$183	$154	$250	$154
9	$665	$692	$680	$613	$550	$550	$720	$550	$649	$554	$550	$550	$522	$613
10	$101	$101	$488	$581	$547	$491	$462	$597	$462	$555	$466	$462	$462	$436
11	$576	$576	$305	$181	$154	$154	$157	$154	$281	$154	$242	$157	$154	$154
12	$468	$490	$339	$456	$422	$366	$312	$312	$312	$289	$289	$289	$289	$312
13	$406	$406	$439	$417	$417	$417	$417	$420	$417	$531	$417	$496	$420	$396

Table 27. Registration Renewal Costs, (Compact Car).

		PHEV												
Vehicle life	CV	0	5	10	15	20	25	30	35	40	45	50	55	60
2	$238	$286	$294	$301	$308	$316	$322	$328	$334	$340	$346	$352	$358	$364
3	$192	$228	$234	$240	$245	$251	$255	$260	$264	$269	$273	$278	$283	$287
4	$150	$176	$180	$184	$188	$192	$195	$198	$202	$205	$208	$211	$215	$218
5	$98	$110	$112	$114	$116	$118	$120	$121	$123	$124	$126	$127	$129	$130
6	$93	$104	$106	$108	$110	$111	$113	$114	$116	$117	$119	$120	$122	$123
7	$87	$98	$100	$102	$103	$105	$106	$108	$109	$111	$112	$113	$115	$116
8	$83	$93	$94	$96	$97	$99	$100	$102	$103	$104	$106	$107	$108	$110
9	$78	$88	$89	$90	$92	$93	$95	$96	$97	$98	$100	$101	$102	$103
10	$43	$43	$43	$43	$43	$43	$43	$43	$43	$43	$43	$43	$43	$43
11	$40	$40	$40	$40	$40	$40	$40	$40	$41	$41	$41	$41	$41	$41
12	$38	$38	$38	$38	$38	$38	$38	$38	$38	$38	$38	$38	$38	$38
13	$36	$36	$36	$36	$36	$36	$36	$36	$36	$36	$36	$36	$36	$36

Table 28. Registration Renewal Costs, (Mid-size Car).

		PHEV												
Vehicle life	CV	0	5	10	15	20	25	30	35	40	45	50	55	60
1	$413	$481	$489	$497	$505	$513	$522	$531	$540	$549	$558	$567	$576	$585
2	$297	$343	$349	$354	$360	$365	$371	$377	$383	$389	$396	$402	$408	$414
3	$237	$272	$276	$280	$284	$288	$293	$298	$302	$307	$311	$316	$320	$325
4	$183	$207	$210	$213	$216	$219	$222	$226	$229	$232	$235	$239	$242	$245
5	$114	$126	$127	$129	$130	$132	$133	$135	$136	$138	$139	$141	$142	$144
6	$108	$119	$120	$121	$123	$124	$126	$127	$129	$130	$131	$133	$134	$136
7	$102	$112	$113	$115	$116	$117	$118	$120	$121	$123	$124	$125	$127	$128
8	$96	$106	$107	$108	$109	$110	$112	$113	$114	$116	$117	$118	$120	$121
9	$91	$100	$101	$102	$103	$104	$105	$107	$108	$109	$110	$112	$113	$114
10	$44	$44	$44	$44	$44	$44	$44	$44	$44	$44	$44	$44	$44	$44
11	$41	$41	$42	$42	$42	$42	$42	$42	$42	$42	$42	$42	$42	$42
12	$39	$39	$39	$39	$39	$39	$39	$39	$39	$39	$39	$39	$39	$39
13	$37	$37	$37	$37	$37	$37	$37	$37	$37	$37	$37	$37	$37	$37

Table 29. Registration Renewal Costs, (Mid-size SUV).

		PHEV												
Vehicle life	CV	0	5	10	15	20	25	30	35	40	45	50	55	60
1	$560	$659	$672	$685	$699	$712	$720	$728	$736	$745	$753	$761	$769	$777
2	$398	$465	$474	$483	$493	$502	$508	$513	$519	$525	$531	$537	$542	$548
3	$314	$365	$372	$379	$386	$393	$398	$402	$407	$412	$416	$421	$425	$430
4	$238	$275	$280	$285	$290	$296	$299	$302	$306	$309	$313	$316	$320	$323
5	$143	$160	$163	$166	$169	$172	$174	$176	$178	$180	$182	$184	$186	$188
6	$135	$151	$154	$157	$160	$162	$164	$166	$168	$170	$172	$174	$175	$177
7	$127	$143	$145	$148	$150	$153	$155	$157	$158	$160	$162	$164	$166	$167
8	$120	$135	$137	$140	$142	$144	$146	$148	$149	$151	$153	$154	$156	$158
9	$113	$127	$129	$132	$134	$136	$138	$139	$141	$143	$144	$146	$147	$149
10	$47	$48	$49	$49	$50	$50	$51	$52	$52	$53	$53	$54	$55	$55
11	$45	$45	$46	$46	$47	$48	$48	$49	$49	$50	$50	$51	$51	$52
12	$42	$43	$43	$44	$44	$45	$45	$46	$46	$47	$47	$48	$49	$49
13	$40	$40	$41	$41	$42	$42	$43	$43	$44	$44	$45	$45	$46	$46

Table 30. Registration Renewal Costs, (Large SUV).

		PHEV												
Vehicle life	CV	0	5	10	15	20	25	30	35	40	45	50	55	60
1	$568	$668	$676	$684	$693	$701	$712	$722	$733	$744	$754	$765	$775	$786
2	$408	$475	$481	$486	$492	$498	$505	$512	$519	$527	$534	$541	$548	$555
3	$324	$375	$379	$384	$388	$392	$398	$403	$409	$414	$420	$425	$431	$436
4	$249	$285	$288	$291	$294	$297	$301	$305	$309	$313	$317	$321	$325	$329
5	$154	$171	$173	$174	$176	$177	$179	$181	$183	$185	$187	$189	$191	$193
6	$145	$161	$163	$164	$166	$167	$169	$171	$173	$175	$176	$178	$180	$182
7	$137	$152	$154	$155	$156	$158	$160	$161	$163	$165	$166	$168	$170	$172
8	$129	$144	$145	$146	$148	$149	$151	$152	$154	$155	$157	$159	$160	$162
9	$122	$135	$137	$138	$139	$140	$142	$144	$145	$147	$148	$150	$151	$153
10	$57	$57	$57	$57	$57	$57	$57	$57	$58	$58	$58	$58	$58	$58
11	$53	$53	$54	$54	$54	$54	$54	$54	$54	$54	$55	$55	$55	$55
12	$50	$50	$51	$51	$51	$51	$51	$51	$51	$51	$52	$52	$52	$52
13	$47	$48	$48	$48	$48	$48	$48	$48	$48	$48	$49	$49	$49	$49

Table 31. Insurance Costs, (Compact Car).

		PHEV												
Vehicle life	CV	0	5	10	15	20	25	30	35	40	45	50	55	60
1	$1,093	$1,093	$1,104	$1,114	$1,125	$1,135	$1,146	$1,156	$1,167	$1,177	$1,188	$1,198	$1,209	$1,219
2	$1,067	$1,067	$1,077	$1,088	$1,098	$1,108	$1,118	$1,129	$1,139	$1,149	$1,159	$1,170	$1,180	$1,190
3	$1,042	$1,042	$1,052	$1,062	$1,072	$1,082	$1,092	$1,102	$1,112	$1,122	$1,132	$1,142	$1,152	$1,162
4	$1,017	$1,017	$1,027	$1,037	$1,047	$1,057	$1,066	$1,076	$1,086	$1,096	$1,105	$1,115	$1,125	$1,135
5	$993	$993	$1,003	$1,013	$1,022	$1,032	$1,041	$1,051	$1,060	$1,070	$1,079	$1,089	$1,098	$1,108
6	$970	$970	$979	$989	$998	$1,007	$1,017	$1,026	$1,035	$1,045	$1,054	$1,063	$1,073	$1,082
7	$947	$947	$956	$965	$974	$984	$993	$1,002	$1,011	$1,020	$1,029	$1,038	$1,047	$1,056
8	$925	$925	$934	$943	$951	$960	$969	$978	$987	$996	$1,005	$1,014	$1,023	$1,031
9	$903	$903	$912	$920	$929	$938	$946	$955	$964	$972	$981	$990	$998	$1,007
10	$882	$882	$890	$899	$907	$916	$924	$933	$941	$949	$958	$966	$975	$983
11	$861	$861	$869	$877	$886	$894	$902	$911	$919	$927	$935	$944	$952	$960
12	$841	$841	$849	$857	$865	$873	$881	$889	$897	$905	$913	$921	$929	$938
13	$821	$821	$829	$837	$844	$852	$860	$868	$876	$884	$892	$900	$908	$915

Table 32. Annual Insurance Costs, (Mid-size Car).

		PHEV												
Vehicle life	CV	0	5	10	15	20	25	30	35	40	45	50	55	60
1	$1,159	$1,159	$1,167	$1,175	$1,183	$1,191	$1,199	$1,207	$1,214	$1,222	$1,230	$1,238	$1,246	$1,254
2	$1,132	$1,132	$1,139	$1,147	$1,155	$1,163	$1,170	$1,178	$1,186	$1,194	$1,201	$1,209	$1,217	$1,224
3	$1,105	$1,105	$1,113	$1,120	$1,128	$1,135	$1,143	$1,150	$1,158	$1,165	$1,173	$1,180	$1,188	$1,196
4	$1,079	$1,079	$1,086	$1,094	$1,101	$1,108	$1,116	$1,123	$1,131	$1,138	$1,145	$1,153	$1,160	$1,167
5	$1,053	$1,053	$1,061	$1,068	$1,075	$1,082	$1,089	$1,097	$1,104	$1,111	$1,118	$1,125	$1,133	$1,140
6	$1,029	$1,029	$1,036	$1,043	$1,050	$1,057	$1,064	$1,071	$1,078	$1,085	$1,092	$1,099	$1,106	$1,113
7	$1,004	$1,004	$1,011	$1,018	$1,025	$1,032	$1,039	$1,046	$1,052	$1,059	$1,066	$1,073	$1,080	$1,087
8	$981	$981	$987	$994	$1,001	$1,007	$1,014	$1,021	$1,028	$1,034	$1,041	$1,048	$1,054	$1,061
9	$958	$958	$964	$971	$977	$984	$990	$997	$1,003	$1,010	$1,016	$1,023	$1,029	$1,036
10	$935	$935	$941	$948	$954	$961	$967	$973	$980	$986	$992	$999	$1,005	$1,012
11	$913	$913	$919	$925	$932	$938	$944	$950	$957	$963	$969	$975	$982	$988
12	$891	$891	$897	$904	$910	$916	$922	$928	$934	$940	$946	$952	$958	$964
13	$870	$870	$876	$882	$888	$894	$900	$906	$912	$918	$924	$930	$936	$942

Table 33. Annual Insurance Costs, (Mid-size SUV).

		PHEV												
Vehicle life	CV	0	5	10	15	20	25	30	35	40	45	50	55	60
1	$1,050	$1,050	$1,068	$1,087	$1,105	$1,123	$1,142	$1,160	$1,178	$1,197	$1,215	$1,233	$1,252	$1,270
2	$1,025	$1,025	$1,043	$1,061	$1,079	$1,097	$1,115	$1,133	$1,151	$1,168	$1,186	$1,204	$1,222	$1,240
3	$1,001	$1,001	$1,019	$1,036	$1,053	$1,071	$1,088	$1,106	$1,123	$1,141	$1,158	$1,176	$1,193	$1,211
4	$977	$977	$995	$1,012	$1,029	$1,046	$1,063	$1,080	$1,097	$1,114	$1,131	$1,148	$1,165	$1,182
5	$954	$954	$971	$988	$1,004	$1,021	$1,038	$1,054	$1,071	$1,088	$1,104	$1,121	$1,138	$1,154
6	$932	$932	$948	$964	$981	$997	$1,013	$1,030	$1,046	$1,062	$1,078	$1,095	$1,111	$1,127
7	$910	$910	$926	$942	$958	$973	$989	$1,005	$1,021	$1,037	$1,053	$1,069	$1,085	$1,101
8	$888	$888	$904	$919	$935	$950	$966	$982	$997	$1,013	$1,028	$1,044	$1,059	$1,075
9	$867	$867	$883	$898	$913	$928	$943	$958	$974	$989	$1,004	$1,019	$1,034	$1,049
10	$847	$847	$862	$877	$891	$906	$921	$936	$951	$965	$980	$995	$1,010	$1,025
11	$827	$827	$841	$856	$870	$885	$899	$914	$928	$943	$957	$971	$986	$1,000
12	$808	$808	$822	$836	$850	$864	$878	$892	$906	$920	$934	$949	$963	$977
13	$789	$789	$802	$816	$830	$844	$857	$871	$885	$899	$912	$926	$940	$954

Table 34. Annual Insurance Costs, (Large SUV).

		PHEV												
Vehicle life	CV	0	5	10	15	20	25	30	35	40	45	50	55	60
1	$1,089	$1,089	$1,111	$1,133	$1,156	$1,178	$1,200	$1,222	$1,244	$1,266	$1,289	$1,311	$1,333	$1,355
2	$1,063	$1,063	$1,085	$1,107	$1,128	$1,150	$1,172	$1,193	$1,215	$1,236	$1,258	$1,280	$1,301	$1,323
3	$1,038	$1,038	$1,059	$1,081	$1,102	$1,123	$1,144	$1,165	$1,186	$1,207	$1,228	$1,250	$1,271	$1,292
4	$1,014	$1,014	$1,034	$1,055	$1,076	$1,096	$1,117	$1,138	$1,158	$1,179	$1,199	$1,220	$1,241	$1,261
5	$990	$990	$1,010	$1,030	$1,050	$1,070	$1,091	$1,111	$1,131	$1,151	$1,171	$1,191	$1,211	$1,232
6	$966	$966	$986	$1,006	$1,026	$1,045	$1,065	$1,085	$1,104	$1,124	$1,144	$1,163	$1,183	$1,203
7	$944	$944	$963	$982	$1,001	$1,021	$1,040	$1,059	$1,078	$1,097	$1,117	$1,136	$1,155	$1,174
8	$921	$921	$940	$959	$978	$996	$1,015	$1,034	$1,053	$1,071	$1,090	$1,109	$1,128	$1,147
9	$900	$900	$918	$936	$955	$973	$991	$1,010	$1,028	$1,046	$1,065	$1,083	$1,101	$1,119
10	$878	$878	$896	$914	$932	$950	$968	$986	$1,004	$1,022	$1,039	$1,057	$1,075	$1,093
11	$858	$858	$875	$893	$910	$928	$945	$963	$980	$997	$1,015	$1,032	$1,050	$1,067
12	$838	$838	$855	$872	$889	$906	$923	$940	$957	$974	$991	$1,008	$1,025	$1,042
13	$818	$818	$834	$851	$868	$884	$901	$918	$934	$951	$968	$984	$1,001	$1,018

Table 35. Fuel Economy Parameters and Incremental Costs, (Compact Car).

PHEV	FCT, kWh mile^{-1}		PCT, mile gallon^{-1}		UF Petro FE Adj	UF		
Range	FCT_U	FCT_Hwy	PCT_U	PCT_Hwy	MPG	UF_U	UF_Hwy	Inc Cost
CV	0	0	31.6	49.3	32.2	0	0	0
0	0.235	0.237	48.50	50.50	42	0	0	$4,051
5	0.235	0.237	48.63	52.38	48	0.17	0.06	$4,661
10	0.235	0.236	48.75	54.25	56	0.32	0.12	$5,270
15	0.235	0.236	48.88	56.13	64	0.44	0.17	$5,880
20	0.235	0.235	49.00	58.00	74	0.54	0.23	$6,489
25	0.235	0.235	49.29	58.30	84	0.62	0.28	$6,995
30	0.235	0.234	49.58	58.60	95	0.69	0.32	$7,500
35	0.235	0.234	49.86	58.90	107	0.74	0.37	$8,006
40	0.235	0.233	50.15	59.20	119	0.79	0.41	$8,511
45	0.235	0.233	50.44	59.50	133	0.82	0.45	$9,017
50	0.235	0.232	50.73	59.80	148	0.85	0.48	$9,522
55	0.235	0.232	51.01	60.10	164	0.88	0.52	$10,028
60	0.235	0.231	51.30	60.40	181	0.9	0.55	$10,533

Table 36. Fuel Economy Parameters and Incremental Costs, (Mid-size Car).

PHEV	FCT, kWh mile^{-1}		PCT, mile gallon^{-1}		UF Petro FE Adj	UF		
Range	FCT_U	FCT_Hwy	PCT_U	PCT_Hwy	MPG	UF_U	UF_Hwy	Inc Cost
CV	0	0	23.2	41.4	24.8	0	0	0
0	0.29	0.303	40.60	43.70	35	0	0	$3,831
5	0.29	0.302	40.68	44.55	41	0.17	0.06	$4,284
10	0.289	0.301	40.75	45.40	47	0.32	0.12	$4,736
15	0.288	0.299	40.83	46.25	53	0.44	0.17	$5,188
20	0.288	0.298	40.90	47.10	61	0.54	0.23	$5,641
25	0.287	0.297	41.09	47.43	69	0.62	0.28	$6,144
30	0.286	0.296	41.28	47.75	78	0.69	0.32	$6,647
35	0.286	0.295	41.46	48.08	88	0.74	0.37	$7,150
40	0.285	0.293	41.65	48.40	98	0.79	0.41	$7,653
45	0.284	0.292	41.84	48.73	109	0.82	0.45	$8,156
50	0.284	0.291	42.03	49.05	122	0.85	0.48	$8,659
55	0.283	0.29	42.21	49.38	135	0.88	0.52	$9,163
60	0.282	0.288	42.40	49.70	149	0.9	0.55	$9,666

Table 37. Fuel Economy Parameters and Incremental Costs, (Mid-size SUV)

PHEV	FCT, kWh mile^{-1}		PCT, mile gallon^{-1}		UF Petro FE Adj	UF		
Range	FCT_U	FCT_Hwy	PCT_U	PCT_Hwy	MPG	UF_U	UF_Hwy	Inc Cost
CV	0	0	18.4	29.7	19	0	0	0
0	0.356	0.359	30.60	36.50	28	0	0	$5,505
5	0.354	0.357	31.05	36.85	32	0.17	0.06	$6,191
10	0.351	0.354	31.50	37.20	37	0.32	0.12	$6,877
15	0.349	0.352	31.95	37.55	43	0.44	0.17	$7,563
20	0.347	0.349	32.40	37.90	49	0.54	0.23	$8,249
25	0.345	0.347	32.54	38.01	55	0.62	0.28	$8,651
30	0.343	0.345	32.68	38.13	62	0.69	0.32	$9,053
35	0.341	0.342	32.81	38.24	70	0.74	0.37	$9,456
40	0.339	0.34	32.95	38.35	78	0.79	0.41	$9,858
45	0.337	0.337	33.09	38.46	86	0.82	0.45	$10,261
50	0.335	0.335	33.23	38.58	96	0.85	0.48	$10,663
55	0.333	0.332	33.36	38.69	106	0.88	0.52	$11,065
60	0.33	0.33	33.50	38.80	116	0.9	0.55	$11,468

Table 38. Fuel Economy Parameters and Incremental Costs, (Large SUV).

