

**ASSESSING POLICIES FOR REDUCING GREENHOUSE
GAS EMISSIONS FROM PASSENGER VEHICLES**

by

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RESEARCH PROJECT SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF RESOURCE MANAGEMENT

In the
School of Resource and Environmental Management
of Simon Fraser University

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SIMON FRASER UNIVERSITY

Fall 2007

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ABSTRACT

Passenger vehicles are a large and growing source of greenhouse gas (GHG) emissions. Policies aimed at inducing technological change in vehicles will likely contribute to curbing emissions. A hybrid energy-economy model of the passenger vehicle sector was built to evaluate policies in reducing emissions, and in particular, increasing the adoption of zero-emission vehicles (ZEVs). The model is technologically explicit, behaviourally realistic and incorporates drivers of technological change. It was applied to California to assess a tax on GHG emissions, a standard mandating ZEV adoption, a ZEV purchase subsidy and a research and development subsidy for ZEVs. Combinations of these policies were also examined. A standard combined with a tax was found to most cost-effectively reduce emissions and increase ZEV diffusion. The purchase subsidy was least cost-effective. More moderate emission reductions can be achieved with diffusion of ultra low-emission vehicles, but deep reductions will likely require adoption of zero-emission vehicles.

Keywords: technological change; zero-emission vehicles; hybrid model; climate change policy; transportation model; uncertainty

Subject Terms: Transportation, Automotive -- Environmental aspects; Technological innovations -- Environmental aspects; Climatic changes -- Government policy; Climatic changes -- Economic aspects; Environmental policy -- Economic aspects; Climatic changes -- Mathematical models

ACKNOWLEDGEMENTS

I would like to thank Mark Jaccard for providing both vision and inspiration in my beginning and completing this project. I valued Mark's leadership and enthusiasm throughout this project. Nic Rivers offered assistance throughout this research on many levels. I thank Nic for his exceptional input as well as his endless encouragement. I thank all the members of the Energy and Materials Research Group, particularly Jotham Peters for sharing his extensive knowledge of economic costing, as well as Jonn Axsen, Bill Tubbs, Steve Groves and Katherine Muncaster for their valued input and support. I also appreciate the insight Hadi Dowlatabadi provided at the beginning of this project.

I thank the National Science and Engineering Research Council of Canada, the British Columbia Automobile Association, and the Canadian Institute of Energy for funding support.

Lastly, I thank Ian Bruce and my family for their encouragement and support throughout the completion of this project.

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ABBREVIATIONS

AEEI	Autonomous Energy Efficiency Index
BAU	Business as usual
BEV	Battery electric vehicle
BPHEV	Biofuel plug-in hybrid electric vehicle
CARB	California Air Resources Board
CO ₂	Carbon dioxide
CO ₂ e	Carbon dioxide equivalent
ESUB	Elasticities of Substitution
GHG	Greenhouse gas
GJ	Gigajoule
HEV	Hybrid-electric vehicle
HFCV	Hydrogen fuel cell vehicle
IPCC	Intergovernmental Panel on Climate Change
Mt	Megatonnes
R&D	Research and development
SUV	Sport utility vehicle
ULEV	Ultra-low emission vehicle
VMT	Vehicle-miles-travelled
ZEV	Zero-emission vehicle

CHAPTER 1: INTRODUCTION AND BACKGROUND

There is a near consensus among climate experts that anthropogenic greenhouse gas emissions will have to be significantly constrained to stabilize their concentrations in the atmosphere and thus prevent “dangerous interference” with the climate system. New technology is often cited as a way to reconcile conflicts between the need to reduce emissions and economic well-being. There is a particular interest for assessing how various policies can stimulate the innovation and adoption of low or zero greenhouse gas emitting technologies.

Light duty vehicles are a large and growing source of greenhouse gas emissions in many jurisdictions.¹ Several new technologies hold promise for eliminating the greenhouse gas emissions of cars and trucks. These so-called zero-emission technologies are at an early stage in their development and diffusion, and policies to support their innovation, demonstration and adoption may be warranted. However, there continues to be debate surrounding which policy instruments would be best suited for this task.

In this study, I analyzed several policies under a dual goal of reducing greenhouse gas emissions and promoting the innovation and adoption of zero-emission vehicles. For this analysis, I built a model of the passenger-vehicle transportation sector. The model characterizes how consumers make decisions when purchasing a vehicle. Key features of the process of technological development and adoption were included in the model. As a

¹ Light duty vehicles are generally characterized as passenger vehicles. In the U.S. they are defined as vehicles weighing less than 8,500 lbs (Environmental Protection Agency [EPA], 2006a). In this study I use light duty vehicles and passenger vehicles interchangeably.

case study, I applied this model to California, comparing how various policies perform based on this dual goal in California over the mid to long-term.

In the following chapter, I introduce a number of topics that are significant to this study. First, I examine the connections between technology and environmental policy and introduce various types of policy (Section 1.1). Second, I analyze trends in the light duty vehicle sector and discuss why investigating policy to reduce emissions and stimulate the innovation and adoption of new technologies in this sector is particularly relevant (Section 1.2). Third, I identify a number of policies that are pertinent to the light duty vehicle sector and summarize previous policy analyses targeted at this sector. This informs the selection of policies which I assessed (Section 1.3). Fourth, I detail the scenario under which selected policies were compared and describe why California provides a good case study for this analysis (Section 1.4). Finally, I briefly discuss a number of considerations in modelling the passenger vehicle sector (Section 1.5). I conclude by summarizing and outlining my research objectives (Section 1.6).

1.1 Technological Change and Environmental Policy

1.1.1 Technological Change, the Environment and the Potential for Policy

Addressing climate change will require substantial efforts over a long timescale to stabilize greenhouse gas emissions at what is considered an acceptable or “safe” level (International Panel on Climate Change [IPCC], 2007). New technologies and processes hold promise for resolving the inherent conflict between economic prosperity and our desire for a stable climate system (Jaffe & Stavins, 1995). Through the adoption of new technologies, we may benefit from the same or better goods and services while emitting

fewer greenhouse gases. For example, in the transportation sector, the adoption of hybrid electric vehicles can lower greenhouse gas emissions while meeting the same consumer demands for vehicle travel.

The discovery and use of new technologies and processes is referred to as technological change. However, technological change is not simply a substitution of one technology for another but is characterized by a number of stages (Grubler, Nakicenovic, & Victor, 1999).² Typically, when a technology is invented it is uncompetitive for two reasons. First, the financial costs of the invented technology may be higher than competing technologies. Second, the new technology may have some real or perceived drawbacks that contribute to its non-competitiveness (Walls, 1996). For instance, the consumer may perceive a loss of quality with the new technology or an increase in risk because the technology lacks a record of past performance. These non-financial costs are termed intangible costs.

R&D investments and demonstration projects can improve a new technology such that the financial and intangible costs decline. These cost improvements allow the new technology to become viable in small markets not addressed by existing products. Once the technology is able to compete successfully in these so-called niche markets, its costs are expected to further decline as cumulative experience with the technology increases (Boston Consulting Group, 1968). This may lead to the standardization and mass production of the technology, known as diffusion.

² Uncertainty and non-linearities are prevalent in the process of technological change. For example, many technologies that are invented are not widely adopted. Further, related technologies have been observed to evolve in clusters, as the benefits of one technology are amplified by the adoption of a related technology (Grubler et al., 1999).

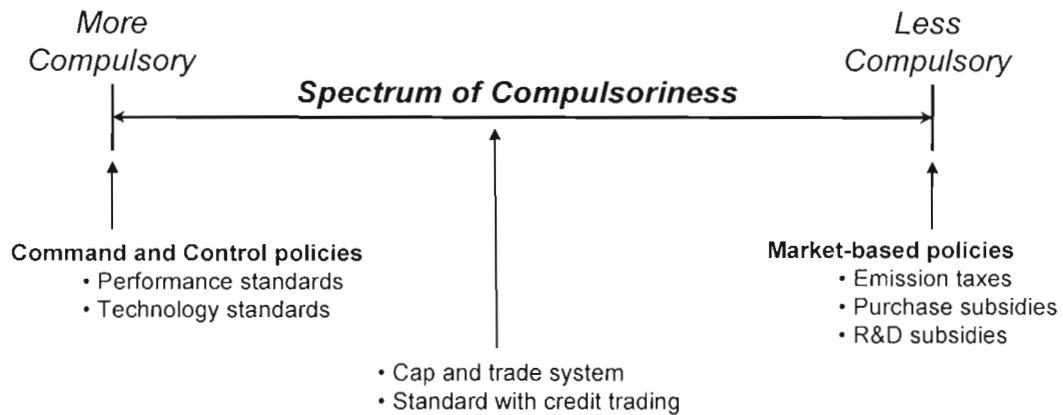
Technological change occurs naturally in markets and depending on its direction and extent, technological change has the potential to both increase and decrease our emissions. Increasingly, a pathway of technological change that lowers emissions without changes in human activity is thought to be the “line of least resistance” for reducing society’s greenhouse gas emissions (Azar & Dowlatabadi, 1999). Thus, policymakers are interested in influencing the direction of technological change by promoting the innovation and adoption of less greenhouse gas intensive technologies. Technological change stimulated through policy is known as induced technological change (Goulder, 2004).