PHEV	FCT, kWh mile^{-1}		PCT, mile gallon^{-1}		UF Petro FE Adj	UF		
Range	FCT_U	FCT_Hwy	PCT_U	PCT_Hwy	MPG	UF_U	UF_Hwy	Inc Cost
CV	0	0	14.9	24.8	16	0	0	0
0	0.400	0.425	25.60	30.50	23	0	0	$5,636
5	0.401	0.422	26.10	30.93	27	0.17	0.06	$6,100
10	0.402	0.419	26.60	31.35	31	0.32	0.12	$6,563
15	0.403	0.416	27.10	31.78	36	0.44	0.17	$7,026
20	0.404	0.413	27.60	32.20	41	0.54	0.23	$7,489
25	0.405	0.410	27.71	32.26	47	0.62	0.28	$8,078
30	0.406	0.407	27.83	32.33	53	0.69	0.32	$8,668
35	0.408	0.404	27.94	32.39	59	0.74	0.37	$9,257
40	0.409	0.401	28.05	32.45	66	0.79	0.41	$9,846
45	0.410	0.398	28.16	32.51	73	0.82	0.45	$10,435
50	0.411	0.394	28.28	32.58	81	0.85	0.48	$11,024
55	0.412	0.391	28.39	32.64	89	0.88	0.52	$11,613
60	0.413	0.388	28.50	32.70	98	0.90	0.55	$12,202

Table 39. Vehicle Miles Traveled (VMT) and Fuel Prices in 2010$

Calendar Year	Vehicle Life	VMT, Passenger Car	VMT, Light Truck	Electricity, $ kWh^{-1}	Gasoline, $ gallon^{-1}
2012	1	12,000	15,000	$0.11	$2.84
2013	2	11,754	14,739	$0.11	$3.00
2014	3	11,484	14,437	$0.11	$3.16
2015	4	11,192	14,097	$0.10	$3.32
2016	5	10,881	13,724	$0.10	$3.44
2017	6	10,551	13,321	$0.09	$3.57
2018	7	10,206	12,893	$0.09	$3.66
2019	8	9,848	12,444	$0.09	$3.74
2020	9	9,479	11,978	$0.08	$3.81
2021	10	9,101	11,499	$0.08	$3.83
2022	11	8,716	11,011	$0.08	$3.86
2023	12	8,327	10,518	$0.07	$3.88
2024	13	7,936	10,024	$0.12	$3.88

Table 40. EPRI 2001 Incremental Costs of HEV $2000.

		Incremental cost,			Battery NiMH cost			
		Base	ANL	Average	Base	ANL	Average	Inc cost - NiMH Battery
Compact Car	HEV0	$3,602	$2,490	$3,046	$1,200	$1,400	$1,300	$1,746
	PHEV20	$6,062	$4,483	$5,273	$1,800	$2,600	$2,200	$3,073
	PHEV60	$10,305	$8,077	$9,191	$4,100	$6,400	$5,250	$3,941
Midsize car	HEV0	$4,058	$2,483	$3,271	$2,103	$1,606	$1,855	$1,416
	PHEV20	$5,982	$4,081	$5,032	$3,117	$2,193	$2,655	$2,377
	PHEV60	$10,269	$7,629	$8,949	$7,317	$4,634	$5,976	$2,974
Midsize SUV	HEV0	$5,503	$3,960	$4,732	$1,900	$2,600	$2,250	$2,482
	PHEV20	$8,505	$6,381	$7,443	$2,800	$4,100	$3,450	$3,993
	PHEV60	$13,098	$10,109	$11,604	$6,200	$9,800	$8,000	$3,604
Fullsize SUV	HEV0	$6,282	$4,482	$5,382	$2,500	$3,500	$3,000	$2,382
	PHEV20	$8,542	$6,017	$7,280	$3,500	$5,300	$4,400	$2,880
	PHEV60	$14,505	$11,006	$12,756	$7,100	$11,500	$9,300	$3,456

Table 41. Kalhammer et al. Reported Li Ion Battery and Module costs and Final Incremental Cost $2010.

		2006 data		2008 data, f=6.8%		2000 data	2010$ data	2010$ data
		Module Cost ($/kWh)	Battery Cost	Module Cost ($/kWh)	Battery Cost	(Inc cost – NiMH Battery)		Cost with Li Ion Battery
Compact Car	HEV0	$535	$1,700	$571	$1,816	$1,746	$2,212	$4,051
	PHEV20	$341	$2,400	$364	$2,563	$3,073	$3,892	$6,489
	PHEV60	$256	$5,120	$273	$5,468	$3,941	$4,992	$10,533
Midsize car	HEV0	$470	$1,930	$502	$2,061	$1,416	$1,794	$3,882
	PHEV20	$315	$2,500	$336	$2,670	$2,377	$3,011	$5,716
	PHEV60	$249	$5,570	$266	$5,949	$2,974	$3,767	$9,795
Midsize SUV	HEV0	$390	$2,250	$417	$2,403	$2,482	$3,143	$5,578
	PHEV20	$285	$3,050	$304	$3,257	$3,993	$5,058	$8,359
	PHEV60	$235	$6,520	$251	$6,963	$3,604	$4,564	$11,621
Fullsize SUV	HEV0	$338	$2,420	$361	$2,585	$2,382	$3,018	$5,636
	PHEV20	$275	$3,550	$294	$3,791	$2,880	$3,647	$7,490
	PHEV60	$224	$7,230	$239	$7,722	$3,456	$4,377	$12,202

Table 42. Payments for Compact Car, 2010$, (Sales Tax and Registration Payments are Included in the Loan)

Vehicle Type	MSRP	Down Payment	Monthly Payment	Sales Tax	Title and Registration	Loan
CV	$14,587	$1,459	$330	$977	$248	$14,354
HEV0	$18,639	$1,864	$422	$1,249	$317	$18,340
PHEV5	$19,248	$1,925	$436	$1,290	$327	$18,940
PHEV10	$19,858	$1,986	$450	$1,330	$338	$19,540
PHEV15	$20,467	$2,047	$464	$1,371	$348	$20,140
PHEV20	$21,076	$2,108	$478	$1,412	$358	$20,739
PHEV25	$21,582	$2,158	$489	$1,446	$367	$21,237
PHEV30	$22,087	$2,209	$500	$1,480	$375	$21,734
PHEV35	$22,593	$2,259	$512	$1,514	$384	$22,231
PHEV40	$23,098	$2,310	$523	$1,548	$393	$22,729
PHEV45	$23,604	$2,360	$535	$1,581	$401	$23,226
PHEV50	$24,109	$2,411	$546	$1,615	$410	$23,724
PHEV55	$24,615	$2,461	$558	$1,649	$418	$24,221
PHEV60	$25,120	$2,512	$569	$1,683	$427	$24,718

Table 43. Payments for Mid-size Car, 2010$, (Sales Tax and Registration Payments are Included in the Loan)

Vehicle Type	MSRP	Down Payment	Monthly Payment	Sales Tax	Title and Registration	Loan
CV	$19,373	$1,937	$439	$1,298	$329	$19,063
HEV0	$23,256	$2,326	$527	$1,558	$395	$22,884
PHEV5	$23,714	$2,371	$537	$1,589	$403	$23,335
PHEV10	$24,172	$2,417	$548	$1,620	$411	$23,786
PHEV15	$24,631	$2,463	$558	$1,650	$419	$24,237
PHEV20	$25,089	$2,509	$568	$1,681	$427	$24,688
PHEV25	$25,599	$2,560	$580	$1,715	$435	$25,189
PHEV30	$26,109	$2,611	$592	$1,749	$444	$25,691
PHEV35	$26,619	$2,662	$603	$1,783	$453	$26,193
PHEV40	$27,129	$2,713	$615	$1,818	$461	$26,694
PHEV45	$27,638	$2,764	$626	$1,852	$470	$27,196
PHEV50	$28,148	$2,815	$638	$1,886	$479	$27,698
PHEV55	$28,658	$2,866	$649	$1,920	$487	$28,200
PHEV60	$29,168	$2,917	$661	$1,954	$496	$28,701

Table 44. Payments for Mid-size SUV, 2010$, (Sales Tax and Registration Payments are Included in the Loan)

Vehicle Type	MSRP	Down Payment	Monthly Payment	Sales Tax	Title and Registration	Loan
CV	$27,391	$2,739	$621	$1,835	$466	$26,953
HEV0	$32,969	$3,297	$747	$2,209	$560	$32,442
PHEV5	$33,664	$3,366	$763	$2,256	$572	$33,126
PHEV10	$34,359	$3,436	$778	$2,302	$584	$33,810
PHEV15	$35,055	$3,505	$794	$2,349	$596	$34,494
PHEV20	$35,750	$3,575	$810	$2,395	$608	$35,178
PHEV25	$36,157	$3,616	$819	$2,423	$615	$35,579
PHEV30	$36,565	$3,657	$828	$2,450	$622	$35,980
PHEV35	$36,973	$3,697	$838	$2,477	$629	$36,381
PHEV40	$37,381	$3,738	$847	$2,505	$635	$36,783
PHEV45	$37,788	$3,779	$856	$2,532	$642	$37,184
PHEV50	$38,196	$3,820	$865	$2,559	$649	$37,585
PHEV55	$38,604	$3,860	$875	$2,586	$656	$37,986
PHEV60	$39,012	$3,901	$884	$2,614	$663	$38,387

Table 45. Payments for Large SUV, 2010$, (Sales Tax and Registration Payments are Included in the Loan)

Vehicle Type	MSRP	Down Payment	Monthly Payment	Sales Tax	Title and Registration	Loan
CV	$27,003	$2,700	$612	$1,809	$459	$26,571
HEV0	$32,640	$3,264	$739	$2,187	$555	$32,117
PHEV5	$33,103	$3,310	$750	$2,218	$563	$32,573
PHEV10	$33,566	$3,357	$760	$2,249	$571	$33,029
PHEV15	$34,029	$3,403	$771	$2,280	$578	$33,485
PHEV20	$34,493	$3,449	$781	$2,311	$586	$33,941
PHEV25	$35,082	$3,508	$795	$2,350	$596	$34,520
PHEV30	$35,671	$3,567	$808	$2,390	$606	$35,100
PHEV35	$36,260	$3,626	$822	$2,429	$616	$35,680
PHEV40	$36,849	$3,685	$835	$2,469	$626	$36,259
PHEV45	$37,438	$3,744	$848	$2,508	$636	$36,839
PHEV50	$38,027	$3,803	$862	$2,548	$646	$37,418
PHEV55	$38,616	$3,862	$875	$2,587	$656	$37,998
PHEV60	$39,205	$3,921	$888	$2,627	$666	$38,578

Appendix C- Supporting Material for Chapter 6

Table 46. Tailpipe Emissions, ton/gallon

	GHG emission				Air Pollution emissions				
Technology	CO2	CO4	N2O	Net GHG	CO	NO_x	PM_10	PM_2.5	VOC
CV	8.78E-03	2.65E-07	2.98E-07	8.88E-03	8.66E-05	1.72E-06	7.11E-07	3.64E-07	3.77E-06
HEV	8.78E-03	1.62E-07	4.17E-07	8.91E-03	1.21E-04	2.01E-06	9.96E-07	5.09E-07	3.73E-06
PHEV 5	8.78E-03	1.54E-07	3.98E-07	8.90E-03	1.15E-04	1.91E-06	1.31E-06	5.22E-07	3.55E-06
PHEV 10	8.78E-03	1.44E-07	3.75E-07	8.89E-03	1.08E-04	1.79E-06	1.79E-06	5.40E-07	3.32E-06
PHEV 15	8.78E-03	1.41E-07	3.66E-07	8.89E-03	1.05E-04	1.74E-06	1.74E-06	5.43E-07	3.23E-06
PHEV 20	8.78E-03	1.39E-07	3.58E-07	8.89E-03	1.02E-04	1.70E-06	1.70E-06	5.47E-07	3.14E-06
PHEV 25	8.78E-03	1.37E-07	3.50E-07	8.89E-03	9.95E-05	1.66E-06	1.66E-06	5.51E-07	3.05E-06
PHEV 30	8.78E-03	1.35E-07	3.41E-07	8.89E-03	9.65E-05	1.61E-06	1.61E-06	5.54E-07	2.96E-06
PHEV 35	8.79E-03	1.33E-07	3.33E-07	8.89E-03	9.36E-05	1.57E-06	1.57E-06	5.58E-07	2.87E-06
PHEV 40	8.79E-03	1.30E-07	3.25E-07	8.88E-03	9.06E-05	1.52E-06	1.52E-06	5.61E-07	2.78E-06
PHEV 45	8.79E-03	1.28E-07	3.16E-07	8.88E-03	8.76E-05	1.48E-06	1.48E-06	5.65E-07	2.69E-06
PHEV 50	8.79E-03	1.26E-07	3.08E-07	8.88E-03	8.47E-05	1.43E-06	1.43E-06	5.69E-07	2.60E-06
PHEV 55	8.79E-03	1.24E-07	3.00E-07	8.88E-03	8.17E-05	1.39E-06	1.39E-06	5.72E-07	2.51E-06
PHEV 60	8.79E-03	1.22E-07	2.91E-07	8.88E-03	7.88E-05	1.35E-06	1.35E-06	5.76E-07	2.42E-06

Table 47. Power Generation Emissions, ton/kWh

Direct emissions					Upstream emissions						
GHG, CO2_e	NO_x	PM_10	PM_2.5	SO2	GHG, CO2_e	CO	NO_x	PM_10	PM_2.5	SO2	VOC
5.76E-04	8.72E-07	1.43E-07	1.19E-07	2.39E-06	3.71E-05	2.40E-08	1.06E-07	9.24E-07	2.30E-07	5.30E-08	4.90E-08

Table 48. Gasoline U.S. Refineries Emissions, ton/gallon

CO2	CH4	N2O	CO2_e	NO_x	PM_10	PM_2.5	SO2	VOC	CO
1.39E-03	1.75E-06	1.88E-08	1.44E-03	2.13E-06	5.13E-07	2.63E-07	1.50E-06	2.88E-06	7.38E-07

Table 49. Tailpipe Emissions Cost, $2010/ton

GHG emission				Air Pollution emissions				
CO2	CO4	N2O	Net GHG	CO	NO_x	PM_10	PM_2.5	VOC
$42.00			$42.00	$886.00	$3,445.00	$11,644.00	$75,850.00	$7,159.00

Table 50. Power plant Emission Costs, $2010/kWh

Direct emissions					Upstream emissions						
GHG, CO2_e	NO_x	PM_10	PM_2.5	SO2	GHG, CO2_e	CO	NO_x	PM_10	PM_2.5	SO2	VOC
$0.02403	$0.00137	$0.00007	$0.00120	$0.01550	$0.00155	$0.00000	$0.00008	$0.00055	$0.00053	$0.00013	$0.00001

Table 51. Gasoline U.S. Refineries Emissions Costs, $2010/ton

CO2	CH4	N2O	CO2_e	NO_x	PM_10	PM_2.5	SO2	VOC	CO
$42.00			$42.00	$2,006.00	$6,712.00	$43,844.00	$18,016.00	$4,136.00	$648.00

Table 52. Battery Assembly Emissions Costs, $2010/ton

Technology	CO2_e	VOC	CO	NO_x	PM_10	PM_2.5	SO_x
	$42	$2,400	$448	$2,577	$4,763	$31,966	$12,735

Table 53. Battery Upstream Emissions Costs, $2010/ton

Technology	CO2_e	VOC	CO	NO_x	PM_10	PM_2.5	SO_x
	$42	$2,400	$448	$2,577	$4,763	$31,966	$12,735

Table 54. Passenger Car Battery Assembly Emissions, Tons

Vehicle Class	Technology	GHG	CO	NO_x	PM_10	PM_2.5	VOC	SO_x
Compact Car	CV	3.39E-01	8.70E-05	3.56E-04	4.30E-04	1.13E-04	2.90E-05	7.82E-04
	HEV	1.27E-01	3.22E-05	1.33E-04	1.61E-04	4.29E-05	1.07E-05	2.93E-04
	PHEV 5	1.68E-01	4.26E-05	1.76E-04	2.13E-04	5.69E-05	1.42E-05	3.88E-04
	PHEV 10	2.09E-01	5.31E-05	2.19E-04	2.65E-04	7.08E-05	1.77E-05	4.83E-04
	PHEV 15	2.50E-01	6.36E-05	2.63E-04	3.18E-04	8.47E-05	2.12E-05	5.78E-04
	PHEV 20	2.92E-01	7.40E-05	3.06E-04	3.70E-04	9.87E-05	2.47E-05	6.73E-04
	PHEV 25	3.65E-01	9.26E-05	3.83E-04	4.63E-04	1.23E-04	3.09E-05	8.42E-04
	PHEV 30	4.38E-01	1.11E-04	4.59E-04	5.56E-04	1.48E-04	3.70E-05	1.01E-03
	PHEV 35	5.11E-01	1.30E-04	5.36E-04	6.48E-04	1.73E-04	4.32E-05	1.18E-03
	PHEV 40	5.84E-01	1.48E-04	6.13E-04	7.41E-04	1.98E-04	4.94E-05	1.35E-03
	PHEV 45	6.57E-01	1.67E-04	6.89E-04	8.34E-04	2.22E-04	5.56E-05	1.52E-03
	PHEV 50	7.31E-01	1.85E-04	7.66E-04	9.27E-04	2.47E-04	6.18E-05	1.69E-03
	PHEV 55	8.04E-01	2.04E-04	8.43E-04	1.02E-03	2.72E-04	6.80E-05	1.86E-03
	PHEV 60	8.77E-01	2.22E-04	9.20E-04	1.11E-03	2.97E-04	7.42E-05	2.02E-03
Midsize Car	CV	3.39E-07	8.70E-11	3.56E-10	4.30E-10	1.13E-10	2.90E-11	7.82E-10
	HEV	1.67E-01	4.23E-05	1.75E-04	2.11E-04	5.64E-05	1.41E-05	3.85E-04
	PHEV 5	2.09E-01	5.30E-05	2.19E-04	2.65E-04	7.07E-05	1.77E-05	4.83E-04
	PHEV 10	2.51E-01	6.38E-05	2.64E-04	3.19E-04	8.50E-05	2.13E-05	5.80E-04
	PHEV 15	2.94E-01	7.45E-05	3.08E-04	3.73E-04	9.93E-05	2.48E-05	6.78E-04
	PHEV 20	3.36E-01	8.52E-05	3.52E-04	4.26E-04	1.14E-04	2.84E-05	7.76E-04
	PHEV 25	4.22E-01	1.07E-04	4.42E-04	5.35E-04	1.43E-04	3.57E-05	9.74E-04
	PHEV 30	5.07E-01	1.29E-04	5.32E-04	6.44E-04	1.72E-04	4.29E-05	1.17E-03
	PHEV 35	5.93E-01	1.50E-04	6.22E-04	7.52E-04	2.01E-04	5.01E-05	1.37E-03
	PHEV 40	6.79E-01	1.72E-04	7.12E-04	8.61E-04	2.30E-04	5.74E-05	1.57E-03
	PHEV 45	7.64E-01	1.94E-04	8.02E-04	9.70E-04	2.59E-04	6.46E-05	1.76E-03
	PHEV 50	8.50E-01	2.16E-04	8.91E-04	1.08E-03	2.88E-04	7.19E-05	1.96E-03
	PHEV 55	9.36E-01	2.37E-04	9.81E-04	1.19E-03	3.17E-04	7.91E-05	2.16E-03
	PHEV 60	1.02E+00	2.59E-04	1.07E-03	1.30E-03	3.45E-04	8.64E-05	2.36E-03

Table 55. Light truck Battery Assembly Emissions, Tons

Vehicle Class	Technology	GHG	CO	NO_x	PM_10	PM_2.5	VOC	SO_x
Midsize SUV	CV	3.39E-07	8.70E-11	3.56E-10	4.30E-10	1.13E-10	2.90E-11	7.82E-10
	HEV	2.35E-01	5.96E-05	2.46E-04	2.98E-04	7.94E-05	1.99E-05	5.42E-04
	PHEV 5	2.89E-01	7.33E-05	3.03E-04	3.66E-04	9.77E-05	2.44E-05	6.67E-04
	PHEV 10	3.43E-01	8.70E-05	3.60E-04	4.35E-04	1.16E-04	2.90E-05	7.92E-04
	PHEV 15	3.97E-01	1.01E-04	4.16E-04	5.03E-04	1.34E-04	3.36E-05	9.16E-04
	PHEV 20	4.51E-01	1.14E-04	4.73E-04	5.72E-04	1.52E-04	3.81E-05	1.04E-03
	PHEV 25	5.61E-01	1.42E-04	5.88E-04	7.12E-04	1.90E-04	4.74E-05	1.29E-03
	PHEV 30	6.71E-01	1.70E-04	7.04E-04	8.51E-04	2.27E-04	5.67E-05	1.55E-03
	PHEV 35	7.81E-01	1.98E-04	8.19E-04	9.91E-04	2.64E-04	6.61E-05	1.80E-03
	PHEV 40	8.91E-01	2.26E-04	9.35E-04	1.13E-03	3.01E-04	7.54E-05	2.06E-03
	PHEV 45	1.00E+00	2.54E-04	1.05E-03	1.27E-03	3.39E-04	8.47E-05	2.31E-03
	PHEV 50	1.11E+00	2.82E-04	1.17E-03	1.41E-03	3.76E-04	9.40E-05	2.57E-03
	PHEV 55	1.22E+00	3.10E-04	1.28E-03	1.55E-03	4.13E-04	1.03E-04	2.82E-03
	PHEV 60	1.33E+00	3.38E-04	1.40E-03	1.69E-03	4.50E-04	1.13E-04	3.07E-03
Large SUV	CV	3.39E-07	8.70E-11	3.56E-10	4.30E-10	1.13E-10	2.90E-11	7.82E-10
	HEV	2.97E-01	7.54E-05	3.12E-04	3.77E-04	1.01E-04	2.51E-05	6.87E-04
	PHEV 5	3.56E-01	9.02E-05	3.73E-04	4.51E-04	1.20E-04	3.01E-05	8.21E-04
	PHEV 10	4.14E-01	1.05E-04	4.34E-04	5.25E-04	1.40E-04	3.50E-05	9.55E-04
	PHEV 15	4.72E-01	1.20E-04	4.95E-04	5.99E-04	1.60E-04	3.99E-05	1.09E-03
	PHEV 20	5.30E-01	1.35E-04	5.56E-04	6.73E-04	1.79E-04	4.49E-05	1.22E-03
	PHEV 25	6.61E-01	1.68E-04	6.93E-04	8.39E-04	2.24E-04	5.59E-05	1.53E-03
	PHEV 30	7.92E-01	2.01E-04	8.30E-04	1.00E-03	2.68E-04	6.70E-05	1.83E-03
	PHEV 35	9.22E-01	2.34E-04	9.67E-04	1.17E-03	3.12E-04	7.80E-05	2.13E-03
	PHEV 40	1.05E+00	2.67E-04	1.10E-03	1.34E-03	3.56E-04	8.91E-05	2.43E-03
	PHEV 45	1.18E+00	3.00E-04	1.24E-03	1.50E-03	4.00E-04	1.00E-04	2.73E-03
	PHEV 50	1.31E+00	3.34E-04	1.38E-03	1.67E-03	4.45E-04	1.11E-04	3.03E-03
	PHEV 55	1.45E+00	3.67E-04	1.52E-03	1.83E-03	4.89E-04	1.22E-04	3.34E-03
	PHEV 60	1.58E+00	4.00E-04	1.65E-03	2.00E-03	5.33E-04	1.33E-04	3.64E-03

Table 56. Passenger Car Battery Upstream Emissions, Tons

Vehicle Class	Technology	GHG	CO	NO_x	PM_10	PM_2.5	VOC	SO_x
Compact Car	CV	3.46E-02	1.80E-05	5.90E-05	1.19E-04	4.40E-05	7.20E-06	4.46E-04
	HEV	3.80E-01	1.11E-04	4.44E-04	5.52E-04	1.82E-04	3.65E-05	2.39E-03
	PHEV 5	5.03E-01	1.46E-04	5.89E-04	7.31E-04	2.42E-04	4.83E-05	3.16E-03
	PHEV 10	6.26E-01	1.82E-04	7.33E-04	9.10E-04	3.01E-04	6.02E-05	3.94E-03
	PHEV 15	7.49E-01	2.18E-04	8.77E-04	1.09E-03	3.60E-04	7.20E-05	4.72E-03
	PHEV 20	8.73E-01	2.54E-04	1.02E-03	1.27E-03	4.19E-04	8.39E-05	5.49E-03
	PHEV 25	1.09E+00	3.18E-04	1.28E-03	1.59E-03	5.25E-04	1.05E-04	6.87E-03
	PHEV 30	1.31E+00	3.82E-04	1.53E-03	1.90E-03	6.30E-04	1.26E-04	8.25E-03
	PHEV 35	1.53E+00	4.45E-04	1.79E-03	2.22E-03	7.35E-04	1.47E-04	9.62E-03
	PHEV 40	1.75E+00	5.09E-04	2.05E-03	2.54E-03	8.40E-04	1.68E-04	1.10E-02
	PHEV 45	1.97E+00	5.73E-04	2.30E-03	2.86E-03	9.45E-04	1.89E-04	1.24E-02
	PHEV 50	2.19E+00	6.36E-04	2.56E-03	3.18E-03	1.05E-03	2.10E-04	1.38E-02
	PHEV 55	2.41E+00	7.00E-04	2.81E-03	3.49E-03	1.16E-03	2.31E-04	1.51E-02
	PHEV 60	2.62E+00	7.64E-04	3.07E-03	3.81E-03	1.26E-03	2.52E-04	1.65E-02
Midsize Car	CV	3.46E-08	1.80E-11	5.90E-11	1.19E-10	4.40E-11	7.20E-12	4.46E-10
	HEV	4.99E-01	1.45E-04	5.84E-04	7.25E-04	2.40E-04	4.79E-05	3.14E-03
	PHEV 5	6.25E-01	1.82E-04	7.32E-04	9.09E-04	3.00E-04	6.01E-05	3.93E-03
	PHEV 10	7.52E-01	2.19E-04	8.80E-04	1.09E-03	3.61E-04	7.23E-05	4.73E-03
	PHEV 15	8.79E-01	2.56E-04	1.03E-03	1.28E-03	4.22E-04	8.44E-05	5.53E-03
	PHEV 20	1.01E+00	2.93E-04	1.18E-03	1.46E-03	4.83E-04	9.66E-05	6.33E-03
	PHEV 25	1.26E+00	3.67E-04	1.48E-03	1.83E-03	6.06E-04	1.21E-04	7.94E-03
	PHEV 30	1.52E+00	4.42E-04	1.78E-03	2.21E-03	7.29E-04	1.46E-04	9.55E-03
	PHEV 35	1.77E+00	5.17E-04	2.08E-03	2.58E-03	8.53E-04	1.71E-04	1.12E-02
	PHEV 40	2.03E+00	5.91E-04	2.38E-03	2.95E-03	9.76E-04	1.95E-04	1.28E-02
	PHEV 45	2.29E+00	6.66E-04	2.68E-03	3.32E-03	1.10E-03	2.20E-04	1.44E-02
	PHEV 50	2.54E+00	7.40E-04	2.98E-03	3.69E-03	1.22E-03	2.44E-04	1.60E-02
	PHEV 55	2.80E+00	8.15E-04	3.28E-03	4.07E-03	1.35E-03	2.69E-04	1.76E-02
	PHEV 60	3.06E+00	8.90E-04	3.58E-03	4.44E-03	1.47E-03	2.94E-04	1.92E-02

Table 57. Light Truck Battery Upstream Emissions, Tons

Vehicle Class	Technology	GHG	CO	NO_x	PM_10	PM_2.5	VOC	SO_x
Midsize SUV	CV	3.46E-08	1.80E-11	5.90E-11	1.19E-10	4.40E-11	7.20E-12	4.46E-10
	HEV	7.03E-01	2.05E-04	8.22E-04	1.02E-03	3.38E-04	6.75E-05	4.42E-03
	PHEV 5	8.64E-01	2.52E-04	1.01E-03	1.26E-03	4.15E-04	8.31E-05	5.44E-03
	PHEV 10	1.03E+00	2.99E-04	1.20E-03	1.49E-03	4.93E-04	9.86E-05	6.45E-03
	PHEV 15	1.19E+00	3.46E-04	1.39E-03	1.72E-03	5.70E-04	1.14E-04	7.47E-03
	PHEV 20	1.35E+00	3.93E-04	1.58E-03	1.96E-03	6.48E-04	1.30E-04	8.49E-03
	PHEV 25	1.68E+00	4.89E-04	1.96E-03	2.44E-03	8.06E-04	1.61E-04	1.06E-02
	PHEV 30	2.01E+00	5.84E-04	2.35E-03	2.92E-03	9.65E-04	1.93E-04	1.26E-02
	PHEV 35	2.34E+00	6.80E-04	2.73E-03	3.40E-03	1.12E-03	2.25E-04	1.47E-02
	PHEV 40	2.67E+00	7.76E-04	3.12E-03	3.87E-03	1.28E-03	2.56E-04	1.68E-02
	PHEV 45	3.00E+00	8.72E-04	3.51E-03	4.35E-03	1.44E-03	2.88E-04	1.88E-02
	PHEV 50	3.33E+00	9.68E-04	3.89E-03	4.83E-03	1.60E-03	3.20E-04	2.09E-02
	PHEV 55	3.65E+00	1.06E-03	4.28E-03	5.31E-03	1.76E-03	3.51E-04	2.30E-02
	PHEV 60	3.98E+00	1.16E-03	4.66E-03	5.79E-03	1.91E-03	3.83E-04	2.51E-02
Large SUV	CV	3.46E-08	1.80E-11	5.90E-11	1.19E-10	4.40E-11	7.20E-12	4.46E-10
	HEV	8.90E-01	2.59E-04	1.04E-03	1.29E-03	4.28E-04	8.55E-05	5.60E-03
	PHEV 5	1.06E+00	3.10E-04	1.25E-03	1.55E-03	5.11E-04	1.02E-04	6.69E-03
	PHEV 10	1.24E+00	3.60E-04	1.45E-03	1.80E-03	5.95E-04	1.19E-04	7.79E-03
	PHEV 15	1.41E+00	4.11E-04	1.65E-03	2.05E-03	6.79E-04	1.36E-04	8.89E-03
	PHEV 20	1.59E+00	4.62E-04	1.86E-03	2.31E-03	7.62E-04	1.52E-04	9.98E-03
	PHEV 25	1.98E+00	5.76E-04	2.31E-03	2.87E-03	9.50E-04	1.90E-04	1.24E-02
	PHEV 30	2.37E+00	6.90E-04	2.77E-03	3.44E-03	1.14E-03	2.28E-04	1.49E-02
	PHEV 35	2.76E+00	8.03E-04	3.23E-03	4.01E-03	1.33E-03	2.65E-04	1.74E-02
	PHEV 40	3.15E+00	9.17E-04	3.69E-03	4.58E-03	1.51E-03	3.03E-04	1.98E-02
	PHEV 45	3.54E+00	1.03E-03	4.14E-03	5.15E-03	1.70E-03	3.40E-04	2.23E-02
	PHEV 50	3.93E+00	1.15E-03	4.60E-03	5.71E-03	1.89E-03	3.78E-04	2.47E-02
	PHEV 55	4.32E+00	1.26E-03	5.06E-03	6.28E-03	2.08E-03	4.16E-04	2.72E-02
	PHEV 60	4.72E+00	1.37E-03	5.52E-03	6.85E-03	2.27E-03	4.53E-04	2.97E-02

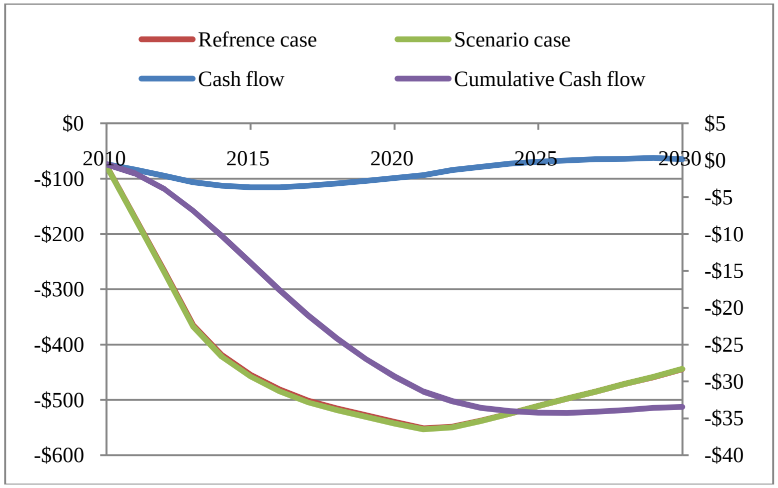

Figure 53. Passenger Car Fleet Cash Flow for Low HEV Scenario, (Reference Case and Scenario Case Left Axis), (In Billions of Dollars)

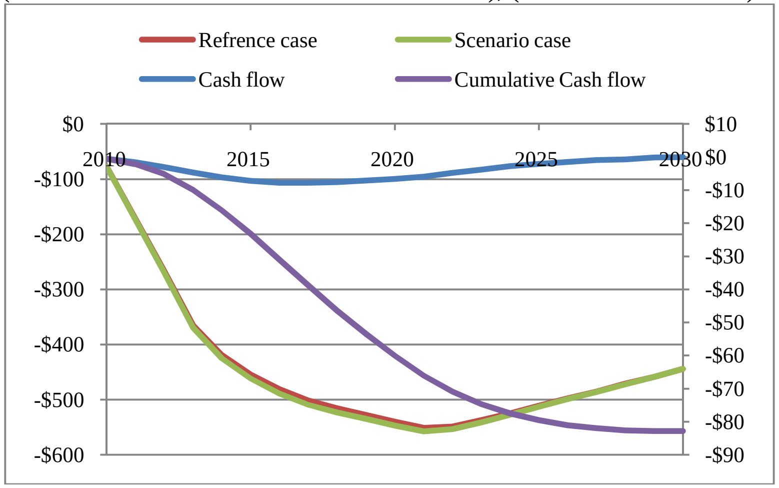

Figure 54. Passenger Car Fleet Cash Flow for High HEV Scenario, (Reference Case and Scenario Case Left Axis), (In Billions of Dollars)

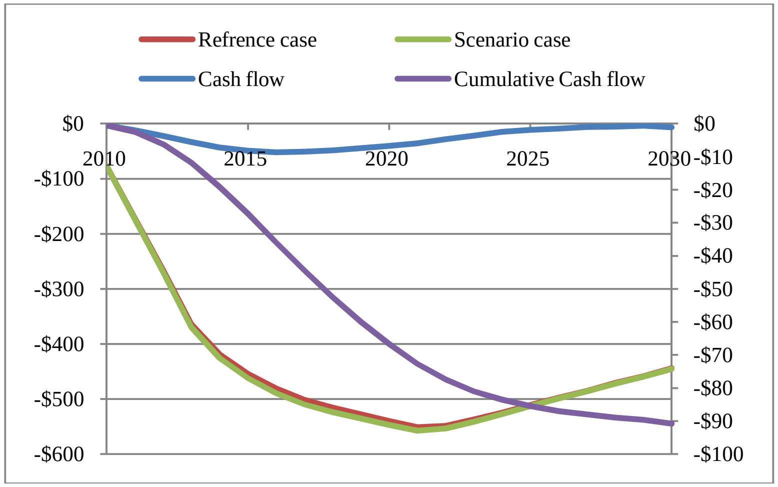

Figure 55. Passenger Car Fleet Cash Flow for Medium HEV & PHEV Scenario, (Reference Case and Scenario Case Left Axis), (In Billions of Dollars))

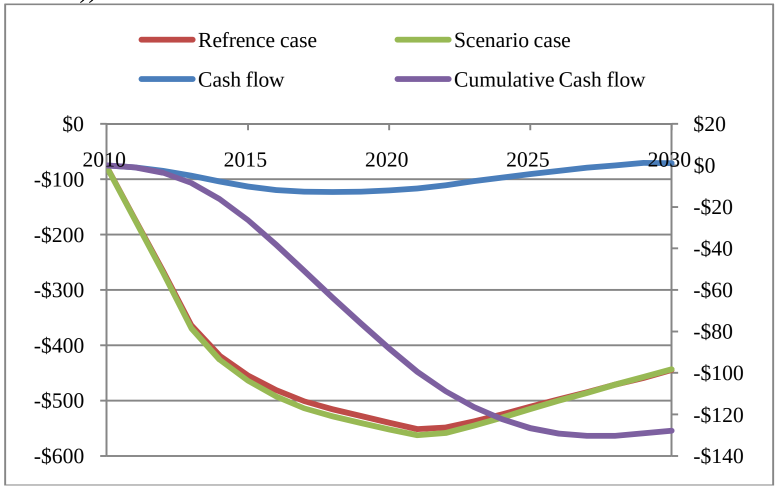

Figure 56. Passenger Car Fleet Cash Flow for High PHEV Scenario, (Reference Case and Scenario Case Left Axis), (In Billions of Dollars))

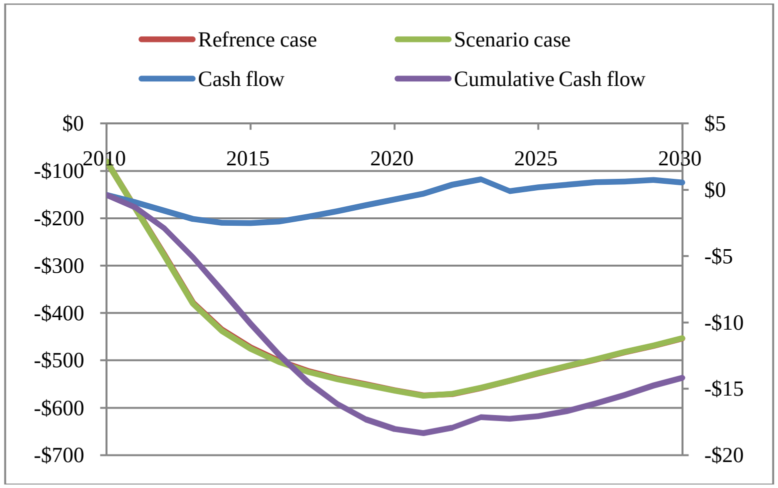

Figure 57. Passenger Car Fleet Cash Flow with Oil Displacement and Emission Costs for Low HEV Scenario, (Reference Case and Scenario Case Left Axis), (In Billions of Dollars)

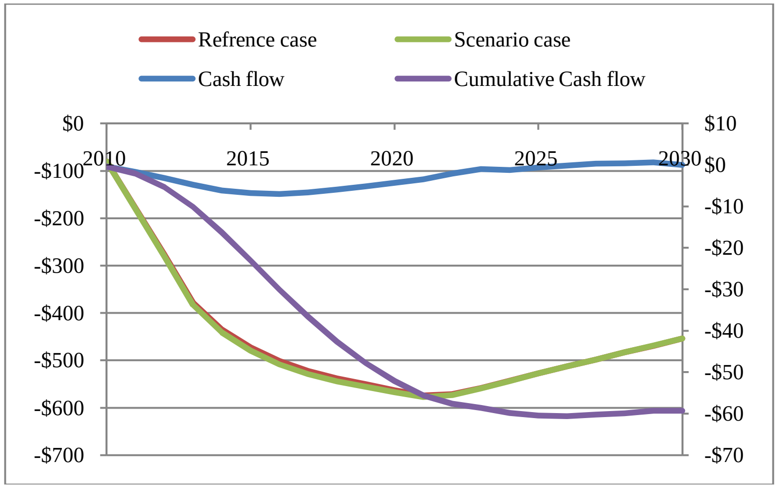

Figure 59. Passenger Car Fleet Cash Flow with Oil Displacement and Emission Costs for Medium HEV & PHEV Scenario, (Reference Case and Scenario Case Left Axis), (In Billions of Dollars)