It is generally agreed that environmental policy can induce technological change (for a review of the literature see Jaffe, Newell, & Stavins, 2002). However, much debate remains on what kinds of policies are most likely to generate innovative, low-cost solutions to environmental problems. In the following, I present commonly discussed environmental policies.

1.1.2 Environmental Policies

One approach in categorizing environmental policy is in terms of a policy’s compulsoriness, or the extent to which certain behaviour is required by the government. Within a range of compulsoriness, various policies and proposals employ an array of incentives to induce technological change and reduce greenhouse gas emissions. Figure 1 shows where a selection of policies fall within this spectrum of compulsoriness. In the following, I describe each of these policies, beginning with the most compulsory policies and progressing to less compulsory policies.

Figure 1: Selected Policies within Spectrum of Compulsoriness



Command-and-control regulations, such as performance and technology standards, regulate specific emission levels or technologies which a firm or individual must meet or adopt. These compulsory policies are enforced through financial or legal penalties. These policies may create a viable market for targeted low-emission technologies. Performance and technology standards can further induce technological change by explicit “technology-forcing”, which is mandating the use of technologies that are in their early stages or not fully developed.

Technology-forcing standards are intended to exploit natural tendencies of technological change by providing a market for new technologies regarded as environmentally superior. A new technology may benefit from increased market share by two means, learning-by-doing and the neighbour effect. Learning-by-doing describes a phenomenon in which the financial costs of new technologies are observed to decline with increases in cumulative experience with a technology (McDonald & Schrattenholzer, 2001). Further, as the market share of a technology increases, there is some evidence to

suggest that the intangible costs of a technology also decline. This observation, deemed the neighbour effect, is attributed to factors such as consumers' increased perceptions of a technology's reliability and learning from other consumers' experiences with the new technology (Yang & Allerby, 2003).

Market based policies, such as *pollution taxes* and *subsidies*, incite the firm or consumer to take socially desirable actions simply by acting out of financial self-interest (Stavins, 2001). Unlike command-and-control policies, firms and individuals decide how much to reduce their emissions to avoid paying an emissions tax (or at least some of it). Taxes can raise the price of carbon-intensive fuels and technologies by putting a price on carbon emissions. This price signal stimulates technological change by increasing the reward for discovering and/or adopting a low-emission technology. In the case of subsidies, the cost of low-emission technologies is lowered, with the aim of increasing their market share. *R&D subsidies*, in contrast, focus on increasing investment in low-emission technologies, attempting to stimulate technological change through improvements garnered by R&D.

Hybrids of these two categories of policies also exist. A *cap and trade system*, for example, combines a regulatory policy of a cap on emissions with market-based elements of tradable permits. The cap and trade system stimulates technological change in much the same way as a tax, by restricting emissions associated with the use of carbon intensive fuels, resulting in an increase in the cost of emissions or of fuels associated with these emissions. Another hybrid policy is a *performance standard with a credit trading system*, whereby firms who exceed the standard can collect and sell credits to firms that

cannot economically meet the standard. Credit trading of this kind aims to lower the cost of the command and control policy.

Economists typically argue that market-based policies that put a price on emissions, namely taxes, are the most economically efficient tool to meet environmental objectives (Jaffe et al., 2002). Such a tax would account for the environmental cost of greenhouse gas emissions not included in market prices of goods and services (negative externalities) and signal to firms and individuals to reduce emissions based on their true cost to society. Because of its flexibility, a tax should theoretically be an economically efficient means of cutting emissions, as emission reductions occur where they are least costly.

However, the analysis of a broader set of policies is warranted for other reasons. In particular, governments are interested in non-price policies to address environmental problems. Taxes are politically unpopular, often portrayed by opponents as an attempt by government to increase the tax burden (Svendson, Daugberg, Hjollund, & Pederson, 2001). A tax that is high enough to have significant impact on emissions and technological change may be susceptible to public backlash, thereby making it politically unacceptable. The limited number of price-based policies implemented in practice highlights this challenge.

Further, if a specific technological outcome is sought, emissions pricing may not stimulate sufficient market shifts for the desired technologies to enter the market and begin to benefit from both learning-by-doing and the neighbour effect (Sanden & Azar, 2005). Finally, spillover, a market failure resulting from the inability of firms to appropriate all of the benefits of their research and development investment, results in

less R&D investment than would be desirable for society. Spillovers imply that solely accounting for environmental costs through emission pricing may not be sufficient to induce socially optimal levels of innovation in climate-friendly technologies (Popp, 2006).³

In the following section, I will discuss why an analysis of various policy instruments targeted at reducing greenhouse gas emissions and inducing technological change is particularly salient for the light duty vehicle sector.

1.2 Technological Change in Light Duty Vehicles

In the U.S., the transportation sector emits 33% of total energy-related CO₂ emissions, and is experiencing more growth than any other energy-using sector (Energy Information Administration [EIA], 2005). Passenger vehicle transportation in the form of cars and light duty trucks (vans, sport utility vehicles, pick-up trucks) contributes 62% of the transportation greenhouse gas (GHG) emissions. Further, GHG emissions from the passenger vehicle sector grew 19% from 1990 to 2003 (EPA, 2006b). Because of the magnitude and continued growth of light duty vehicle emissions, any plan for dramatic reductions in GHG emissions will likely address passenger vehicle emissions.

1.2.1 Trends in the Light Duty Vehicle Sector

GHG emissions from the light duty vehicle sector are determined by several factors, namely population, vehicle ownership, vehicle usage and the composition of the vehicle fleet in terms of both fuel economy and fuel type. The identity in Equation 1

³ While the effect of spillovers has significant impact on the broader economy, solely addressing this market failure without correcting the negative externality associated with environmental costs would be unlikely to lead to innovation in climate-friendly technologies, but rather developments in energy-using (or climate-damaging) technologies.

where Pop is population, E is energy, i is the class of vehicle (for example small car or light truck) and j indexes the fuel type, can be used to calculate GHG emissions from the passenger vehicle sector. A number of trends in the elements making up Equation 1 drive the growth in U.S. emissions.

$$GHG = Pop \cdot \frac{Vehicles}{Pop} \cdot \sum_{i=1}^N \sum_{j=1}^M \frac{Vehicles_i}{Vehicles} \cdot \frac{Miles_i}{Vehicles_i} \cdot \frac{E_i}{Miles_i} \cdot \frac{GHG_{ij}}{E_{ij}} \quad \text{Equation 1}$$

First, both population and vehicle ownership have increased. Between 1990 and 2005, the U.S. population grew 16% (U.S. Census Bureau, 2007). Between 1990 and 2003, vehicle ownership grew from 0.72 to about 0.78 vehicles per person (Oak Ridge National Laboratory, 2006). Further, in the past decade, consumer preferences have shifted increasingly to light trucks and sport-utility vehicles (SUVs) which tend to have lower fuel economy and therefore higher GHG emissions per mile relative to cars (EPA, 2006b).⁴ Vehicle use has also increased. Overall vehicle travel in the passenger vehicle sector increased 34% between 1990 and 2003 (EPA, 2006b).

In addition to increases in vehicle usage, the energy efficiency or fuel economy of vehicles is an important contributor to overall GHG emissions. The fuel economy of vehicles in the U.S. fleet has improved very little over the last several decades. There was some improvement in the fuel economy of cars and light trucks in the 1980s, largely induced by the Corporate Average Fuel Efficiency (CAFE) standard implemented by the

⁴ This trend has begun to reverse somewhat because of increases in the price of gasoline observed in 2005 (Edmonds.com, 2006).

U.S. government. However, since then fuel economy has remained relatively flat for both cars and trucks (EPA, 2006b).

Finally, the fuel used in vehicles influences GHG emissions. A number of alternative fuels have a lower GHG intensity per unit of energy than gasoline. Currently gasoline is the dominant fuel type, followed by diesel. Some low-GHG intensity alternative fuels, namely ethanol and natural gas, play a minor role. However, gasoline is expected to continue to dominate fuel consumption with alternative fuels forecasted to comprise only 2.2% of light-duty vehicle fuel consumption by 2025 (EIA, 2006).⁵

There are two channels by which GHG emissions can be reduced in the passenger vehicle sector. The first channel is by reducing the demand for vehicle usage and the second is by inducing technological change towards more climate-friendly vehicles and fuels. Much attention has been given to the promise of zero-emission vehicles to reduce emissions in the passenger vehicle sector. This study focuses on technological change, particularly the potential for zero-emission vehicles in significantly reducing emissions in this sector.

1.2.2 Status of Zero-Emission Vehicle Technologies

There are a number of technologies that have the potential to reduce the GHG intensity of vehicles. I define zero-emission vehicles (ZEVs) as having zero tailpipe emissions (also referred to as direct emissions) or, in the case of biofuel vehicles, where combustion GHG emissions are captured by the plant cycle during growth of fuel

⁵ The EIA's forecast does not include the recently announced low-carbon fuel standard in California. The initial goal of the policy is to reduce the GHG-intensity of fuels sold in California by 10% by 2020 (Crane & Prusnek, 2007). Much of this goal is expected to be met by increasing the amount of ethanol blended into gasoline fuel.

biomass, as having zero full-cycle emissions.⁶ There are a number of vehicle propulsion technologies and fuel combinations that have potential for ZEVs (Maclean & Lave, 2003; Odgen, Williams, & Larson, 2004). Here I review the technologies most typically considered for substantially decreasing the GHG intensity of cars and trucks, namely, battery electric vehicles, fuel cell vehicles, hybrid electric vehicles, plug-in hybrids and biofuel vehicles.

Battery electric vehicles run on an onboard battery powered by electricity. The largest technical challenge for battery electric vehicles has been their limited range (the distance they can travel on a single charge). Additionally, batteries are still very costly (McLean & Lave, 2003). Thus, for the time being battery electric vehicles have been relegated to more targeted applications such as travel within gated communities and business parks (Larrue, 2003). Battery research, to improve the performance and cost of these vehicles, is ongoing (United States Council for Automotive Research, 2006).

Fuel cell vehicles are powered by a fuel cell that generates electricity from an electric motor. Fuel cell vehicles may use other fuels but their zero-emission option is typically predicted to use hydrogen. While fuel cell vehicles are expected to have a greater range than battery electric vehicles, the costs of fuel cells are still prohibitive. Additionally, there remains technical uncertainty about on-board fuel storage and the infrastructure requirements needed for significant market penetration of hydrogen fuel cell vehicles (Farrell, Keith, & Corbett, 2003). Hydrogen fuel cell vehicles are experiencing considerable private and public R&D investment (Hanisch, 2000; Office of

⁶ I define full-cycle emissions as emissions from biofuel combustion minus emissions captured in the plant cycle during growth of fuel biomass. I define life-cycle emissions of biofuels as the full-cycle emissions plus the emissions resulting from energy used in the cultivation and processing of biomass.

Technology Policy, 2003). Nonetheless, the potential of this technology is still highly uncertain and mass commercialization is at least a decade or more away (McLean & Lave, 2003).

Fuels made entirely out of biomass, known as biofuels, also have the potential to reduce the GHG-intensity of vehicles. While biofuels are carbonaceous, the emissions released during their combustion are captured by the plant cycle while growing the fuel biomass. Depending on how they are produced, biofuels could eventually result in net zero life-cycle emissions (International Energy Agency, 2004). Ethanol, an alcohol-based biofuel largely produced from corn, and biodiesel, a biofuel produced from plant oils with similar properties to petroleum diesel, are in use today in low volumes. In practice, both ethanol and biodiesel may be mixed with fossil-fuels to lower oil consumption and reduce GHG emissions. However, engine modifications can be made for vehicles to run purely on biofuel.

Biofuels share similar properties to fossil fuels and as such require less vehicle adjustments from conventional vehicles and limited changes in infrastructure. However, unlike electricity and hydrogen, vehicles combusting biofuels also produce many of the same air pollutants as fossil fuels. Further, resource availability in terms of feedstocks, as well as water and land-use concerns might limit their ability to substitute fossil fuels in vehicles (MacLean & Lave, 2003).

Increasingly, plug-in hybrid technology has been identified as a promising zero or near-zero-emission technology that may have fewer challenges than battery electric and fuel cell vehicles (Romm, 2006). Plug-in hybrids build on the relatively successful

penetration of gasoline-electric hybrid vehicles, which run on gasoline but are also propelled by an electric drive train.

Gasoline-electric hybrids had a market share of 1.2% of new U.S. vehicles in 2005 and their share is predicted to grow over the coming years (R.L. Polk & Co., 2006; J.D. Power and Associates, 2005). Hybrid electric vehicles have lower GHG intensities than vehicles of a similar make and model. However, there are questions regarding their ability to sizably reduce GHG emissions without some form of policy. For example, many new hybrid vehicles are being used to increase the power of larger vehicles, effectively negating many of their fuel economy benefits.

Plug-in hybrids would allow even further reductions in gasoline consumption than hybrids, by allowing it to be supplemented with electricity. Plug-in hybrids have larger onboard batteries, charged by electricity, to enable significant range by battery alone. For longer trips, this electricity-only range can be extended by using gasoline. The precise level of emissions from plug-in hybrid vehicles is uncertain as it largely depends on the fuel mix of gasoline versus electricity used in practice. However, a plug-in hybrid that uses electricity and replaces gasoline with a fuel that results in zero greenhouse gas emissions, such as hydrogen or biofuel would result in a zero-emission vehicle.

For the purposes of this study, I have selected three technologies that hold promise as ZEVs: battery electric vehicles, hydrogen fuel cell vehicles and biofuel plug-in electric hybrid vehicles. This selection was made based on my judgement of the technology's potential, prominence in the literature and ongoing R&D interest. To gain market share, all of these technologies will require further R&D investment, demonstration projects and niche market development. Moreover, there is uncertainty in

the extent of effort required and the probability of success. In the following section, I review a number of policies typically proposed to induce technological change and reduce emissions in the passenger vehicle sector.

1.3 Alternative Environmental and Technology Policies in Light Duty Vehicles

As discussed in Section 1.1, while price-based policies tend to be favoured by economists, a broader portfolio of policies are generally preferred by politicians. A number of the policies described in Section 1.1.2 have either been proposed or implemented in the passenger vehicle sector in varying form and degree. Here I review a subset of these, examining five policies aimed at reducing GHG emissions and inducing technological change in this sector.⁷

First, a *greenhouse gas emissions tax (carbon tax)* requires emitters to pay a fee per unit of greenhouse gas released into the atmosphere. Implementing such a tax effectively puts a price on the greenhouse gas emissions of fossil-fuel based products, like gasoline and diesel, used for transportation.⁸ Carbon taxes would be generally applied to the producer or importer of these fuels, the cost of which would largely be passed down to the consumer. The increase in the price of fossil-fuel based products would provide incentives to reduce vehicle usage as well as make cars and trucks that use relatively large amounts of these fuels more costly to operate than vehicles that are more fuel-efficient or that use lower emission fuels. This policy would foster a market for less GHG intensive vehicles and fuels, thus providing an incentive for innovation.

⁷ This list is not exhaustive but encapsulates the principal instruments typically proposed for significant emission reductions in this sector.

⁸ Biofuels, while carbonaceous, have the potential to have net zero life-cycle emissions. These fuels would be exempt from a carbon tax.

As discussed, a GHG emission tax should theoretically result in an economically efficient means of reducing emissions. The flexibility of a tax results in emission reductions occurring in the economy where they are least costly. Greenhouse gas taxes have been applied in Sweden, Denmark, Finland, Norway, and the Netherlands, but the share of GHG reductions from their passenger vehicle sectors has not been quantified. However, increases in the price of gasoline (one result of a carbon tax) are shown to decrease vehicle usage and gasoline consumption (Comeau & Chapman, 2002). As noted, taxes tend to face some public and industry opposition.