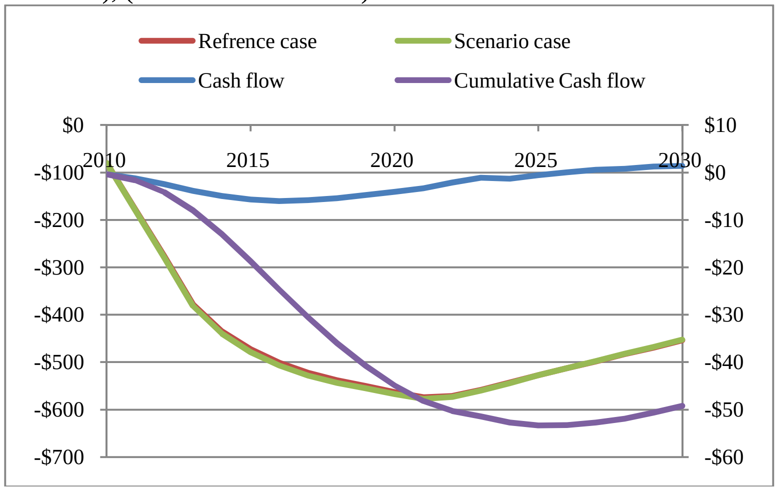

Figure 58. Passenger Car Fleet Cash Flow with Oil Displacement and Emission Costs for High HEV Scenario, (Reference Case and Scenario Case Left Axis), (In Billions of Dollars)

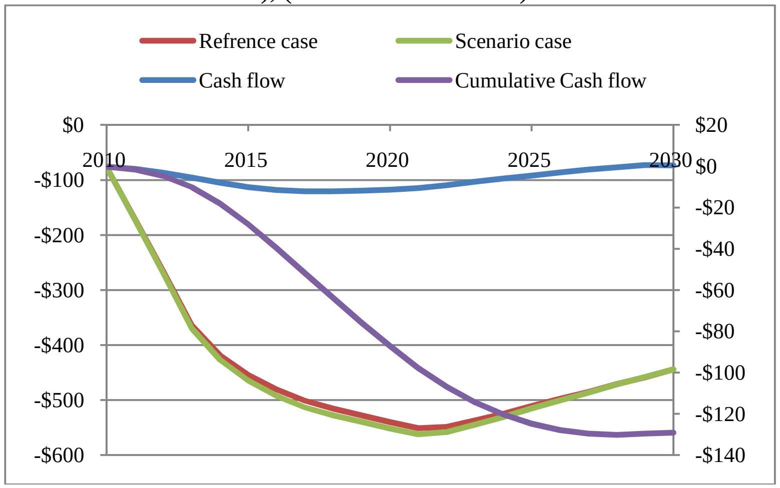

Figure 60. Passenger Car Fleet Cash Flow with Oil Displacement and Emission Costs for High PHEV Scenario, (Reference Case and Scenario Case Left Axis), (In Billions of Dollars)

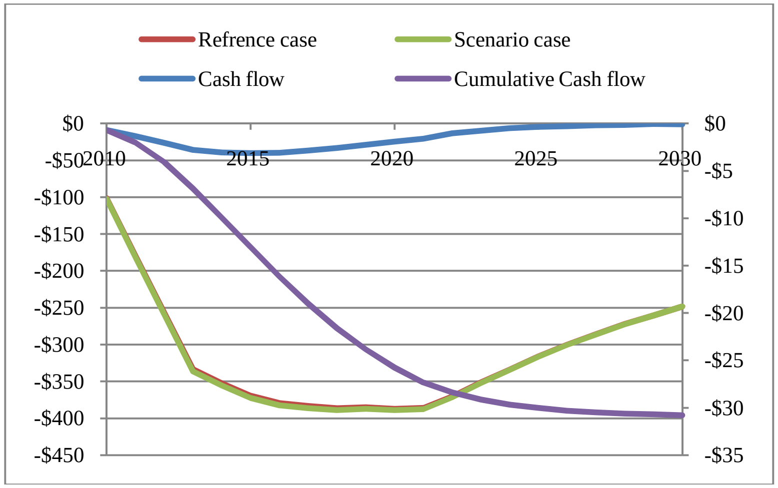

Figure 61. Light Truck Fleet Cash Flow for Low HEV Scenario, (Reference Case and Scenario Case Left Axis), (In Billions of Dollars)

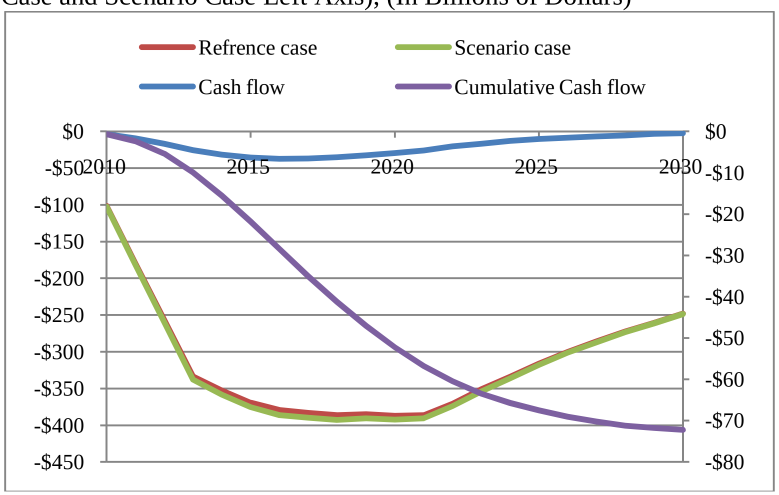

Figure 62. Light Truck Fleet Cash Flow for High HEV Scenario, (Reference Case and Scenario Case Left Axis), (In Billions of Dollars)

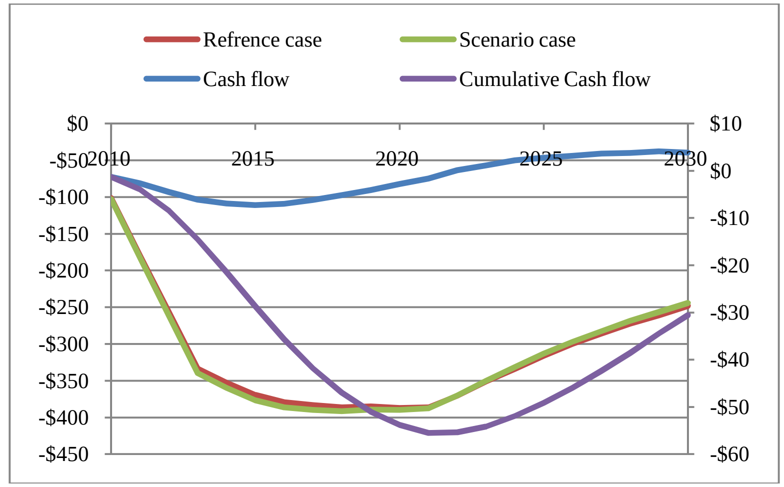

Figure 63. Light Truck Fleet Cash Flow for Medium HEV & PHEV Scenario, (Reference Case and Scenario Case Left Axis), (In Billions of Dollars)

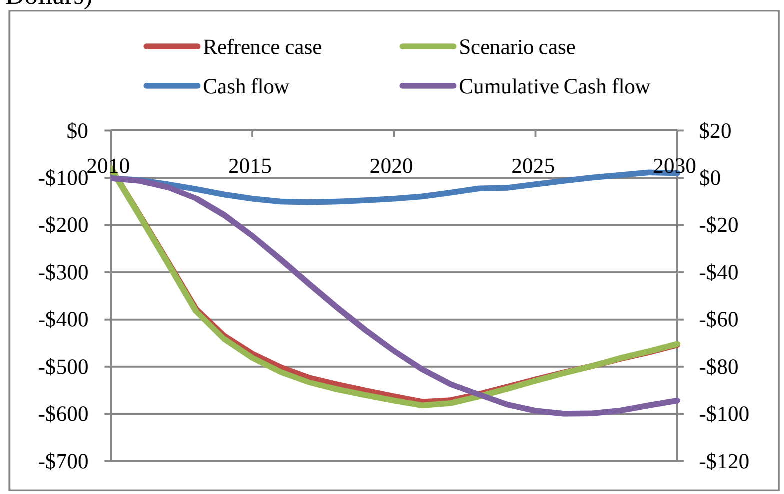

Figure 64. Light Truck Fleet Cash Flow for High PHEV Scenario, (Reference Case and Scenario Case Left Axis), (In Billions of Dollars)

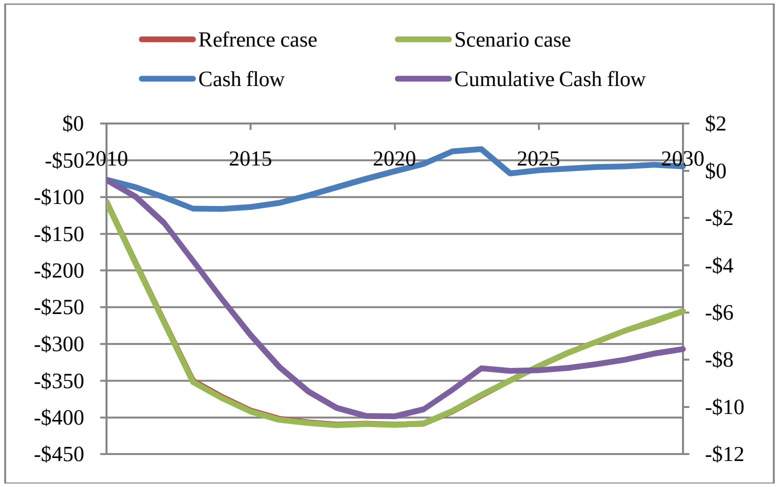

Figure 65. Light Truck Fleet Cash Flow with Oil Displacement and Emission Costs for Low HEV Scenario, (Reference Case and Scenario Case Left Axis), (In Billions of Dollars)

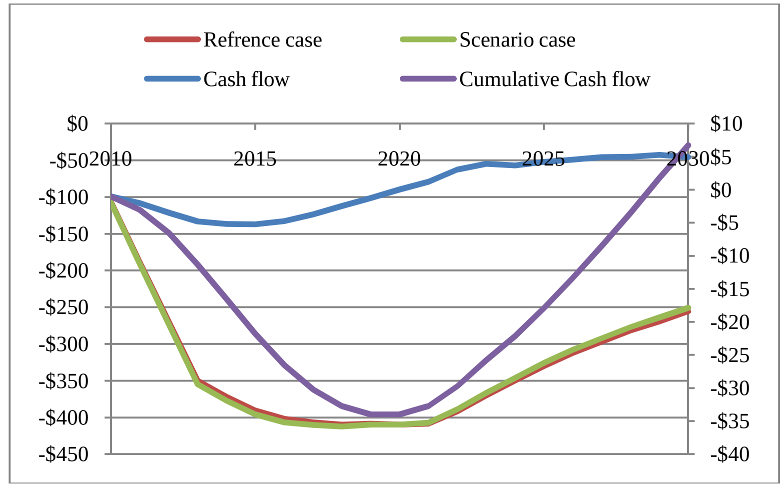

Figure 67. Light Truck Fleet Cash Flow with Oil Displacement and Emission Costs for Medium HEV & PHEV Scenario, (Reference Case and Scenario Case Left Axis), (In Billions of Dollars)

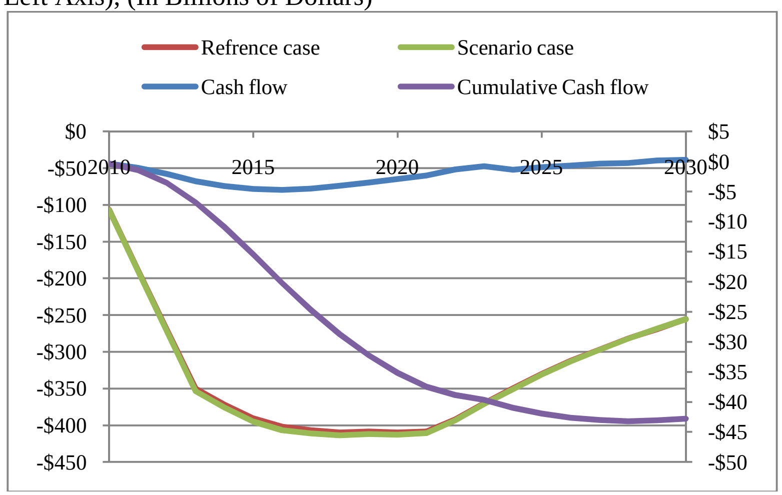

Figure 66. Light Truck Fleet Cash Flow with Oil Displacement and Emission Costs for High HEV Scenario, (Reference Case and Scenario Case Left Axis), (In Billions of Dollars)

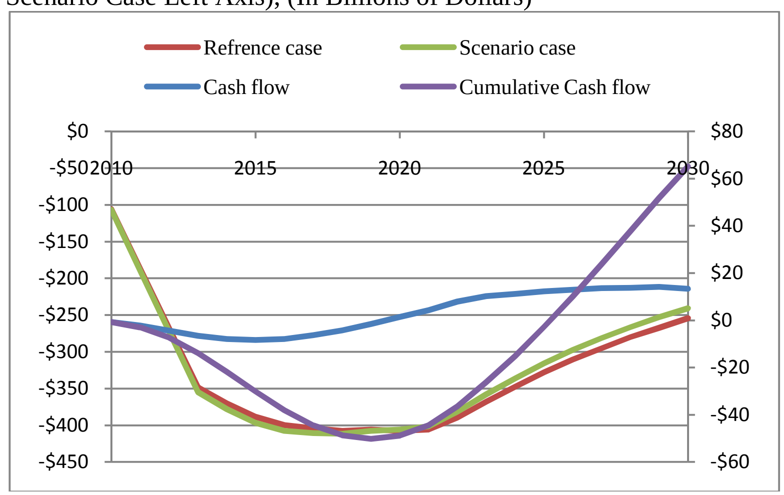

Figure 68. Light Truck Fleet Cash Flow with Oil Displacement and Emission Costs for High PHEV Scenario, (Reference Case and Scenario Case Left Axis), (In Billions of Dollars)

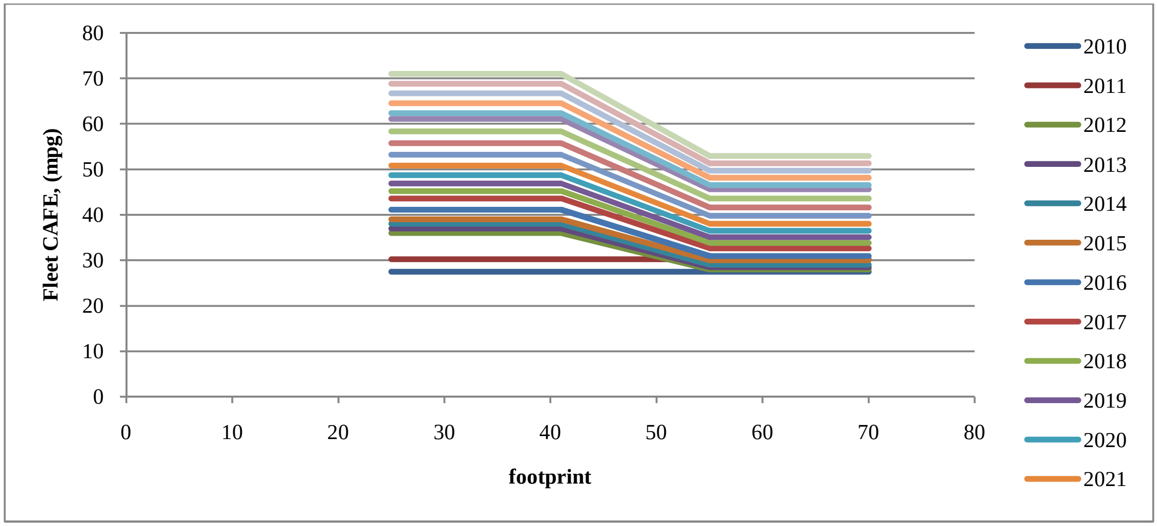

Figure 69. Reported and Forecasted Required Footprint CAFE at the Passenger Car Fleet

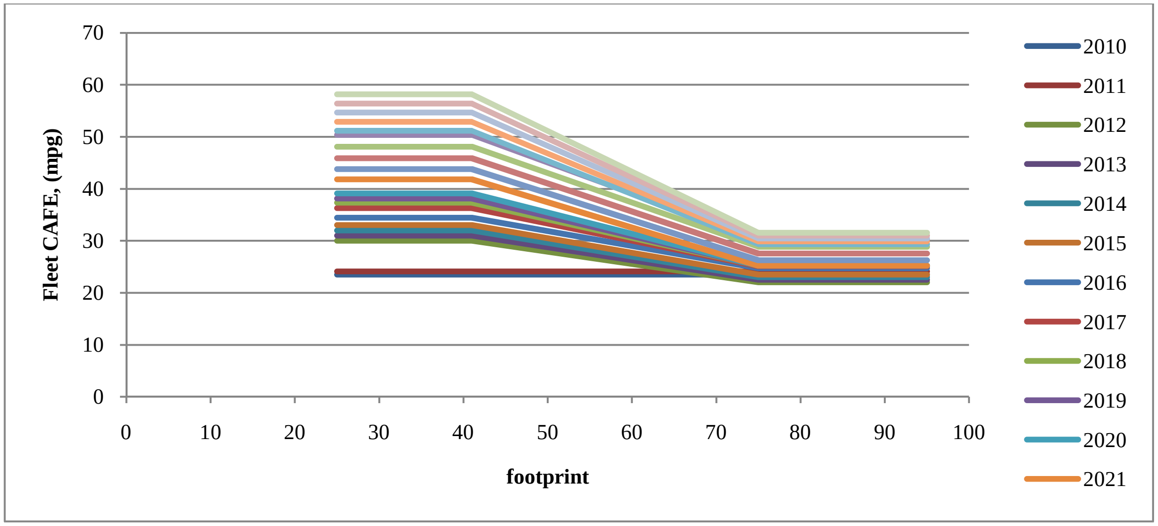

Figure 70. Reported and Forecasted Required Footprint CAFE at the Light Truck Fleet

Table 58. Forecasted Gasoline Price, Electricity Price and Gasoline Tax, with NHTSA Forecasted Fleet sales, Based on NHTSA and EIA Projections, 2009 [2,143]

	Gasoline price, $/gallon	Electricity price, $/kWh	Gasoline tax, 2010$	Passenger Car	Light Truck
2010	$2.73	$0.10	$0.45	5,136,304	5,270,257
2011	$2.85	$0.11	$0.45	7,922,670	5,457,537
2012	$2.86	$0.11	$0.45	9,122,736	5,798,295
2013	$3.02	$0.10	$0.44	9,797,100	6,038,091
2014	$3.11	$0.10	$0.44	10,231,299	5,947,426
2015	$3.19	$0.10	$0.44	10,626,436	5,826,239
2016	$3.23	$0.10	$0.43	10,831,738	5,669,364
2017	$3.31	$0.10	$0.43	10,694,688	5,490,255
2018	$3.35	$0.10	$0.43	10,688,660	5,281,916
2019	$3.39	$0.10	$0.42	10,930,975	5,191,409
2020	$3.43	$0.10	$0.42	11,387,039	5,154,528
2021	$3.44	$0.10	$0.41	11,411,599	5,048,215
2022	$3.51	$0.10	$0.41	11,406,247	4,938,710
2023	$3.52	$0.10	$0.41	11,512,041	4,900,411
2024	$3.58	$0.10	$0.40	11,744,449	4,938,249
2025	$3.60	$0.10	$0.40	11,997,263	4,968,891
2026	$3.62	$0.10	$0.40	12,196,569	4,995,376
2027	$3.67	$0.10	$0.40	12,379,459	5,018,973
2028	$3.69	$0.11	$0.39	12,554,529	5,025,871
2029	$3.74	$0.11	$0.39	12,711,839	5,027,889
2030	$3.70	$0.11	$0.39	12,888,821	5,068,244

Table 59. Technology Incremental Costs in 2010$.