Second, *subsidies* can be used to provide an incentive to consumers for purchasing zero-emission vehicles. A subsidy improves the competitiveness of zero-emission vehicles with respect to other vehicles. A purchase subsidy targets the upfront cost of a technology, which has been shown to have a considerable weight in consumer decision-making (Kurani & Turrentine, 2004; Jaffe & Stavins, 1995). Purchase incentives in the form of tax credits have been used to boost the competitiveness of hybrid vehicles in several jurisdictions, including the U.S., Japan, the European Union and a number of Canadian provinces. Additionally, tax credits for zero-emission vehicles have been implemented in Japan, France and various U.S. states. While subsidies are a popular instrument with governments because of their political acceptability, subsidies may be expensive to governments (and not as effective) because of the high numbers of free-riders who benefit from such programs (Sutherland, 2000).⁹ Further, subsidies do not send any signal to reduce rates of vehicle use and because

⁹ Free-riders are consumers who would have bought the targeted vehicle without the subsidy.

subsidized technologies like zero-emission vehicles may actually reduce the cost of driving such a policy could result in increases in vehicle use.

Third, *performance standards* (a form of regulation) mandate characteristics of the vehicles sold. Performance standards can come in several forms. *Average fuel-efficiency* or *average greenhouse gas efficiency standards* direct the overall vehicle fleet of the regulated entity to meet a mandated level of fuel or greenhouse gas efficiency. Such standards are often directed at the manufacturer level. A *vehicle emission standard* mandates minimum market shares for certain types of technologies, such as zero-emission and/or near-zero-emission vehicles. The mandated market share generally grows over time, creating a niche market for technologies that meet the mandate. These standards have a penalty associated with not meeting the required fleet or market-share performance, as well as a system in which credits received for exceeding the standard may be traded among regulated firms. Depending on their design, standards may provide incentive to firms to innovate as long as the standard pushes the frontiers of available technology, encouraging firms to cross-subsidize new or more efficient technologies from sales of conventional vehicles and apply their marketing efforts to these new, lower emission technologies.

The U.S. has had CAFE, an average fuel efficiency standard, in place for a number of years. Japan and China have also implemented fuel efficiency standards. The state of California has recently implemented a GHG efficiency standard. Vehicle emission standards for local air emissions have been applied first in California, followed by New York, Vermont and Massachusetts. Careful design and monitoring of performance standards is critical. Standards will also likely face opposition from

automakers. Both fuel efficiency and vehicle emissions standards do not provide a signal to reduce vehicle usage and could therefore result in increases in vehicle use from ensuing reductions in the cost of driving.

Finally, *subsidies for R&D investment* into zero-emission vehicles are common and tend to be a popular instrument with governments. The state of California has provided R&D subsidies for electric battery technology and has recently shifted to investing in fuel cells. The U.S. government has also invested in R&D for electric and fuel cell vehicles. Canada, Japan and France all have provided R&D support to zero-emission vehicles. While subsidies may increase R&D investment, they do not provide a signal to increase market penetration of zero-emission vehicles or reduce vehicle use. Additionally, R&D subsidies may suffer from the free-rider problem, where public investment in R&D ends up substituting for rather than adding to private investment that would have occurred without the policy (Kemp, 2000; Popp, 2006).

In practice, policy instruments may be combined to form an overall GHG reduction strategy. The U.S. has a federal average fuel efficiency standard while also providing incentives for low and zero-emission vehicles. California has applied a vehicle emission standard for local air emissions, an average GHG efficiency standard, incentives for low and zero-emission vehicles as well as R&D support for zero-emission technology. Norway has a greenhouse gas tax in addition to tax incentives for electric and fuel cell vehicles. Some theoretical research has shown that certain policy instruments perform better in combination (Popp, 2006). Policy combinations must be implemented with care to ensure that they are complementary, not counterproductive, and

that the administration and implementation of various policies does not become burdensome (Gunningham & Sinclair, 1999).

1.3.1 Analysis of Light Duty Vehicle Sector Policies

Policy analysis targeted at the light duty vehicle sector has largely focused on incremental improvements to the fuel economy of vehicles, with a large number of studies examining the effectiveness of the CAFE average fuel efficiency standard (e.g. Greene, 1998; National Research Council, 2002). Further to this, a number of studies have compared CAFE-like policies to gasoline taxes. These studies generally reach the conclusion that gasoline taxes would be more economically efficient than the CAFE standard (Congressional Budget Office, 2003); however, the tax required to produce equivalent reductions in fuel consumption to the CAFE may be too large for public acceptability (Goldberg, 1998).

The use of vehicle emission standards has also been discussed in the literature. A number of analysts argue that the vehicle emission standard targeted at zero-emission vehicles, namely the ZEV mandate as implemented in California, largely contributed to the technical gains in electric drive trains, hybrids and hydrogen fuel cells (Kemp, 2002; Calef & Goble, 2005). However, others criticize the mandate for not meeting its stated goals of ZEV penetration and being too expensive an approach for reducing emissions, particularly, in the short term (Larrue, 2003; Dixon, Porche, & Kulick, 2002).

Analysts who take a more long-term view have generally focused on the costs of technological pathways to zero-emission vehicles and not necessarily on the policies needed to meet this requirement (e.g. Odgen et al., 2004; Schafer, Heywood, & Weiss,

2006; Azar, Lindgren, & Andersson, 2003). Some analysts have put forward suggestions for policy packages for aggressive emission reductions and a transition to zero-emission vehicles, but do not compare various policy instruments under these goals (Greene & Plotkin, 2001; Ogden, Williams, & Larson, 2001).

1.4 Study Scenario: The California Light Duty Vehicle Sector

There has been little assessment of policies under the goal of deep emission cuts and a transition to zero-emission vehicles. In the following analysis, I aim to begin to fill this gap in the literature by exploring a scenario in which zero-emission vehicles are deemed a requirement to meet our long-term objectives regarding climate change.

In order to make the results of this analysis more meaningful I have chosen to apply this model to California. California's light duty vehicle sector was selected for a number of reasons. First, California has identified a need for deep cuts in GHG emissions and air pollutants from its light duty vehicle sector (California Air Resources Board [CARB], 2005; Aufhammer, Hanemann, & Szambelan, 2006). Second, California has a strong history of environmental regulation with respect to the light duty vehicle sector. As described above, the state has established a vehicle emission standard mandating minimum market shares of zero and near-zero-emission vehicle technologies (CARB, 2006). Thus, California provides a good case for examining how other policies, such as greenhouse gas taxes or R&D subsidies, compare to the vehicle emission standard currently legislated in the state. Finally, the size of California's market makes it a good test case for policy. California's vehicle market is likely too large for automakers to dismiss even when faced with stringent environmental policy. While this study focuses on California, I expect that the results could be more broadly applied.

This paper therefore compares a diverse set of policies, over the period from 1990 to 2045, under the following two-fold target.

1. *Deep Emissions Reductions*: Reduce California's passenger vehicle GHG emissions to 60% below 1990 levels by 2045.
2. *Widespread ZEV diffusion*: One-half (50%) of all vehicle stock in California is zero-emission by 2045.

All policies tested must be stringent enough to result in deep emission reductions as well as widespread ZEV diffusion as defined above. The goal of deep emission reduction is based on California's target of reducing its overall emissions to 80% below 1990 levels by 2050 (Office of Governor, 2006). In selecting this goal, I assumed that some sectors would likely have lower costs in reducing GHG emissions and thus be required to reduce more than the vehicle sector. The goal of widespread ZEV diffusion was chosen such that ZEVs in the vehicle stock are sufficiently high to depict their mass commercialization.

There has been debate on the validity of ZEV diffusion as a policy goal, particularly with respect to cost-effectiveness (Dixon et al., 2002). Deep emission reductions may be possible without ZEV diffusion, for example through the adoption of low-emission vehicles such as hybrid electric gasoline vehicles. To understand how separating these two policy goals may affect the results, analysis was also completed to explore how the emission reduction target may be met without ZEV diffusion.

Policies selected for analysis include a *greenhouse gas tax*, *vehicle purchase subsidies*, *performance standards*, *R&D subsidies* and combinations of these. Policies

will be assessed primarily on their costs in meeting the two-fold target. This analysis will assist policy-makers in understanding the trade-offs associated with one policy instrument over another, particularly when other factors (such as political acceptability) may make certain instruments less desirable. Further details on how selected policies are simulated and assessed, including the definition of policy cost used in this study, are discussed in the following chapter.

To evaluate these policies, a model is required. In the next section, I give a brief overview of key issues in developing such a model.

1.5 Modelling Considerations

Energy-economy simulation models are often used to assess and rank policy alternatives in meeting environmental objectives. In the past, energy-economy models have generally fit into two categories: “top-down” and “bottom-up” models (Jaccard, 2005).

“Top-down” models use historical data and a high level of aggregation to estimate relationships between energy and other inputs to the economy such as capital and labour. These relationships are linked to sector and economy-wide outputs, typically in an equilibrium framework. Two key relationships are used to model the response of consumers and firms to changing conditions. First, elasticities of substitution (ESUBs) are used to represent the substitution of inputs driven by price. Second, an autonomous energy efficiency index (AEEI) is used to represent non-price induced energy efficiency improvements in the economy. Both ESUBs and AEEI are generally derived from long-

run data of market behaviour. Thus, where informed by data, top-down models are considered to have a high degree of behavioural realism.

However, there are two pitfalls to a top-down modelling approach. First, it may not be realistic to assume that the relationships used in top-down models based on historical trends will persist in the long-run (Grubb, Kohler, & Anderson, 2002). Second, top-down models are aggregated depictions of the economy, usually lacking technical detail. Therefore, modelling non-price policies that target specific technologies such as a performance standard is not possible.

On the other hand, “bottom-up” models are disaggregated depictions of the energy-economy and tend to emphasize the details of energy technologies such as their financial costs and performance characteristics. In a bottom-up model, a technology is adopted when it becomes financially cheaper than the current technology that provides the same service. Thus, conventional bottom-up models lack information on how firms and households make decisions, such as the influence of intangible factors such as risk and quality. Further, this approach does not account for macroeconomic feedbacks, such as the rebound effect, where increased energy efficiency can decrease the cost of energy and thus stimulate increased consumption. Therefore, bottom-up models tend to overestimate market share predictions for efficient technology and underestimate the true costs of technological change.

To reduce the weaknesses and build on the strengths of these two approaches, modelling efforts, including passenger vehicle sector models, are increasingly moving towards the hybridization of these two types of models (EIA, 2001; Greene, Patterson, Singh, & Li, 2005). A hybrid model aims to contain technological detail (like bottom-up

models) while maintaining a high degree of behavioural realism (Bohringer, 1998; Rivers & Jaccard, 2005)

The treatment of technological change in models used to analyze environmental policy has been shown to have a significant impact on modelling results (Azar & Dowlatabadi, 1999; Carrero, Gerlaght, & van der Zwaan, 2003). Some models that contain technical detail use the concept of learning-by-doing to endogenize technological change.¹⁰ These models incorporate a function that allows the costs of technologies to decline with cumulative production of the technology. On the other hand, more aggregated models may endogenize technological change by including R&D investment as an input factor and incorporating relationships between R&D investment and the other factors in the model. Few models characterize the connection between market share of a technology and consumers' perceptions of the technology's intangible costs, the so-called neighbour effect. Because the development and dissemination of zero-emission vehicles may involve R&D investments, learning-by-doing and the neighbour effect, ideally all of these elements are integrated into the model.

CIMS is a hybrid energy-economy model housed at Simon Fraser University (Jaccard, Nyboer, Bataille, & Sadownik, 2003). Its transportation component, CIMS-T, contains a variety of transportation technologies, such as gasoline vehicles, hybrid electric vehicles and fuel cell vehicles (Jaccard, Murphy, & Rivers, 2004). CIMS-T uses empirically estimated parameters to represent consumers' preferences and purchase decisions regarding transportation technologies. CIMS-T endogenizes technological change by allowing capital costs to decline as a function of cumulative production

¹⁰ Endogenous technological change refers to technological change that is determined in part by other parameters and the workings of a model.

(learning-by-doing) and intangible costs to decline as a function of market share (neighbour effect). CIMS-T can be used in isolation, or within the whole CIMS model, which incorporates macroeconomic feedbacks and shifts in energy supply and demand.

In this study, I develop a model of the California passenger vehicle sector based on CIMS-T functions and algorithms. Using this model, I seek to assess various policies in reducing emissions and inducing technological change in the transportation sector. The model is run under a set of assumptions simulating an unconstrained business-as-usual (BAU) scenario and then under the same set of assumptions simulating a policy. The results of the policy run are then compared to the BAU with respect to GHG emissions, penetration of zero-emission vehicles and cost. The model used in this analysis is discussed in further detail in Chapter 2.

1.6 Research Objectives

While the connection between environmental policy and technological change has been made in the literature, there remain gaps in our understanding of how various policy instruments perform under diverse criteria such as policy cost, inducing technological change and reducing emissions. The main objectives of this research are to:

1. Build a behaviourally realistic and technically explicit model of the California light duty vehicle sector, incorporating endogenous technological change.
2. Compare several policies and policy combinations under the criteria of GHG emission reduction, ZEV diffusion and cost.

3. Perform analysis to understand how uncertainties in various parameters affect the results and the rank order of the policy instruments under each criterion.

The remainder of this paper discusses the implementation of these objectives. Chapter 2 describes the methodology used, including details of the model, the criteria by which policies were assessed, the selection of policies tested and the uncertainty analysis undertaken. Chapter 3 provides the results of the policy assessment. Chapter 4 concludes with a discussion of implications for policymakers and provides recommendations for future research in this area.

CHAPTER 2: METHODS

In this chapter, I describe the model developed for this analysis. I detail the functions that characterize technological change (Section 2.1), the criteria by which the various policy measures will be assessed (Section 2.2), the input parameters used in applying this model to the state of California (Section 2.3), and the policies selected for this study (Section 2.4). Finally, I present how the uncertainty of the results is analyzed (Section 2.5).

2.1 The Model

A model, based on CIMS-T, was developed in order to assess the application of various policies to the light duty vehicle sector. The basic approach is to simulate how the characteristics of the light duty vehicle sector, such as vehicle stock and demand for vehicle use, might change over time from a business as usual scenario when a policy is applied. The resulting simulation estimates the reduction in greenhouse gas emissions from the policy, the change in vehicle stock, the cost of the policy and the change in demand for vehicles and vehicle use.

The model simulates the evolution of the vehicle stock over the period of 1990 to 2045. The simulation is based on a forecast of demand for vehicle use measured in vehicle-miles-travelled (VMT), assumptions regarding the average VMT per vehicle per year and the lifespan of vehicles. A portion of the vehicle stock is retired each year based on lifespan. New vehicles enter the stock as required to meet the demand for VMT.

Using this method, the model produces a depiction of the various vintages in the light duty vehicle stock at any given time.

A forecast for demand for VMT in the business-as-usual scenario is supplied to the model. In policy simulations, the demand for VMT is adjusted endogenously depending on the overall cost of vehicles and vehicle usage. Technological change is also endogenous to the model. This model represents a partial equilibrium scenario as macroeconomic feedbacks, such as shifts in energy supply and demand, are excluded and energy prices are supplied exogenously.¹¹ I provide details on the model's technology competition function, technological change dynamics and other feedback effects in the following sections.

2.1.1 Technology Competition

The model contains a range of vehicles representing the characteristics of conventional gasoline cars and trucks. Alternative car and truck technologies available today and promising technologies forecasted to be available in the future are also represented in the model. Car and truck passenger vehicles are defined by fuel type and efficiency. Figure 2 shows the technologies available in the passenger vehicle model. The technical and cost characteristics of these technologies are defined in Section 2.3.2.

¹¹ An exogenous variable is supplied externally and is not determined by the workings of the model. As noted, as part of the economy-wide model CIMS, CIMS-T can incorporate macroeconomic feedbacks due to shifts in energy supply and demand. However, an economy-wide hybrid model of California was unavailable for this study. In addition, excluding macroeconomic feedbacks accelerates the run-time of the model increasing the practicality of the uncertainty analysis discussed later in this chapter.

Figure 2: Light Duty Vehicle Competition

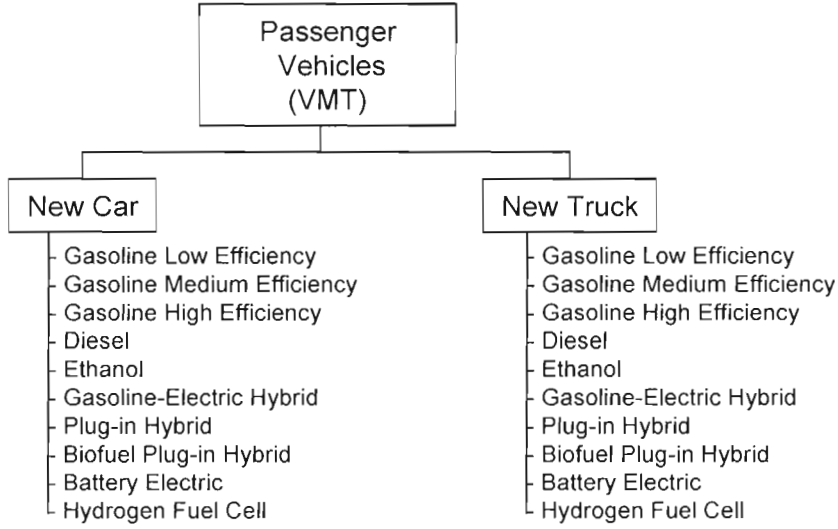


Figure 2 depicts the light duty vehicle competition between the technologies. The technology competition simulates how vehicles are acquired and enter the stock to meet the demand for VMT. The model has a nested competition, whereby there is a competition among vehicles in the same class (either car or truck) as well as competition between the truck and car classes, to meet the overall demand for passenger VMT.