Technology	Subcompact Car	Compact Car	Midsize Car	Large Car	Midsize SUV	Large SUV	Minivan	Large Pickup
CV	$0	$0	$0	$0	$0.00	$0.00	$0.00	$0.00
HEV	$4,051	$4,051	$3,882	$3,882	$5,578.37	$5,636.31	$5,578.37	$5,636.31
PHEV5	$4,661	$4,661	$4,341	$4,341	$6,273.47	$6,099.60	$6,273.47	$6,099.60
PHEV10	$5,270	$5,270	$4,799	$4,799	$6,968.57	$6,562.88	$6,968.57	$6,562.88
PHEV15	$5,880	$5,880	$5,258	$5,258	$7,663.67	$7,026.16	$7,663.67	$7,026.16
PHEV20	$6,489	$6,489	$5,716	$5,716	$8,358.77	$7,489.44	$8,358.77	$7,489.44
PHEV25	$6,995	$6,995	$6,226	$6,226	$8,766.53	$8,078.48	$8,766.53	$8,078.48
PHEV30	$7,500	$7,500	$6,736	$6,736	$9,174.28	$8,667.52	$9,174.28	$8,667.52
PHEV35	$8,006	$8,006	$7,245	$7,245	$9,582.04	$9,256.56	$9,582.04	$9,256.56
PHEV40	$8,511	$8,511	$7,755	$7,755	$9,989.80	$9,845.60	$9,989.80	$9,845.60
PHEV45	$9,017	$9,017	$8,265	$8,265	$10,397.56	$10,434.64	$10,397.56	$10,434.64
PHEV50	$9,522	$9,522	$8,775	$8,775	$10,805.31	$11,023.68	$10,805.31	$11,023.68
PHEV55	$10,028	$10,028	$9,285	$9,285	$11,213.07	$11,612.72	$11,213.07	$11,612.72
PHEV60	$10,533	$10,533	$9,795	$9,795	$11,620.83	$12,201.76	$11,620.83	$12,201.76

Table 60. Calculated CVs MSRPs

EPA Class	Technology	Weighted average MSRP, 2010$
SupCompact Car	CV	$24,011
Compact Cars	CV	$21,840
Midsize Cars	CV	$26,646
Large Car	CV	$30,011
Midsize SUV	CV	$27,101
Large SUV	CV	$38,942
Minivan	CV	$29,197
Large Pickup	CV	$29,699

Table 61. Technology Incremental Cost Decline Rate 2010-2030, (ANL) [102]

Technology	Subcompact Car	Compact Car	Midsize Car	Large Car	Midsize SUV	Large SUV	Minivan	Large Pickup
CV	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
HEV	-0.61%	-0.61%	-0.96%	-0.96%	-1.38%	-1.49%	-1.38%	-1.49%
PHEV5	-0.74%	-0.74%	-1.12%	-1.12%	-1.51%	-1.61%	-1.51%	-1.61%
PHEV10	-0.86%	-0.86%	-1.28%	-1.28%	-1.64%	-1.72%	-1.64%	-1.72%
PHEV15	-0.99%	-0.99%	-1.45%	-1.45%	-1.77%	-1.84%	-1.77%	-1.84%
PHEV20	-1.11%	-1.11%	-1.61%	-1.61%	-1.90%	-1.96%	-1.90%	-1.96%
PHEV25	-1.24%	-1.24%	-1.77%	-1.77%	-2.04%	-2.08%	-2.04%	-2.08%
PHEV30	-1.37%	-1.37%	-1.93%	-1.93%	-2.17%	-2.20%	-2.17%	-2.20%
PHEV35	-1.49%	-1.49%	-2.09%	-2.09%	-2.30%	-2.32%	-2.30%	-2.32%
PHEV40	-1.62%	-1.62%	-2.25%	-2.25%	-2.43%	-2.44%	-2.43%	-2.44%
PHEV45	-1.74%	-1.74%	-2.41%	-2.41%	-2.57%	-2.56%	-2.57%	-2.56%
PHEV50	-1.87%	-1.87%	-2.57%	-2.57%	-2.70%	-2.68%	-2.70%	-2.68%
PHEV55	-1.99%	-1.99%	-2.73%	-2.73%	-2.83%	-2.80%	-2.83%	-2.80%
PHEV60	-2.12%	-2.12%	-2.90%	-2.90%	-2.96%	-2.91%	-2.96%	-2.91%

Table 62. Passenger Car Fleet Fuel Economy Change Rate 2010-2030, (ANL) [102]

	Compact and Subcompact Cars				Mid-size and Large cars			
Year	FCT_u	FCT_h	PCT-u	PCT_h	FCT_u	FCT_h	PCT-u	PCT_h
CV	0.00%	0.00%	0.34%	0.60%	0.00%	0.00%	0.60%	0.31%
HEV	0.00%	0.00%	0.75%	0.67%	0.00%	0.00%	0.67%	0.70%
PHEV5	-0.43%	-0.39%	0.57%	0.55%	-0.61%	-0.87%	1.70%	1.69%
PHEV10	-0.45%	-0.41%	0.63%	0.60%	-0.65%	-0.87%	1.70%	1.69%
PHEV15	-0.46%	-0.43%	0.68%	0.64%	-0.70%	-0.87%	1.70%	1.69%
PHEV20	-0.48%	-0.46%	0.74%	0.69%	-0.75%	-0.87%	1.70%	1.69%
PHEV25	-0.50%	-0.48%	0.80%	0.73%	-0.79%	-0.87%	1.70%	1.69%
PHEV30	-0.52%	-0.50%	0.85%	0.78%	-0.84%	-0.87%	1.70%	1.69%
PHEV35	-0.54%	-0.53%	0.91%	0.82%	-0.88%	-0.87%	1.70%	1.69%
PHEV40	-0.56%	-0.55%	0.97%	0.87%	-0.93%	-0.87%	1.70%	1.69%
PHEV45	-0.57%	-0.57%	1.02%	0.91%	-0.98%	-0.87%	1.70%	1.69%
PHEV50	-0.59%	-0.59%	1.08%	0.96%	-1.02%	-0.87%	1.70%	1.69%
PHEV55	-0.61%	-0.62%	1.14%	1.00%	-1.07%	-0.87%	1.70%	1.69%
PHEV60	-0.63%	-0.64%	1.20%	1.05%	-1.11%	-0.87%	1.70%	1.69%

Table 63. Light Truck Fleet Fuel Economy Change Rate 2010-2030, (ANL) [102]

	Mid-size SUV and Minivan				Large SUV and Pick Up trucks			
Year	FCT_u	FCT_h	PCT-u	PCT_h	FCT_u	FCT_h	PCT-u	PCT_h
CV	0.00%	0.00%	0.46%	0.63%	0.00%	0.00%	0.22%	0.29%
HEV	0.00%	0.00%	0.84%	0.76%	0.00%	0.00%	0.63%	0.50%
PHEV5	-0.59%	-0.42%	1.80%	1.46%	-0.74%	-0.56%	1.58%	1.35%
PHEV10	-0.63%	-0.45%	1.87%	1.53%	-0.75%	-0.57%	1.70%	1.41%
PHEV15	-0.66%	-0.47%	1.94%	1.60%	-0.76%	-0.58%	1.81%	1.47%
PHEV20	-0.70%	-0.50%	2.02%	1.67%	-0.76%	-0.59%	1.92%	1.53%
PHEV25	-0.73%	-0.53%	2.09%	1.74%	-0.77%	-0.59%	2.03%	1.59%
PHEV30	-0.76%	-0.56%	2.16%	1.81%	-0.78%	-0.60%	2.15%	1.65%
PHEV35	-0.80%	-0.59%	2.23%	1.88%	-0.78%	-0.61%	2.26%	1.71%
PHEV40	-0.83%	-0.62%	2.30%	1.95%	-0.79%	-0.62%	2.37%	1.77%
PHEV45	-0.87%	-0.65%	2.38%	2.02%	-0.80%	-0.62%	2.49%	1.83%
PHEV50	-0.90%	-0.68%	2.45%	2.09%	-0.80%	-0.63%	2.60%	1.89%
PHEV55	-0.94%	-0.70%	2.52%	2.16%	-0.81%	-0.64%	2.71%	1.95%
PHEV60	-0.97%	-0.73%	2.59%	2.23%	-0.82%	-0.65%	2.82%	2.01%

Table 64. Vehicles Unadjusted Fuel Economy, (mpg)

Technology	Subcompact Car	Compact Car	Midsize Car	Large Car	Midsize SUV	Large SUV	Minivan	Large Pickup
CV	33.15	33.15	31.58	27.93	27.04	22.12	25.08	19.75
HEV	49.38	49.38	41.94	37.39	33.00	27.59	30.74	24.59
PHEV5	57.42	57.42	48.40	43.26	38.31	32.18	35.80	28.64
PHEV10	66.67	66.67	55.76	49.97	44.32	37.39	41.55	33.25
PHEV15	77.26	77.26	64.09	57.58	51.10	43.29	48.07	38.45
PHEV20	89.33	89.33	73.46	66.18	58.69	49.93	55.38	44.29
PHEV25	101.62	101.62	83.54	75.48	66.61	56.62	63.05	50.18
PHEV30	115.15	115.15	94.64	85.75	75.31	63.96	71.49	56.62
PHEV35	129.95	129.95	106.80	97.03	84.79	71.95	80.72	63.63
PHEV40	146.06	146.06	120.06	109.36	95.08	80.61	90.77	71.22
PHEV45	163.51	163.51	134.44	122.77	106.19	89.95	101.64	79.40
PHEV50	182.32	182.32	149.98	137.29	118.13	99.98	113.36	88.17
PHEV55	202.52	202.52	166.70	152.93	130.91	110.69	125.92	97.54
PHEV60	224.13	224.13	184.62	169.72	144.55	122.10	139.34	107.51

Appendix D- Multi-Criteria Decision Support System and Negotiation Process System

The objective of this study is to provide a tool for understanding the tradeoffs among various vehicle technologies, and vehicle technologies penetration scenarios of HEVs and PHEVs for the North American market. This tool will enable the qualitative and quantitative comparison of the benefits and costs of design alternatives to inform decision makers (DMs). This section starts with literature review of decision support systems (DSS) and negotiation support systems (NSS). Then two DSS methods are used to investigate the preferred PHEV design and PHEV penetration scenario through the development of decision support environment.

Previous studies have developed many decision support systems and negotiation support systems but few have tested the impact of the decision support system with negotiation process on the outcomes. The negotiation process involves two or more decision makers with a conflict-of-interest. Negotiation support systems use different approaches including model-driven, data drive and communication driven. Negotiation support system will assist DMs by providing them with a modeled communication process integrated into the decision making process. A feedback loop between the DMs and the DSS is established in a way that the final result needs to satisfy each DM. Several prior studies have considered the negotiation support system to be an area within the DSS. Consumers, automakers and policy makers should be able to choose a vehicle among different vehicle technologies based on different criteria. Each DM should interact and negotiate to arrive at the preferred vehicle technology alternative.

Kersten and Lo (2001) [147] describe the steps of the Negotiation Support Systems (NSS) to be:

- Help and advice negotiators

- Structure and analyze the problem
- Elicit preferences to be used for constructing a utility function
- Find feasible and efficient alternatives
- Visualize different aspects of the problem and the process
- Facilitate communication

Schoop (2004) state that there are three different approaches in the NSS: automation-oriented for finding an economic best solution; communication-oriented to support the communication processes; and document-oriented for document exchange management [148]. There is a need to combine the automation-oriented and communication-oriented approaches with the document-oriented approach in the decision support to achieve the goal of electronic negotiation support than enables complex negotiation. Arnott and Pervan (2005) describe that the negotiation support systems as a subfield of the decision support system [149]. Power (2007) argues "Negotiation Support Systems is not a new subfield related to decision support [150]. There has been a Negotiation Support Systems mini track at the Hawaii International Conference on System Sciences (HICSS) since 1991. Articles on this type of system began appearing in the literature in 1986." Arnott and Provan (2005) divided the negotiation system into problem-oriented and process-oriented [149]. The problem-oriented phase was mainly focused on providing support to a specific problem type such as Co-Op and MEDIATOR. The process - oriented system provided a support of the give-and-take process of negotiation.

Matsatsinis and Delias (2004) defined a multi-criteria prototype negotiation protocol that allowed agents to follow a process toward finding an optimal decision [151]. The model found a convenient solution based on agents estimated preferences. One advantage of the methodology was implementation through the internet [151]. Oliveira et al., (2008) introduced a multi-issue negotiation protocol for one-buyer-to-many-sellers interactions [152]. The study included an illustration of the negotiation process that showed the usefulness as a product and market brokering tool [152]. Goeltner (1987) developed a prototype systems whereby a computer acted as a third party in the negotiation process between two parties in a single or multi-issue case [153]. The study developed two computer programs, ONDINE I, dealing with two parties Single-Issue Negotiation where optimization was not possible. ONDINE II dealt with two party Multi-Issue Negotiations [153].

Lai et al., (2004) reviewed the existing research on Multi-attribute Negotiation in the field of Economics and Artificial Intelligence [154]. The motivation and difficulties of multi-attributes negotiations were examined where only two parties multiple issues were considered. Turban et al., (2011) described the use of collaboration 2.0 software to improve the process and tasks in virtual group decision making [155]. A fit-viability model was used to find if the social software fit a decision task and to determine what important organizational factors were needed to make it an effective tool. Utomo et al., (2009) study developed a model of agreement options on negotiation support for civil engineering decision [156]. An analytical hierarchy process (AHP) approach was created with three level of decision hierarchy. One advantage of the AHP approach was to assist decision makers evaluate and rank alternatives in advance prior to the negotiation process. In et al., (2001) found the requirements for negotiation to be very critical [157]. A multi-criteria preference analysis requirements negotiation model was presented that assisted agents in the evaluation, negotiation and agreement process.

Bellucci et al., (2008) developed a system that used empirical evidence to dynamically modify the initial preferences during the negotiation process [158]. The system used trade-offs and compensation to allocate issues. Bui and Sebastian (2010) based their model on the Pareto concepts that maximize the social utility function [159]. An optimization technique based on a mixed integer linear programming (MILP) model was combined with a negotiation approach using multi-attribute utility functions using a hybrid and iterative method [159]. Espinasse et al., (1997) developed a negotiation support system that is based on a multi-criteria conceptual framework of the negotiation and development [160]. Wang et al., (2011) used a game theory approach to develop a quantitative methodology to support negotiations over the allocation of costs and benefits of brownfield redevelopment projects [161]. In. and Olson (2004) proposed a "Multi-Criteria Preference Analysis Requirements Negotiation (MPARN)." [162] The step-by-step process in the MPARN model resulted in unbiased aspects for the stakeholders through cooperation and trust. Jaramillo et al., (2005) presented multi-objective decision support systems with a negotiation process that helped decision makers reach a satisfactory solution [163]. The model solved a problem where conflict of interest's existed between decision makers. The model allowed the DMs to propose their preferred alternatives and then for that set of alternatives to define the region for each criterion to be negotiated. The model proposed a balanced solution and if the DMs were not satisfied with it they would adjust their preferences and the process continue when the DMs agreed on the proposed alternative [163].

Multi-Criteria Decision Support System Methods and Results

This section presents the methods, models and results of applying multi-criteria decision support systems (MCDSSs) methods to find the preferred vehicle technology and scenario of vehicles technology options. Two MCDSSs used were PROMOTHEE and Compromise Programming methods. Methods were chosen because of simplicity, clearness and the ability to integrate criteria weighting.

The objective of this study is to create a decision support system (DSS) that allows decision makers (DM) to evaluate different vehicle technology alternatives and scenarios. The stakeholders groups of this MCDSS are:

a) Fuel manufacturers

b) Fuel distributers

c) Vehicle manufacturers (including material and parts)

d) Vehicle distributers (including maintenance and repairs)

e) Customers for vehicles and fuel

f) Government at all levels whose cognizance covers environmental, safety, zoning and other aspects of new technologies including promoting their development

Each stakeholder has need, goals and constraints. The main stakeholders in this system are consumers, automakers, and policymakers. Some of the goals and need for the main stakeholders are:

Consumers:

- The decision to purchase a technology (CV, HEV or PHEV)
- Purchase and ownership costs
- Weighting or prioritizing local emissions or global warming

Manufacturer:

- The decision to invest in PHEV
- The decision to adopt or support PHEV
- How many vehicles to make
- What PHEV design to make
- What PHEV class to make

Policymakers:

- CAFE and GHG emission standards
- Required Energy
- Use of renewable energy
- Imported oil dependency
- Improving oil security

PROMOTHEE Method

PROMOTHEE method is an outranking method that performs a pairwise comparison of each alternative in each single criterion in order evaluates and calculates the strength of preference of each alternative over other alternatives. In PROMOTHEE method it is required to provide weights for each criteria and to specify the preference function when comparing criterion contribution [164].

In this analysis the two types of PROMETHEE tools used are PROMETHEE I partial ranking, and PROMETHEE II complete ranking. PROMETHEE I provides a ranking of alternatives by comparing each alternative to other alternatives but in some cases some alternatives cannot be compared and the ranking will be incomplete. PROMETHEE II provides a complete ranking of the alternatives from the best to the worst one. It compares each alternative to others and other alternatives to it in which calculates each alternative rank and outrank with relative to other alternatives. In the PROMOTHEE method the preference function (P_j) assigns a score from 0 to 1 based on the difference between the evaluations of two alternatives for the chosen criterion. In this analysis only two preference functions were chosen; U-shape function and V-shape function as in Figure 1 and Figure 2. The U-shaped is applied where there is a strict preference between two alternatives where the V-shaped is applied where there is increasing preference between two alternatives. The preference function has two elements called threshold. Indifference threshold (*q*) represents the largest difference in the decision criterion between the two alternatives and strict preference threshold (*p*).