The function used in the light duty vehicle competition is shown in Equation 2. This technology competition function, developed for the CIMS model, attempts to capture the key factors affecting how consumers make vehicle purchase decisions. The function calculates the market share of each type of vehicle purchased each period.

$$MS_j = \frac{\left[CC_j * \frac{r}{1-(1+r)^{-n}} + MC_j + EC_j + i_j \right]^{-v}}{\sum_{k=1}^K \left[CC_k * \frac{r}{1-(1+r)^{-n}} + MC_k + EC_k + i_k \right]^{-v}} \quad \text{Equation 2}$$

Market share is allocated between K technologies where MS_j is the market share of technology j relative to the set of K technologies. This function is based on the costs of a technology over its lifespan (life-cycle costs) and attempts to capture the various factors that go into a consumer purchase decision. CC_j , MC_j and EC_j are the capital, maintenance and energy costs of technology j respectively.

Three behavioural parameters are incorporated into the function. First, i_j , the perceived intangible costs of j , represents the non-financial aspects of adopting a technology. Second, r , the perceived discount rate, represents the trade-offs made by consumers between present costs and benefits and future costs and benefits. Finally, ν , the variance parameter, is a measure of market heterogeneity to enable a more realistic allotment of market share between the various technologies. The market share function used in the model is a logistic curve whose slope is determined by the ν parameter. The ν parameter represents the sensitivity of the technology competition to relative life-cycle costs of the technology. A high ν will result in the lowest life-cycle cost technology capturing almost all new market share, whereas a low ν will result in a more even distribution in market shares despite costs. Together the i , r and ν parameters represent consumer behaviour.

For simplicity, the number of technologies and vehicle models allowed to compete is limited. For example, the model contains only one variety of each alternative vehicle and three varieties of gasoline vehicles. In reality, there are numerous varieties of gasoline vehicles on the market. Moreover, while alternative vehicles generally have limited availability as they enter the market, availability could increase as market share in an alternative technology grows.

The difference in model availability between gasoline and alternative vehicles can be considered an intangible cost that one would expect to decline as market share increases and more models become available. Therefore, I attributed a larger intangible cost to less available alternative technologies to reflect the differences in model availability between conventional and alternative vehicles. These intangible costs are modelled to decline as market share increases and more models become available, potentially rivalling the availability of gasoline vehicles. The function used to capture declining intangible costs is discussed in the following section.

2.1.2 Endogenous Technological Change

By making several factors in Equation 2 dynamic, technological change is endogenized in the model. The CIMS model currently includes functions to allow capital and intangible costs to decline with cumulative experience and market share respectively (Rivers & Jaccard, 2006). I included both of these functions in the model.

Learning-by-Doing

To model learning-by-doing, the declining capital cost function allows CC_j , the capital costs of technology j , to decline with cumulative production of the technology. This declining capital cost function is shown in Equation 3:

$$CC_j(t) = CC_j(t_0) \cdot \left(\frac{N_j(t)}{N_j(t_0)} \right)^{\log_2 PR} \quad \text{Equation 3}$$

$CC_j(t)$ represents the cost of technology j at time t , $CC_j(t_0)$ is the cost of technology j at t_0 , the beginning of the simulation period. $N_j(t)$ is cumulative production

of technology j up to but not including time t and $N_j(t_0)$ represents cumulative production of technology j at the initial simulation period, t_0 . PR is the progress ratio representing the speed of learning. The progress ratio denotes how much costs decline for every doubling of cumulative production.

Neighbour Effect

The neighbour effect represents how consumers' perceived intangible costs of a technology decline with increases in the technology's market share. The neighbour effect is represented in the model using the function shown in Equation 4:

$$i_j(t) = i_{Fj} + \frac{i_j(t_0)}{1 + Ae^{k*MS_j(t-1)}} \quad \text{Equation 4}$$

Where $i_j(t)$ is the intangible cost of a given technology at time t , i_{Fj} is the fixed portion of the intangible cost of the technology, $i_j(0)$ is the initial variable intangible cost of a technology, $MS_j(t-1)$ is the market share of the technology at time $t-1$. Splitting the intangible costs into a fixed and variable portion allows the analyst to attribute some (or none) of the intangible cost of a technology to factors considered to be unaffected by market share. The A and k parameters generate the shape of the intangible cost curve and the rate of change of the intangible cost expected from increases in market share.

The declining capital cost function described above is widely accepted in the literature as a method to capture learning-by-doing (Loeschel, 2002). On the other hand, the declining intangible cost function to capture a "neighbour effect" is a relatively new proposition that has only begun to be tested empirically and implemented in models (Mau, 2005; Axsen, 2006a).

Learning-by-Searching

As discussed, I drew on functions currently used in CIMS to capture the dynamics of learning-by-doing and the neighbour effect. However, improvements garnered from R&D activity, so-called learning-by-searching, are not included in CIMS. I have endeavoured to include learning-by-searching in the model because of the importance of R&D, particularly with respect to the potential of zero-emission vehicles.

As noted in Chapter 1, while endogenizing R&D is relatively straightforward in more aggregated models, it is challenging in a model that contains explicit technical detail. Researchers have begun to address this challenge by building on the experience curves used to model learning-by-doing by combining these curves with the effect of R&D investment (Barreto & Kypreos, 2004). These new curves are deemed two-factor learning curves and they generally take the form depicted in Equation 5:

$$CC_j(t) = CC_j(t_0) \cdot \left(\frac{N_j(t)}{N_j(t_0)} \right)^{-b} \cdot \left(\frac{RD_j(t)}{RD_j(t_0)} \right)^{-c} \quad \text{Equation 5}$$

Where b is the learning-by-doing index, $RD_j(t)$ is the R&D investment up to but not including time t towards technology j , $RD_j(t_0)$ represents cumulative R&D investment at time 0 in technology j and c is the learning-by-searching index, representing how much costs decline with cumulative investments in R&D. Because of the disaggregated formulation of the two-factor learning curve, a technology's learning-by-doing indexes b and PR used in Equation 3 and Equation 5 respectively will differ.

R&D investment contributes to knowledge, which then results in technology improvements. However, there may be a time lag between R&D investment and technology improvement; additionally knowledge gained by R&D investment may depreciate over time. Incorporating these attributes of R&D using a so-called knowledge stock function has been found to better represent the effects of R&D investment (Criqui, Klaassen, & Schratzenholzer, 2000; Miketa & Schratzenholzer, 2004). The knowledge stock function is shown in Equation 6:

$$K_{j,t} = (1-\delta) \cdot K_{j,t-1} + RD_{j,t-n} \quad \text{Equation 6}$$

Where $K_{j,t}$ is the knowledge stock in year t of technology j , $K_{j,t-1}$ is the knowledge stock in year $t-1$, δ is the annual depreciation rate of knowledge, $RD_{j,t-n}$ is the lagged annual R&D expenditures for the technology j and n is the lag in years between R&D expenditures and knowledge stock. Incorporating knowledge stock into 2-factor learning curve is shown in Equation 7:

$$CC_j(t) = CC_j(t_0) \cdot \left(\frac{N_j(t)}{N_j(t_0)} \right)^{-b} \cdot \left(\frac{K_j(t)}{K_j(t_0)} \right)^{-d} \quad \text{Equation 7}$$

Where $K_j(t)$ represents the cumulative knowledge stock at time t , and $K_j(t_0)$ is the cumulative knowledge stock at time 0. Thus, capital costs of a technology, CC_j , will decline with increases in knowledge stock (and thus increases in cumulative R&D investment) in addition to increases in production. As in Equation 5, b is the learning-by-doing index, whereas d is the learning-by-searching index, now representing the effectiveness of the knowledge stock in lowering costs. Equation 7 was used in the

model to predict the effect on a technology's market share given an exogenously supplied R&D investment.