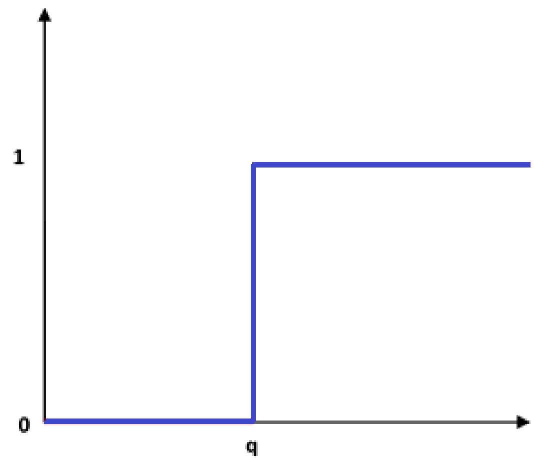

Figure 71. U-shape Preference Function

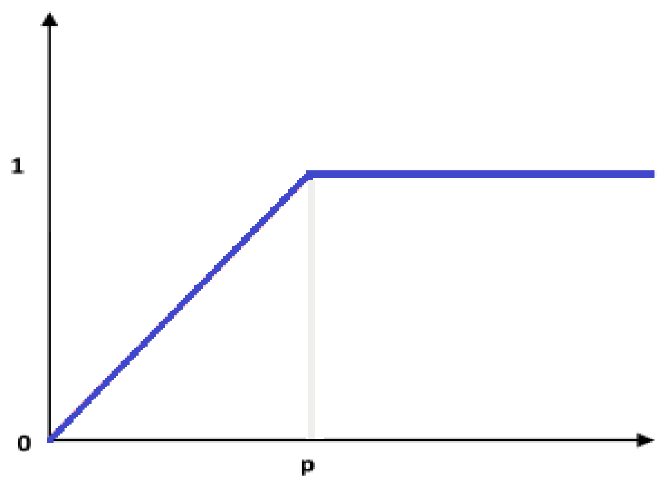

Figure 72. V-shape Preference Function

The intensity of preference between *a* and *b* actions is represented as:

$P_j(a, b) = 0$ an indifference between *a* and *b*, or no preference of *a* over *b*;

$P_j(a, b) \sim 0$ weak preference of *a* over *b*

$P_j(a, b) \sim 1$ strong preference of *a* over *b*

$P_j(a, b) = 1$ strict preference of *a* over *b*

Where this preference function is a function of the difference between the two evaluations:

$$P_j(a, b) = P_j(f(a) - f(b))$$

Then the computation of the multi-criteria preference index and ranking value for each alternative *a* and *b*:

$$\pi_r(a,b)= \sum_{j=1}^{k} P_j(a,b)w_{r,j},$$

$w_{r,j}$: criteria weight

Finally the evaluation of each alternative A will be by using the outranking relation

Leaving flow $\varphi^+(a)=\Sigma_{b \epsilon A}\, \pi_r(a,b),$

Entering flow $\varphi^-(a)=\Sigma_{b \epsilon A}\, \pi_r(b,a),$

Net flow $\varphi(a)= \varphi^+(a)- \varphi^-(a)$

Compromise Programming Method

Some of the multicriteria decision support systems are goal programming (GP), multiobjective programming (MOP) and compromise programming (CP). Compromise programming was preferred over goal programming because it does not requires the specification of DM's target value and weights for each variable deviation which are not easily determined. It is preferred over multiobjective programming because it does not require a lot of computations [165]. Compromise Programming (CP) optimizes objective subjects to a set of constraints by seeking a solution that is as close as possible to the ideal point [166]. It was first introduced by Zeleny (1973). The equation for the compromise programming is:

$$L_j = \left[\sum_{z=1}^{t} \left\{ w_z^p \left(\frac{f_z^* - f_z}{f_z^* - f_z^-} \right)^p \right\} \right]^{\frac{1}{p}}$$

Where

Z	1,2,3…t and represents t criteria or objectives;
J	1,2,3…n and represents n alternatives;
L_j	distance metric of alternative j;
w_z	corresponds to a weight of a particular criteria or objective;
p	parameter (p = 1,2,inf)
f_z^* *and* f_z^-	best and the worst value for criteria z, respectively
f_z	actual value of criterion z.

Decision Support System at Vehicle Level Model

In this multi-criteria decision support system analysis we have investigated a set of vehicle technology and a vehicle technology scenario that might leads to PHEV market success. Two decision support system models were developed, one at vehicle technology level and another at set of vehicles scenario level.

Vehicle level Model Components

Vehicle class:

- Compact Car
- Mid-size Car
- Mid-size SUV
- Large SUV

Alternatives (Vehicle Technology):

- CV, gasoline
- CV diesel
- HEV
- PHEV 5-60
- EV

Criteria Used in the DSS model:

Consumer:

- MSRP
- Performance
- Fuel Economy
- Driving Range
- Safety
- Lack of refueling Infrastructure
- GHG emission, (tons)
- Pay back

- New Technology
- Lifetime Cost, 13 years
- Gasoline price

Automaker:

- Cost of Technology
- Marginal cost of technology to charge consumer
- Impact of technology on the brand
- Expertise required to bring technology
- CO2 emissions
- CAFE

Policymaker:

- Oil dependency
- Use of Clean Energy
- GHG emission
- Fuel prices effect
- Infrastructure Cost or need

DSS Methods:

- PROMOTHEE I
- PROMOTHEE II
- Compromise Programming

DSS Model I/O:

Model Inputs:

1. Criteria weights and thresholds
2. Inputs for each scenario

Model Outputs:

1. Preferred technology for each DMs
2. Preferred technology for a combination of or all DMs
3. Final DM's preferred alternative ranking

This multi-criteria decision support system model uses PROMETHEE I & II outranking method to rank alternatives based on each decision makers and choice the preferred alternative for each decision maker inputs and for all decision makers inputs. Then a Compromise Programming method is used to rank the preferred alternative chosen for each decision maker.

The model could be used by consumers, automakers or policy makers. Based on each decision makers preference towered each criteria the model will give the preferred vehicle technology within each vehicle class.

Instruction:

1) The threshold levels for each criterion within each vehicle class can be changed
2) Each decision maker will adjust the weights (between 0-10) for each criterion on the main model window for each vehicle class

3) The results will be presented for each decision maker but results could be presented for individual or combination of decision maker's inputs by choosing the decision maker type.

4) Adjust the weights of each criteria to have a value between 0-10

5) The result will be presented in the graph and table

6) The results in the table will show the preferred alternative in each vehicle class for PROMETHEE I and II method

7) Compromise Programming method will rank each preferred alternative chosen by PROMOTHEE II method for each DM.

Note:

Phi + : PROMETHEE I, partial preorder

Phi: PROMETHEE II, net outranking flow where all actions are compared

PROMETHEE I & II Methods Results

Main Model Decision Maker Control	
Consumer	YES
Automaker	YES
Policymaker	YES

		Main Model	
		PROMETHEE I	PROMETHEE II
Phi+	Phi	Preferred Technology	Preferred Technology
684.00	309.70	EV	PHEV40
684.00	322.19	EV	PHEV40
701.32	374.67	EV	PHEV40
698.00	371.77	EV	PHEV40

Figure 73. Main Model Decision Maker Type Control and Associated Results

			DM1 Consumer	
			PROMETHEE I	PROMETHEE II
	Phi+	Phi	Preferred Technology	Preferred Technology
Compact Car	345.20	196.39	PHEV20	PHEV20
Mid-size Car	295.97	156.38	PHEV20	PHEV20
Mid-size SUV	331.65	165.67	PHEV60	PHEV40
Large Car	309.28	162.77	PHEV50	PHEV40

			DM2 Automaker	
			PROMETHEE I	PROMETHEE II
	Phi+	Phi	Preferred Technology	Preferred Technology
Compact Car	211.00	76.00	EV	EV
Mid-size Car	211.00	76.00	EV	EV
Mid-size SUV	211.00	76.00	EV	EV
Large Car	211.00	81.00	EV	PHEV30

			DM3 Policymaker	
			PROMETHEE I	PROMETHEE II
	Phi+	Phi	Preferred Technology	Preferred Technology
Compact Car	216.00	171.00	PHEV50	PHEV50
Mid-size Car	216.00	171.00	PHEV50	PHEV50
Mid-size SUV	216.00	171.00	PHEV50	PHEV50
Large Car	216.00	171.00	PHEV50	PHEV50

Figure 74. Results for Each Decision Maker

Compromise Programming Method Results

Note that Compromise Programming method was used to rank the preferred alternative technologies chosen by each decision maker using PROMOTHEE II methods.

	Compromise Programming	
	L1	L2
Compact Car	PHEV50	PHEV50
Mid-size Car	PHEV50	PHEV50
Mid-size SUV	PHEV40	PHEV50
Large Car	PHEV40	PHEV40

Compact Car Alternative	L1 Rank	L2 Rank
PHEV20	3	2
EV	2	3
PHEV50	1	1

Mid-Size Car Alternative	L1 Rank	L2 Rank
PHEV20	3	3
EV	2	2
PHEV50	1	1

Mid-Size SUV Alternative	L1 Rank	L2 Rank
PHEV40	1	2
EV	3	3
PHEV50	2	1

Large Car Alternative	L1 Rank	L2 Rank
PHEV40	1	1
PHEV30	3	3
PHEV50	2	2

Figure 75. Ranking PROMETHEE II Results for Each Decision Maker Using Compromise Programming Method

Alternative		Consumer										
		MSRP	Performance	Fuel Ecanomy	Driving Range	Safety	Lack of refueling Infrastructure	GHG emission, ton	Pay back	New Technology	Lifetime Cost, 13 years	Gasoline price
	Criterion	f1	f2	f3	f4	f5	f6	f7	f8	f9	f10	f11
	min or max	min	max	max	max	max	min	min	min	max	min	min
CV(G)	a1	$14,587	5	32.2	2	5	1	2.19	0	1	$45,392	5
CV(D)	a2	$24,000	5	35	2	4	2	2	18	1	$47,000	5
HEV	a3	$18,639	4	42	2	5	1	1.69	21	3	$46,292	4
PHEV5	a4	$19,248	4	48	2	4	3	1.65	14.53	5	$45,710	4
PHEV10	a5	$19,858	3	56	3	4	3	1.62	13.02	5	$45,398	3
PHEV15	a6	$20,467	3	64	3	4	2	1.59	**11.7**	5	$45,174	2
PHEV20	a7	$21,076	3	74	3	4	2	1.56	11.75	5	$45,161	2
PHEV25	a8	$21,582	2	84	3	4	2	1.56	12.07	5	$45,249	2
PHEV30	a9	$22,087	2	95	4	3	2	1.55	13	5	$45,389	2
PHEV35	a10	$22,593	2	107	4	3	2	1.55	13.3	5	$45,515	2
PHEV40	a11	$23,098	2	119	4	3	2	1.55	13.92	5	$45,792	1
PHEV45	a12	$23,604	1	133	4	3	2	1.55	15	5	$46,090	1
PHEV50	a13	$24,109	1	148	5	2	2	1.54	16	5	$46,452	1
PHEV55	a14	$24,615	1	164	5	2	2	1.54	17.6	5	$46,849	1
PHEV60	a15	$25,120	1	181	5	2	2	1.54	19.1	5	$47,266	1
EV	a16	$36,000	1	200	1	1	5	1.20	35	5	$60,000	1
	Criterion Type	III	II	III	II	II	II	III	III	II	III	II
	p	500	1	5	1	1	1	0.05	1	1	500	2
Parameters		5	5	8	5	5	5	6	4	5	7	8
	Weight	5	5	8	5	5	5	6	4	5	7	8

Alternative		Automaker						Policymaker				
		Cost of Technology	Marginal cost of technology to charge consumer	Impact of technology on the brand	Experties required to bring technology	CO2	CAFÉ	Oil dependency	Use of Clean Energy	GHG emission	Fuel prices effect	Infrastructure Cost or need
	Criterion	f12	f13	f14	f15	f16	f17	f18	f19	f20	f21	f22
	min or max	min	min	max	min	min	max	min	max	min	min	min
CV(G)	a1	0	1	1	1	2.19	1	5	1	5	5	1
CV(D)	a2	0	1	2	1	2	1	4	1	5	5	1
HEV	a3	$4,051	2	3	3	1.69	2	3	2	3	4	1
PHEV5	a4	$4,661	2	3	4	1.65	2	2	2	3	4	2
PHEV10	a5	$5,270	2	3	4	1.62	3	2	2	3	3	2
PHEV15	a6	$5,880	3	4	4	1.59	3	2	3	2	3	2
PHEV20	a7	$6,489	3	4	4	1.56	3	2	3	2	2	3
PHEV25	a8	$6,995	3	4	4	1.56	4	2	3	2	2	3
PHEV30	a9	$7,500	3	5	4	1.55	4	2	3	2	2	3
PHEV35	a10	$8,006	4	5	4	1.55	4	2	4	1	2	4
PHEV40	a11	$8,511	4	5	4	1.55	5	1	4	1	1	4
PHEV45	a12	$9,017	4	5	4	1.55	5	1	4	1	1	4
PHEV50	a13	$9,522	4	5	4	1.54	5	1	5	1	1	5
PHEV55	a14	$10,028	5	5	5	1.54	5	1	5	1	1	5
PHEV60	a15	$10,533	5	5	5	1.54	5	1	5	1	1	5
EV	a16	$14,000	5	5	5	1.20	5	1	5	1	1	5
	Criterion Type	II	II	II	II	II	II	II	II	II	II	II
	p	500	1	1	1	0.2	1	1	1	0.2	1	1
Parameters		5	5	7	5	8	8	8	8	8	8	5
	Weight	5	5	7	5	8	8	8	8	8	8	5

Figure 76. Criterion Value, Threshold and Method in the Compact Car Class for Each Decision Maker Over Vehicle Technology

Compact Car

Consumer		MSRP	Performance	Fuel Ecanomy	Driving Range	Safety	Lack of refueling	GHG, 13 years	Pay back	New Technology	Lifetime Cost, 13	Gasoline price
	p	500	1	5	1	1	1	0.05	1	1	500	2
		5	5	8	5	5	5	6	4	5	7	8
	Weight											

Automakeres		Cost of Technology	Marginal cost of technology to	Impact of technology on	Experties required to	CO2	CAFÉ
	p	500	1	1	1	0.2	1
		5	5	7	5	8	8
	Weight						

Policy Makers		Oil dependency	Use of Clean Energy	GHG emission	Fuel prices effect	Infrastructure Cost or need
	p	1	1	0.2	1	1
		8	8	8	8	5
	Weight					

Figure 77. Criterion Weight in the Compact Car Class for Each Decision Maker at the Main I/O GUI

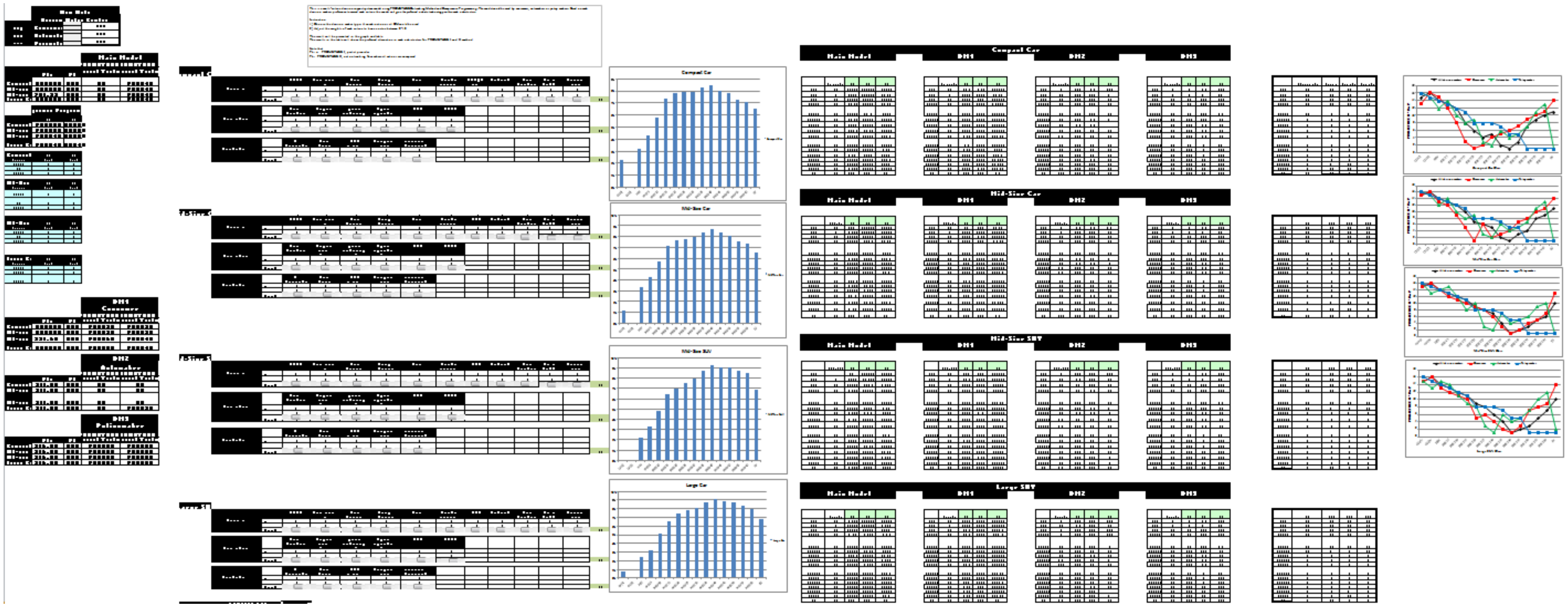

Figure 78. Screenshot of Part of the DSS Main I/O GUI

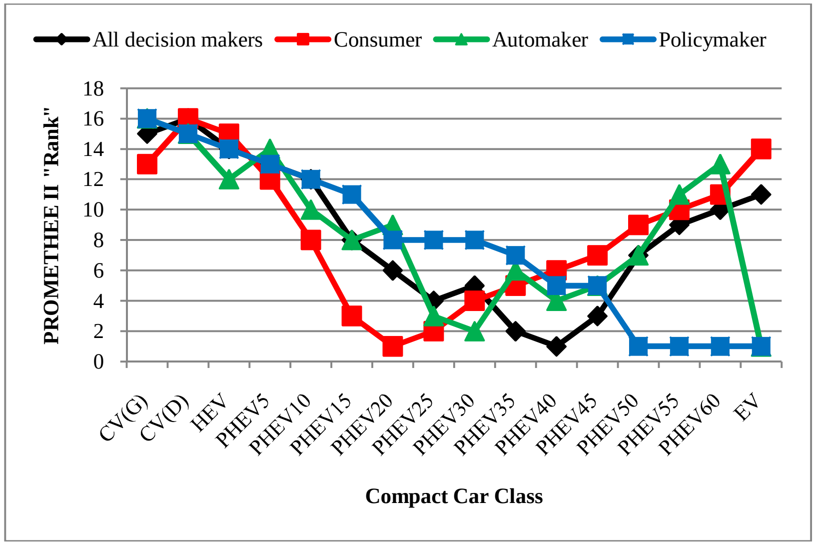

Figure 79. Compact Car Class Technology Ranking

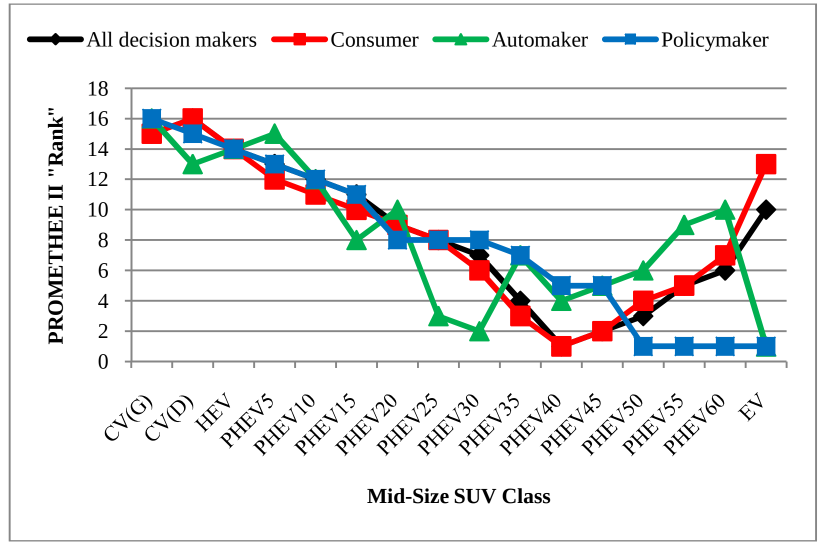

Figure 81. Mid-Size SUV Class Technology Ranking

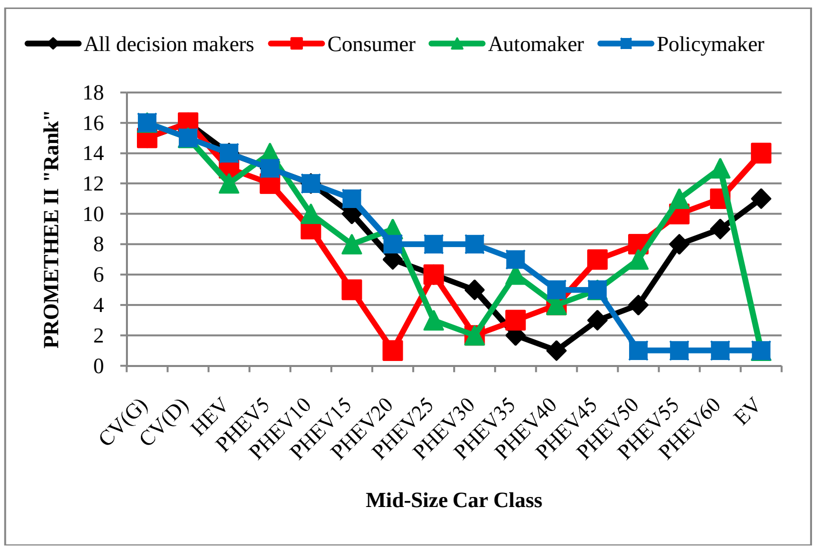

Figure 80. Mid-Size Car Class Technology Ranking

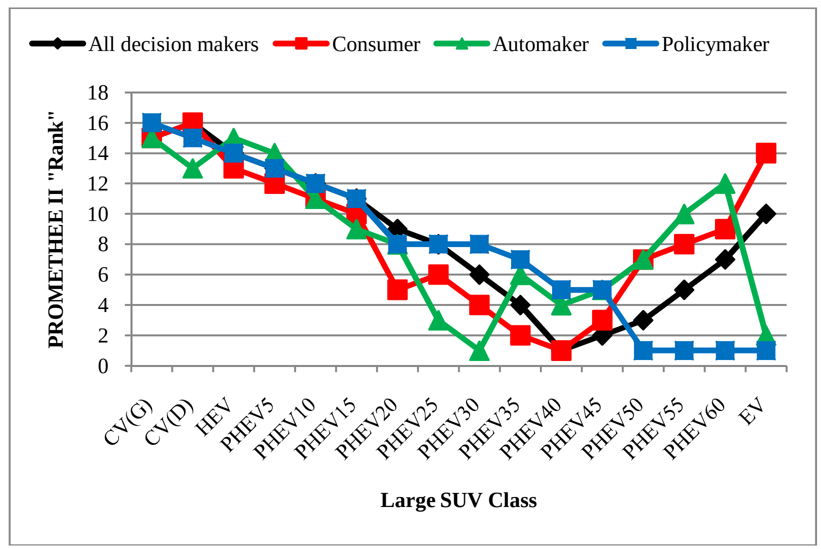

Figure 82. Large SUV Class Technology Ranking

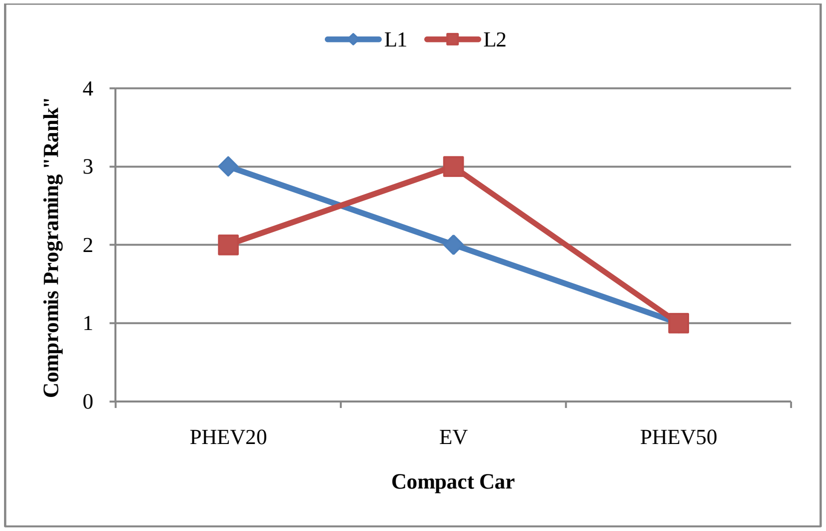

Figure 83. Ranking Preferred Compact Car Class Technology

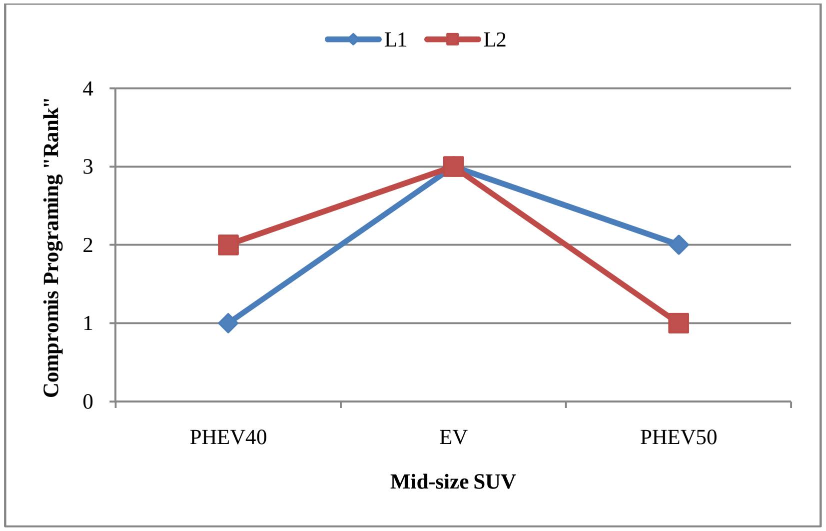

Figure 85. Ranking Preferred Mid-Size SUV Class Technology

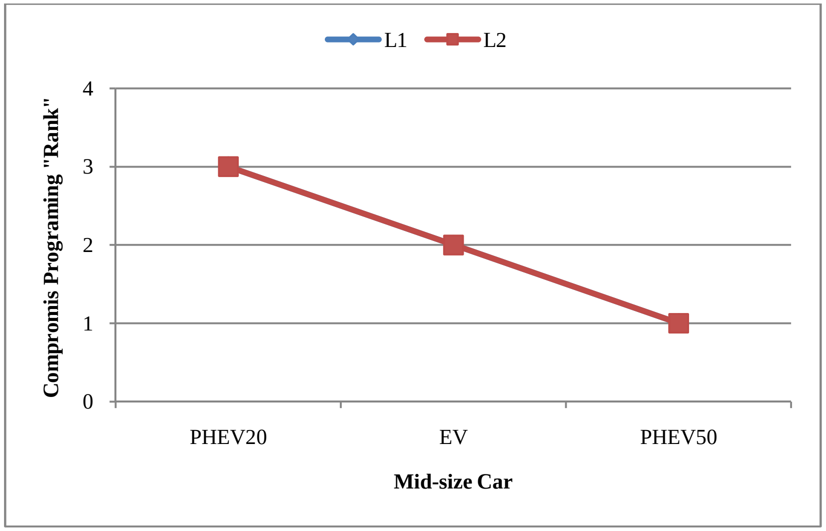

Figure 84. Ranking Preferred Mid-Size Car class technology

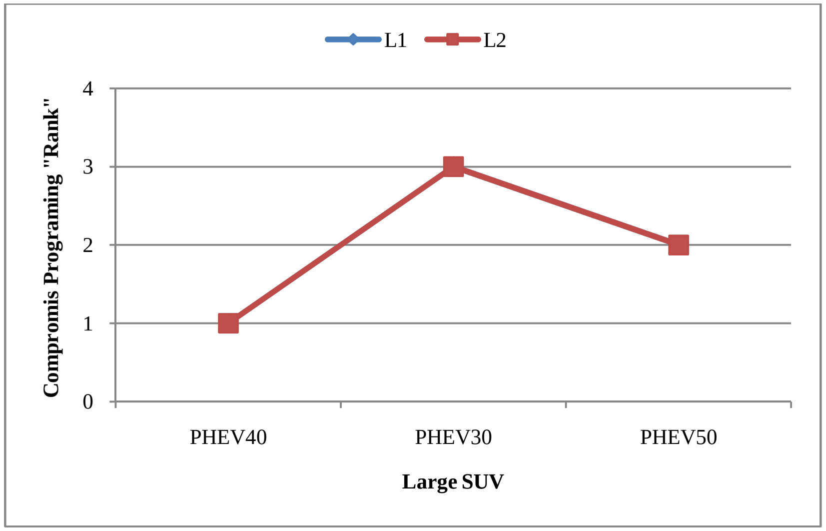

Figure 86. Ranking Preferred Large SUV Class Technology

Vehicle Level Decision Support System Conclusions

- Policymakers are pulled towered more electrified vehicle technology seeking for high fuel economy and lower GHG emissions
- Consumers are resistance to long rang PHEVs and EVs due to their high MSRP costs, and longer payback period
- Automakers are in between, they are seeking high technology vehicle to meet the CAFE and air emissions standards but sensitive towered new technology initiation and costs

Scenario Level Decision Support System Model

In this section the decision support system models are used to rank nine different scenarios from the multi-criteria modeling system. The nine scenarios results and technology penetrations used are shown in Table 65 and Figure 87to Figure 95.

Table 65. Multi-Criteria Modeling System Scenario Results Used in the Decision Support System

		(millions of gallons)	(millions kWh)	(Millions 2010$)	(Billions 2010$)	millions (ton)						
Scenario	CAFE, (mpg)	Gasoline reduction	Electricity usage	Technology Incremental Cost	Cumulative Cash flow	GHG	CO	NO_x	PM_{10}	$PM_{2.5}$	VOC	SO_2
Reference Case	-346.11	0	0	0	0	5,566	54.29	1.09	0.50	0.29	47.26	0.02
Low HEV	-299.90	35,713	0	$129,308	$33	5,277	54.25	1.08	0.54	0.31	51.32	0.15
High HEV	-226.40	77,886	0	$289,083	$83	4,938	54.18	1.08	0.59	0.33	56.69	0.33
Mid	-172.49	97,576	388,978	$287,225	$91	5,043	49.25	1.46	1.09	0.53	101.40	1.54
High PHEV	-9.28	142,361	898,758	$358,257	$129	5,470	46.16	2.21	2.02	0.89	162.79	3.68
Scenario 5	1.37	153,227	774,594	$403,631	$102	4,837	43.94	1.80	1.61	0.72	137.55	2.77
Scenario 6	2.84	155,279	777,749	$408,053	$94	4,814	43.82	1.79	1.60	0.71	132.17	2.75
Scenario 7	1.09	154,278	822,030	$406,058	$129	4,877	43.57	1.87	1.69	0.77	154.27	3.00
Scenario 8	1.51	153,759	816,944	$403,832	$120	4,872	43.61	1.86	1.67	0.76	149.89	2.96
Scenario 9	2.40	154,248	867,126	$401,911	$140	4,915	43.11	1.93	1.76	0.80	164.51	3.18

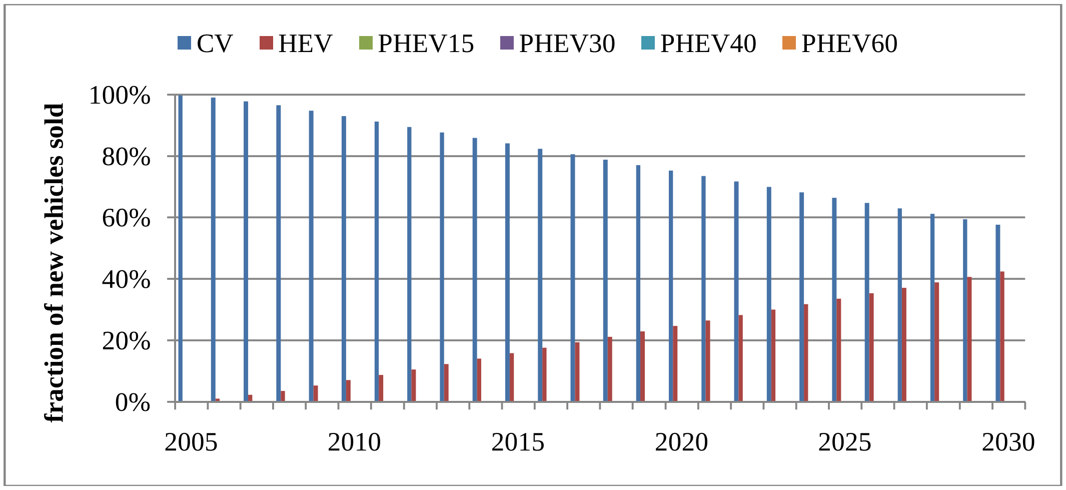

Figure 87. Low HEV Scenario Penetration Rate Share in the Passenger Car Fleet.

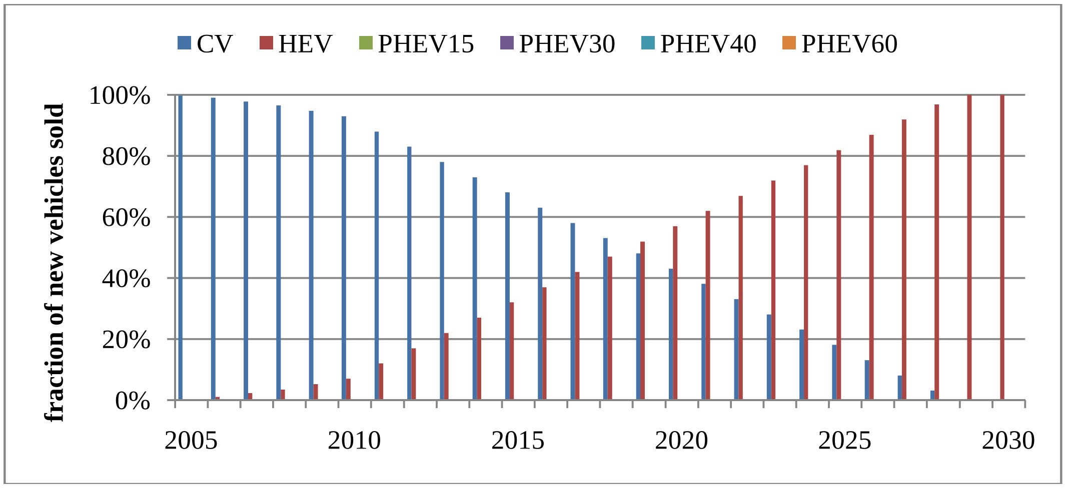

Figure 88. High HEV Scenario Penetration Rate Share in the Passenger Car Fleet.

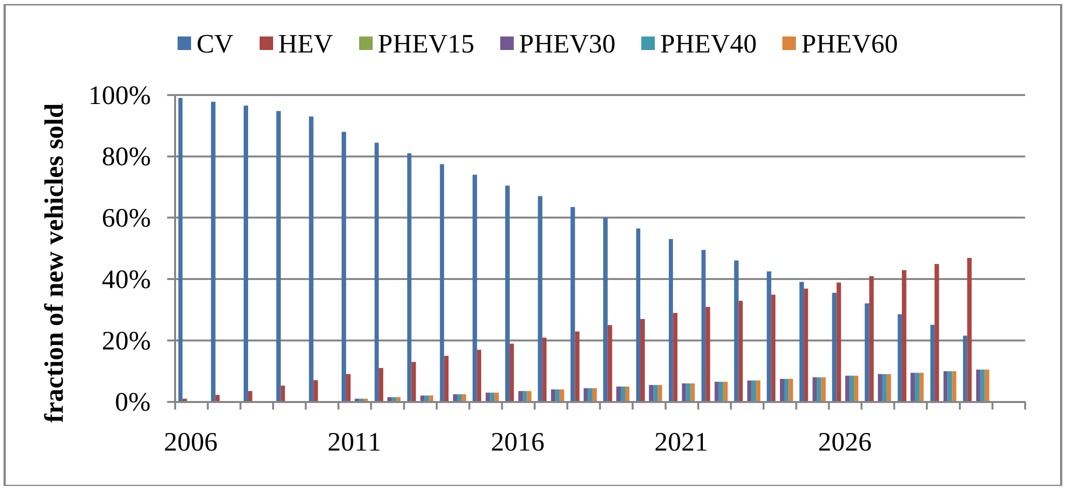

Figure 89. Medium HEV/PHEV Scenario Penetration Rate Share in the Passenger Car Fleet.

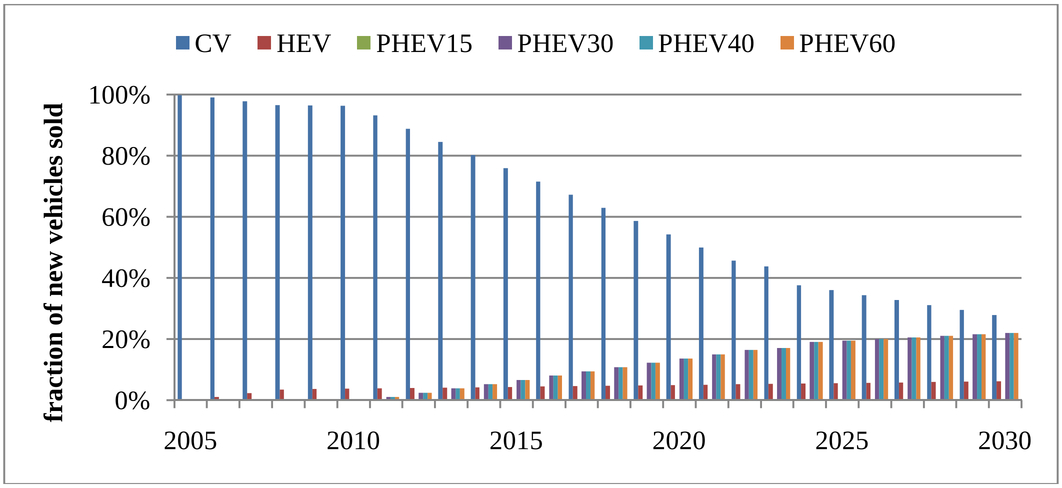

Figure 90. High PHEV Scenario Penetration Rate Share in the Passenger Car Fleet.

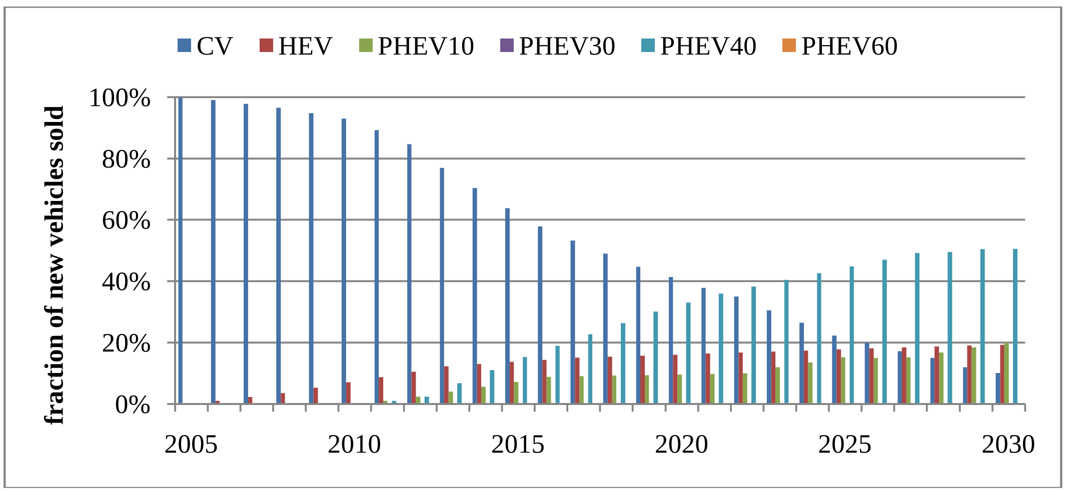

Figure 91. Scenario 5 Penetration Rate Share in the Passenger Car Fleet.