However, the incorporation of this formulation alone does not equate to a complete endogenous treatment of R&D. To endogenize R&D investment fully, levels of technology-specific R&D investment need to be allocated dynamically within the model. In one approach, Fisher and Newell (2005) endogenize R&D investment in a two-period model that assumes firm profit-maximizing behaviour. In their model, which contains minimal technical detail, R&D investment is allocated endogenously in the first period such that the firms' profit is maximized over both periods. The allocation and amount of R&D investment depends on the price to be paid for the technology to be researched, namely the demand for the technology, the returns to R&D and how much of the returns are appropriable to the investing firm (the effect of spillover).

Few modellers have attempted to endogenize R&D investment in technology explicit models. In one example, Barreto and Kypreos (2004) use a two-factor learning curve in their bottom-up optimization model. In their model, they use a "central planner" to endogenously allocate R&D investment optimally for the least cost emission reductions.

While I made several attempts to develop a reasonable approach for endogenizing R&D in this model, a tenable method was not found. First, this model does not rely on a central planner for R&D allocation, it instead simulates the aggregate effect of decisions by individual agents. Second, the model simulates vehicle stocks and new vehicle sales but does not track firm profits. Modelling R&D investment based on profit maximization would require a function that determines firm profits based on vehicle sales. An even

more critical challenge is modelling a profit-maximization function over several sequential periods and over a number of new technologies. This proved to be computationally impractical. Therefore, learning-by-searching was implemented exogenously through the function described in Equation 7. The endogenous treatment of R&D in a hybrid simulation model was left as an area for future research.

Similar to the declining intangible cost function, the two-factor learning curve formulation has been used by a small number of modellers and has had limited empirical testing. Further, while exogenously specifying R&D allows some exploration on how R&D investment may influence the cost of policies, not endogenizing R&D limits the model's capacity to analyze the influence of a policy on R&D investment. As a result, the model cannot test a policy's impact in correcting for the positive externality associated with spillovers. Thus, the effect of spillover is not included in the costs and emission reductions results from this model.

2.1.3 Feedback Effects

Elasticities were used in the model to represent how demand for both vehicles and vehicle miles travelled (VMT) may vary with changes in their respective costs resulting from a policy. Equation 8 shows how change in the demand for vehicles with a policy is characterized in the model.

$$D_{vehiclesPOL}(t) = \frac{(\sum CC_{jBAU} * MS_{jBAU} - \sum CC_{jPOL} * MS_{jPOL})}{\sum CC_{jPOL} * MS_{jPOL}} * \frac{1}{e_{vehicles}} * D_{vehiclesBAU}(t) \quad \text{Equation 8}$$

Where $D_{vehiclesPOL}(t)$ and $D_{vehiclesBAU}(t)$ are the demand for vehicles in business-as-usual (BAU) and policy (POL) scenario at time t , CC_j and MS_j are the capital cost and

market share of technology j in BAU and POL scenario respectively. Multiplying CC_j and MS_j together and summing over all technologies provides the weighted average capital cost of vehicles. Finally, $e_{vehicles}$ is the elasticity of demand for vehicles. Therefore, a 1% change in the aggregated capital costs of vehicles from BAU to POL will change the demand for new vehicles in the policy scenario by an elasticity, $e_{vehicles}$.

Equation 9 below represents the “rebound effect” in the model, whereby a policy may induce increases in VMT by reducing the cost of driving and vice versa.

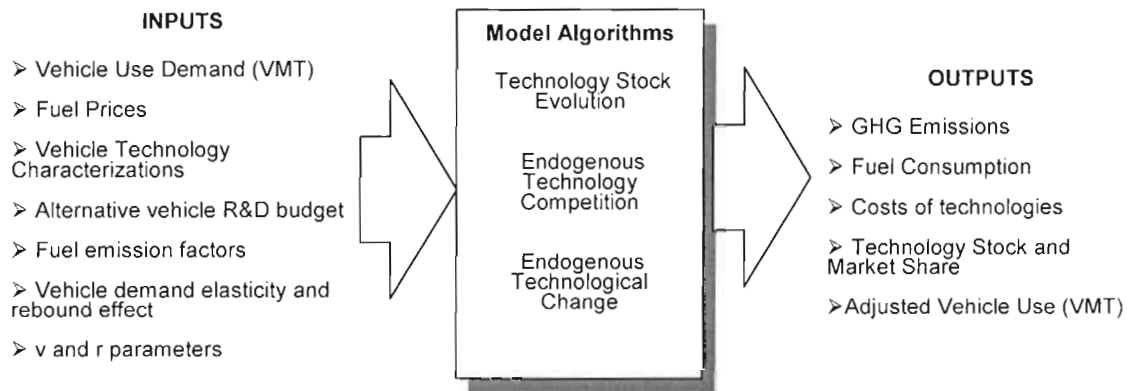
$$D_{VMTPOL}(t) = \frac{(\sum Cd_{j\ BAU} * MS_{j\ BAU} - \sum Cd_{j\ POL} * MS_{j\ POL})}{\sum Cd_{j\ POL} * MS_{j\ POL}} * \frac{1}{e_{VMT}} * D_{VMTBAU}(t) \quad \text{Equation 9}$$

This formulation takes the same form as Equation 8. However, in Equation 9 changes in the aggregated cost of driving, Cd , causes changes in demand for VMT. Cd_j is the cost of driving one mile, namely the sum of the fuel costs, operations and maintenance charges for the vehicle and any emissions charges of technology j in BAU and POL scenario. $D_{VMTPOL}(t)$ and $D_{VMTBAU}(t)$ is the demand for VMT in BAU and policy scenario at time t , MS_j is the market share of technology j in BAU and POL scenario. Finally, e_{VMT} is the elasticity of demand for vehicles. A 1% change from BAU in the cost of driving due to a policy will result in a change in demand from BAU for VMT in the policy by e_{VMT} .

2.1.4 Summary of Model

Figure 3 provides a diagram summarizing the passenger vehicle model as described above.

Figure 3: Diagram of California Light Duty Vehicle Sector Model



The model uses inputs such as demand for vehicle use, energy prices, various behavioural parameters and the technology characteristics of vehicles, such as vehicle cost and fuel efficiency, to provide a technologically explicit and behaviourally realistic representation of the light duty vehicle stock over time. The input assumptions are presented in Section 2.3. The model incorporates important aspects of technological change by endogenizing learning-by-doing and the neighbour effect and providing a simplified approach to examine the effect of learning-by-searching.

To evaluate various policies, the model was run under a set of assumptions for the business-as-usual (BAU) scenario with the technology competition unconstrained and then under the same set of assumptions simulating a policy. Further details on how selected policies were simulated and assessed are discussed in the following sections.

2.2 Analysis of Policies

The model was used to assess various policies and combinations of policies aimed at reducing GHG emissions from California's light duty vehicle sector and increasing the diffusion of zero-emission vehicles (ZEVs). In the following, I describe these two policy

goals, GHG emission reductions and ZEV diffusion, under which the selected policies were assessed. The cost of policy is a key tool in assessing diverse policy measures. Therefore, I also describe a range of approaches to reporting the costs of actions attributable to various policies and present how I have chosen to report cost.

2.2.1 Policy Target

The selected policies were compared in the period from 1990 to 2045 under a two-fold target:

1. *Deep Emissions Reductions*: Reduce emissions to 60% below BAU 1990 levels by 2045.
2. *Widespread ZEV diffusion*: One-half (50%) of all vehicle stock is ZEV by 2045.

In order to compare the policies, each policy was adjusted until it met the two-fold target. In holding the target constant across the alternative policies, I can consider differences in the costs of the policies while the benefits of the policy remain primarily the same. Because emission reductions are possible without the diffusion of ZEVs, I also conducted analysis to explore how the emission reduction target defined above may be met without the adoption of ZEVs. The details of this analysis are presented later in this paper.

Deep Emission Reductions

Under this goal, I adjusted the policy such that it arrives at the targeted level of *direct* GHG emissions by 2045. *Direct* GHG emissions represent the “tail-pipe” emissions of the vehicles. Therefore, to meet the deep emission reduction component of

the target, the policy's direct emissions in 2045 must be 60% lower than the direct emissions in the business-as-usual scenario in 1990.

While direct emissions provide a good starting point for assessing a policy's environmental impact, *indirect* emissions contribute considerably to total emissions in the transportation sector. I define *indirect* emissions as those resulting from upstream fuel-related activities, for example from the extracting, refining and transportation of crude oil in the case of conventional gasoline vehicles, or from the generation of electricity used in powering a battery electric vehicle. Therefore, I also examined the impact of indirect emissions on the total GHG emission levels of the policies assessed.