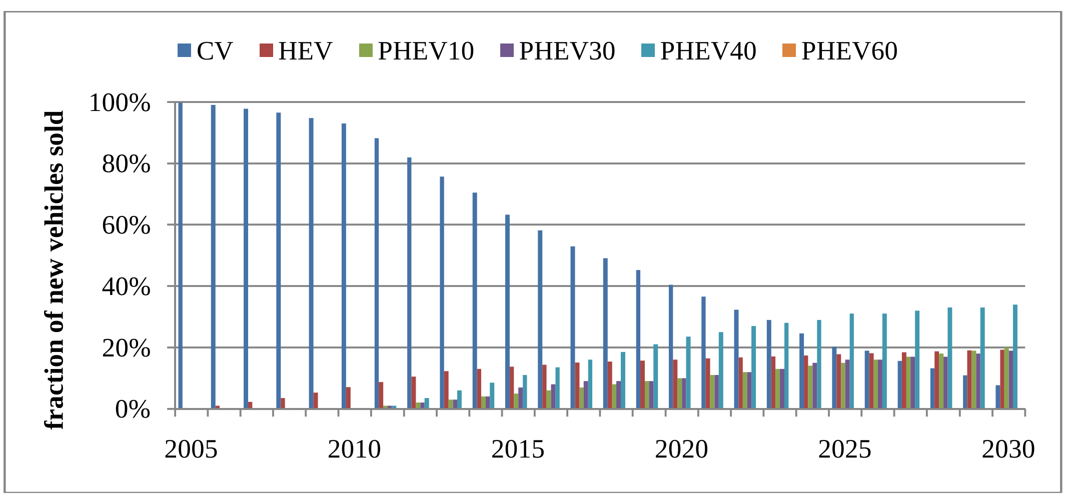

Figure 92. Scenario 6 Penetration Rate Share in the Passenger Car Fleet.

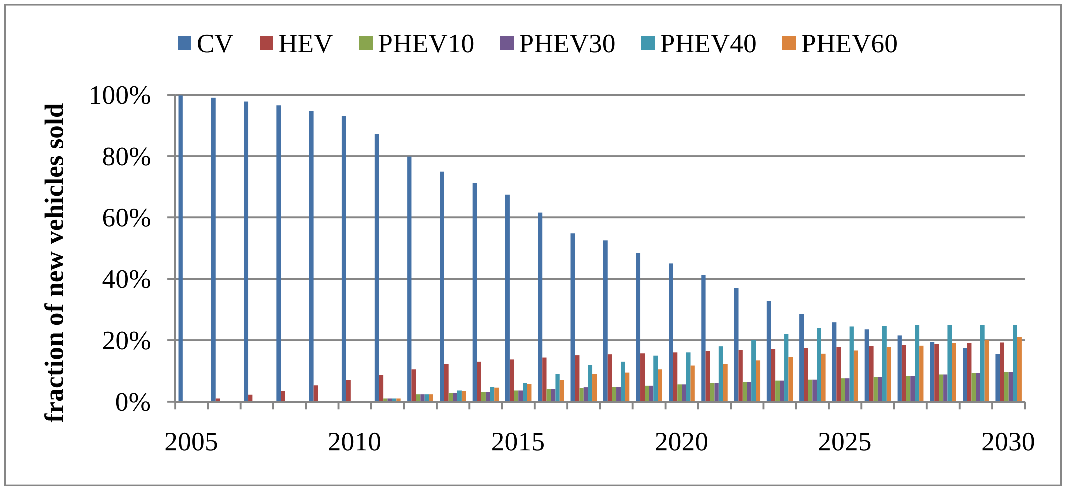

Figure 93. Scenario 7 Penetration Rate Share in the Passenger Car Fleet.

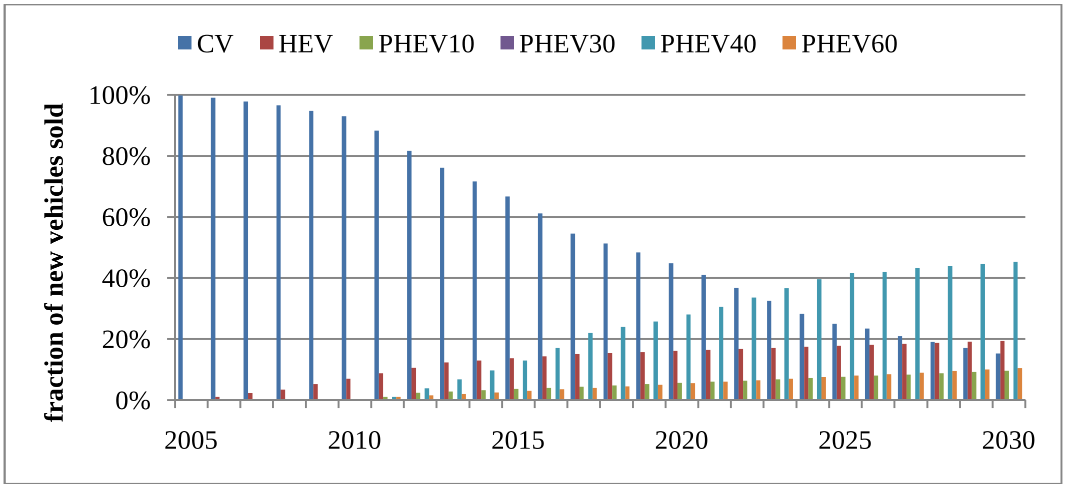

Figure 94. Scenario 8 Penetration Rate share in the Passenger Car Fleet.

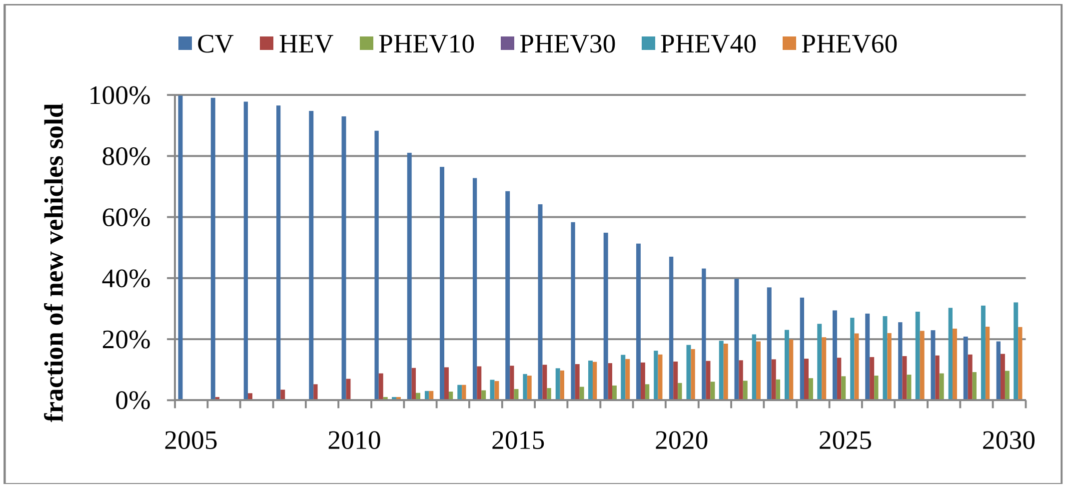

Figure 95. Scenario 9 Penetration Rate Share in the Passenger Car Fleet.

In this section we first present the modeling and results of PROMOTHEE methods and then that of the Compromise Programming method. For each method weight, model components and results for each decision maker are presented.

PROMOTHEE Method Results

Table 66. Compromise Programming Weighs (w_1- w_4) for Each Decision Maker (DMi)

	DM1	DM2	DM3	DM4
Criteria	w_i	w_i	w_i	w_i
Electricity usage (millions kWh)	2	5	10	1
CAFE, different to required	10	5	8	4
Gasoline reduction (millions of gallons)	10	5	10	4
Total Technology Incremental Cost (Millions 2010$)	4	10	5	1
Cumulative Cash flow (Billions 2010$)	4	10	5	1
GHG	10	5	5	10
CO	10	5	6	9
NO_x	5	5	5	8
PM_{10}	3	5	3	8
$PM_{2.5}$	4	5	4	8
VOC	4	5	5	8
SO_2	4	5	4	8
Total weight	70	70	70	70

Table 67. PROMOTHE Method Model Components

Criteria	Criterion Type	*p, q*
Electricity usage (millions kWh)	III	3000
CAFE, different to required	II	0.001
Gasoline reduction (millions of gallons)	III	1000
Total Technology Incremental Cost (Millions 2010$)	II	500
Cumulative Cash flow (Billions 2010$)	III	2
GHG	III	2
CO	III	0.2
NO_x	II	0.05
PM_{10}	II	0.03
$PM_{2.5}$	II	0.05
VOC	II	4
SO_2	II	0.05

Table 68. Preferred Scenario for Each Decision Maker Chosen by PROMOTHEE I & II Methods

			Main Model	
			PROMETHEE I	**PROMETHEE II**
	Phi+	**Phi**	**Preferred Technology**	**Preferred Technology**
DM1	**423.73**	**241.73**	**Scenario 6**	**Scenario 6**
DM2	**420.00**	**246.09**	**Reference Case**	**Reference Case**
DM3	**384.44**	**161.44**	**Scenario 6**	**Scenario 6**
DM4	**372.15**	**158.15**	**Scenario 6**	**Scenario 6**

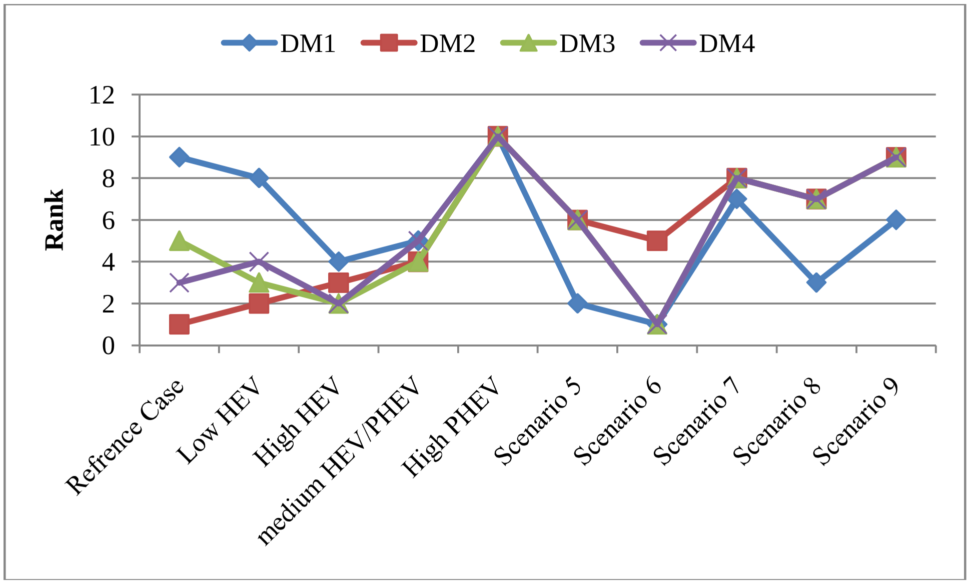

Figure 96. Ranking of Alternative for Each Decision Maker in PROMOTHEE I Method

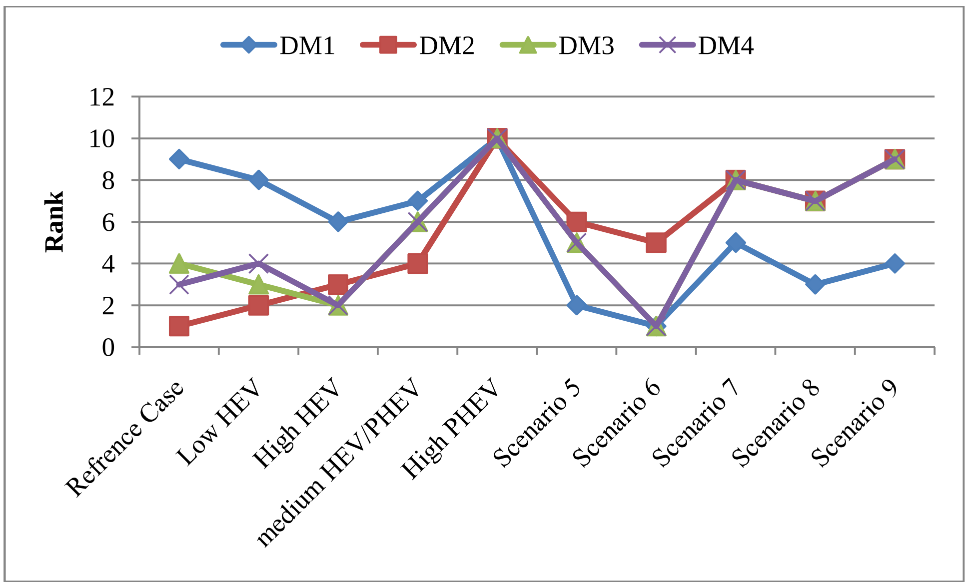

Figure 97. Ranking of Alternative for Each Decision Maker in PROMOTHEE II Method

Compromise Programming Method Results

Table 69. Compromise Programming Weighs (w_1- w_3) for Each Decision Maker (DMi)

	DM1	DM2	DM3
Criteria	w_i	w_i	w_i
Electricity usage (millions kWh)	0.05	0.05	0.01
CAFE, different to required	0.15	0.15	0.2
Gasoline reduction (millions of gallons)	0.15	0.15	0.19
Total Technology Incremental Cost (Millions 2010$)	0.1	0.05	0.05
Cumulative Cash flow (Billions 2010$)	0.1	0.05	0.05
GHG	0.1	0.2	0.15
CO	0.1	0.1	0.1
NO_x	0.05	0.05	0.05
PM_{10}	0.05	0.05	0.05
$PM_{2.5}$	0.05	0.05	0.05
VOC	0.05	0.05	0.05
SO_2	0.05	0.05	0.05
Total weight	1	1	1

Table 70. Preferred Alternative Scenario, (Rank 1)

	s=1	s=2	s=3
DM1	High HEV	Scenario 6	Scenario 6
DM2	High HEV	Scenario 6	Scenario 6
DM3	Scenario 6	Scenario 6	Scenario 6

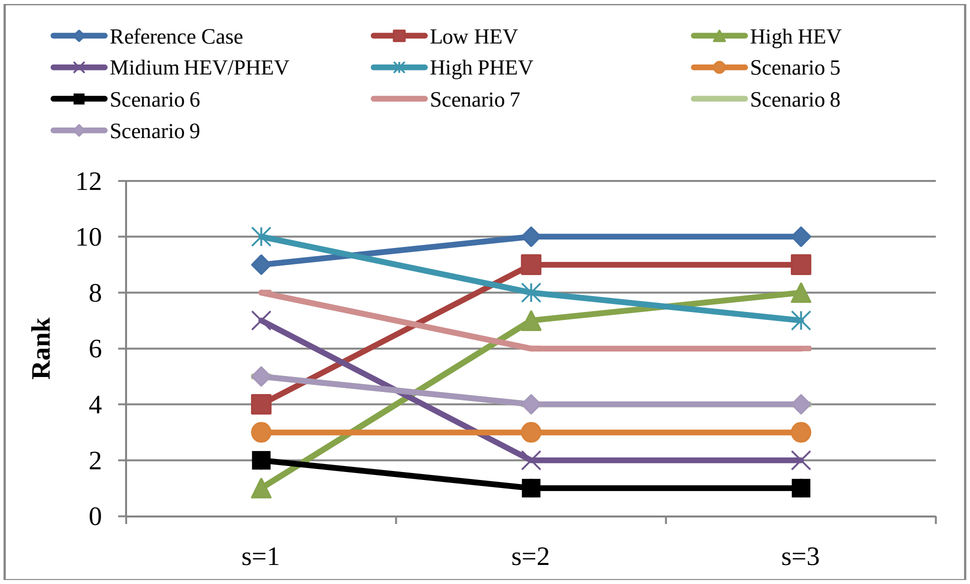

Figure 98. Alternative Scenario Ranking for Decision Maker 1 (DM1)

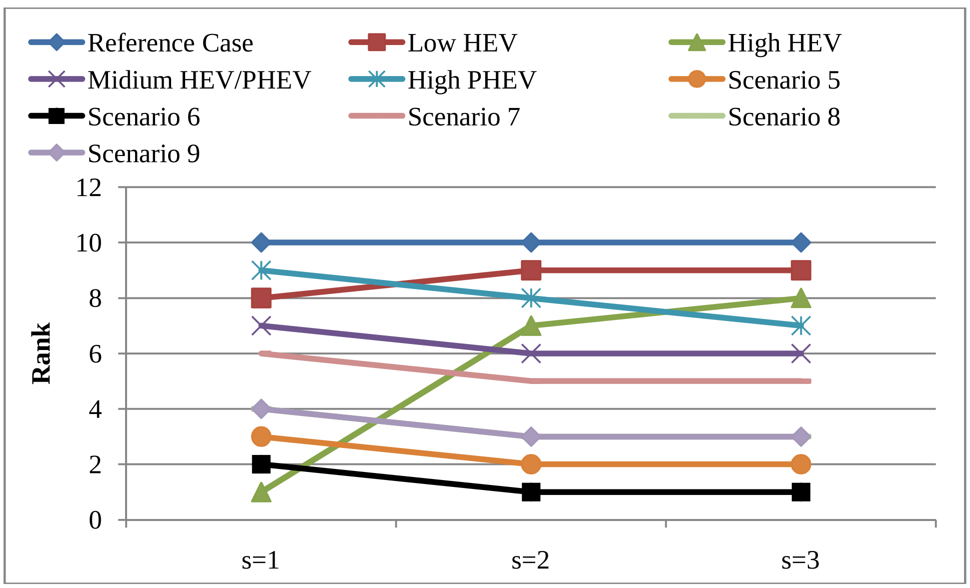

Figure 99. Alternative Scenario Ranking for Decision Maker 2 (DM2)

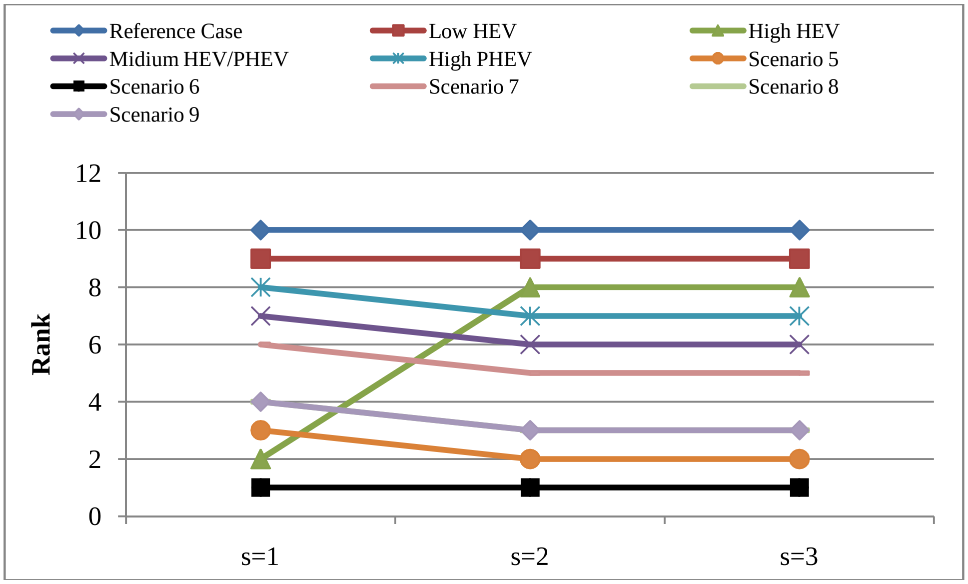

Figure 100. Alternative Scenario Ranking for Decision Maker 3 (DM3)

Scenario Level Decision Support System Conclusions

In this DSS the main DMs were policymakers and automakers who are categorized as low cost technology seekers or high fuel economy and low emission vehicle technology seekers. The preferred technology scenario for DMs in the first case was do nothing (reference case) scenario, but the preferred technology scenario for DMs with interests on high fuel economy and low emission vehicles was scenario 6.