Incorporating indirect emissions adds a layer of complexity to the analysis. For instance, an economy-wide policy that taxes greenhouse gases would induce technological change in the upstream sectors of electricity generation and potentially in the oil and gas sectors. Such a tax on greenhouse gas emissions would likely result in decreasing the indirect emissions intensity of electricity generation. However, because the model represents partial equilibrium, a policy's effect on the indirect emissions and energy prices is not endogenous. To capture some of these impacts exogenously, the indirect emission factors are adjusted in the model over time under the policy scenario. The indirect emissions under the policy scenario are discussed in further detail in Section 2.3.

Widespread ZEV Diffusion

Under this goal, I ensured that the selected policy meets the desired level of ZEV market penetration. That is, at least 50% of the 2045 vehicle stock is zero-emission vehicles. As the 2045 vehicle stock is made up of several vintages of vehicles, zero-

emission vehicle penetration in previous periods has to be sufficiently high to meet this goal. Note that this goal is not tied to a specific ZEV technology.

2.2.2 Evaluating the Cost of Policy Measures

The principle criterion by which these diverse policies were evaluated is cost. In order to calculate the cost of a policy my model was soft-linked to a cost accounting tool.¹² This cost accounting tool was originally developed to link with CIMS in order to cost a diverse portfolio of policies and thus is well suited for this study. For a detailed explanation of the cost-accounting tool, see Peters (2006).

The cost of a policy can be defined and measured in a variety of ways. The cost accounting tool has the ability to return three measures of cost, the financial, perceived and expected resource cost of a policy. Financial cost of a technology is estimated as the sum of its capital costs and the present value of its operating costs over its lifespan, discounted using a social discount rate. The financial costs of a policy represent the traditional “bottom-up” cost measure, in which consumers make purchase decisions on the financial life-cycle costs of a technology alone, all consumers are assumed to have the same cost of adoption, and technology risks are considered non-existent.

The perceived cost provided by the cost accounting tool is defined as the conventional “top-down” definition of cost. The perceived costs include the intangible costs of a technology, a discount rate which takes into account real and perceived risks associated with the technology, and a heterogeneous consumer base. A cost (financial and/or non-financial) is incurred whenever a consumer deviates from their initial choice

¹² As opposed to physically connecting two models, soft-linking involves generating outputs from one model to use as inputs for another model.

of technology due to a policy. Similarly, a cost occurs when a consumer deviates from their initial demand for vehicles and/or vehicle use. Both of these costs make up the perceived cost of a policy.

The expected resource cost provided by the cost accounting tool attempts to capture the *ex poste* costs of switching or adopting a new technology due to a policy. Thus, the expected resource cost includes the financial costs and some portion of intangible costs, a risk premium and market heterogeneity *to the extent that these values are real and not a result of market failures* (for example consumers having imperfect information when purchasing a vehicle). Like the perceived cost, expected resource cost would also include welfare costs associated with changes in demand for vehicle use associated with a policy.¹³

The parameters used by the cost accounting tool to calculate the *ex poste* costs of technologies must be provided by the user. These parameters include the financial costs and the portion of intangible costs, discount rate and consumer heterogeneity not attributable to market failures. As discussed below a number of researchers have begun to collect these data for the light duty vehicle sector. Using these data, I was able to provide an estimate of the expected resource cost of alternative policies. Therefore, in this analysis, I report and compare the expected resource costs of the selected policies.

The expected resource costs of policies provides the *ex poste* cost of consumers switching or adopting a new technology due to a policy. However, to conclude this discussion of cost, it should be noted what is not included in this definition of cost. First,

¹³ Welfare costs represent intangible losses of consumer value associated with abandoning a technology or using it less.

because this cost definition represents the social costs of a policy, emission charges paid under a tax policy are excluded. Taxes are a transfer of income from payer to the government and are therefore assumed to represent a gain elsewhere in society and not a social cost. Second, administration costs associated with alternative policies are not included. Third, infrastructure costs related to the rollout of new technologies are not included. Fourth, I did not include any allocation for benefits from emission reductions in these calculations. Fifth, any macroeconomic costs, for example any costs associated with a loss of economic activity from a policy, are not reflected in the costs presented here.

2.3 Input Assumptions and Application to California

In order for the model to simulate various policies for the vehicle sector in California a number of input assumptions are required. I present the main assumptions used in the business as usual scenario and their sources below. There is uncertainty associated with these parameter assumptions. The incorporation of uncertainty analysis is discussed in Section 2.5.

2.3.1 Demand Forecast and Vehicle Ownership Characteristics

The demand for vehicle use for years 1990 to 2045, measured in passenger vehicle miles travelled (VMT), is based on data and forecasts generated by the California Department of Transportation (2005). The demand for 1990 to 2005 is based on actual data, while the demand for 2005 to 2045 is based on their projected growth rates.

Data from the California Department of Transportation (2005) were also used to generate an assumption for the average vehicle miles travelled per year per vehicle and

the expected lifespan of cars and trucks respectively. The values used are presented in Table 1.

Table 1: Vehicle Ownership Characteristics

New Technology	VMT/year	Lifespan
Car	11,117	16
Truck	14,477	15

For simplicity, I assumed that the average VMT per year for vehicles remains static over the forecasting period. While this may not be the case (past trends show increases in VMT per year), this assumption should not significantly influence the policy comparison done here. Under a policy scenario, demand for VMT is adjusted endogenously with changes in the cost of driving.

2.3.2 Vehicle Technology Characteristics

The characteristics that define a vehicle technology in the model include the introduction year of a technology, the capital cost and fuel efficiency of the technology at introduction, the intangible costs and the indexes by which the costs of specific technologies may decline with learning-by-doing, learning-by-searching and the neighbour effect.

The capital costs of the vehicle technologies were largely based on an unpublished review of the vehicle cost literature by Eyzaguirre (2004a). Data from this review were supplemented by other research where required. The cost of plug-in vehicles was based on reports from Romm (2006) and Calcars (2006). The price of fuel cell vehicles was chosen to be in the lower range of the literature reviewed in Eyzaguirre

(2004a) because a relatively conservative introduction year was selected for this vehicle type. Trucks were assumed to be 25% more expensive than cars of the same technology type (e.g. gasoline or battery electric) and 30% less fuel efficient relative to the same cars. Trucks were also assumed to have equivalent declining cost characteristics to the cars of the same technology type.

The fuel efficiency of vehicle technologies was based on the same review by Eyzaguirre (2004a) and supplemented where needed by fuel efficiency figures provided by the EPA (2006a). The fuel efficiency of most vehicles was assumed to improve autonomously at a rate of 0.1% per year. For vehicles that are considered at their early stages of market diffusion, such as ethanol, hybrid electric, plug-in hybrid and fuel cell vehicles, the fuel efficiency improvement was assumed to be 0.2% per year.

Several flexible fuel vehicles were included in the model. Ethanol vehicles were assumed to have a 15/85 split between gasoline consumption and ethanol consumption. Plug-in electric hybrids were assumed to have a 15/85 split between gasoline and electricity consumption respectively. Biofuel plug-in electric hybrids were assumed to have a 15/85 split between ethanol and electricity consumption.

Declining capital costs for technologies were enabled based on the stage of a technology's development and diffusion. Mature technologies that have reached high levels of market penetration, like conventional gasoline vehicles, were assumed to be unaffected by learning-by-doing or learning-by-searching. I assumed that gasoline-electric hybrids, plug-in hybrids, battery electric and hydrogen fuel cell vehicles could all benefit from learning. As a technology matures and high levels of market share are reached, the cost savings resulting from learning was assumed to decline and eventually

plateau. Therefore, for those technologies impacted by learning, I specified a cost at maturity. The cost at maturity was assumed to vary depending on the technology type, but was set to be a specified level above the lowest cost gasoline vehicle.

There is little empirical evidence for the rate of learning with respect to specific vehicle technologies. The model-T ford was estimated to have a learning index of 85% (Abernathy & Wayne, 1974) and the average for manufactured goods is estimated to be 80% (Argotte & Epple, 1990). Electronic devices, which may mimic the curves of many of the alternative vehicle technologies because of their use of batteries and other electronic features, have an index from between 72-87% (Dino, 1985). I used subjective judgment given the range of figures discussed here, and based on the state of the selected technology's development and diffusion, to establish learning indexes for technology-specific single-factor learning curves. Note that the learning-by-doing index for a single factor curve is different from that of a two-factor learning curve because of its more aggregated formulation.

There is even less evidence for the learning-by-searching index, with the minimal literature available focusing on the electricity sector (Criqui et al., 2000; Miketa & Schrattenholzer, 2004; Watanabe, Wakabayashi, & Miyazawa, 2000). I set the values for selected vehicle technologies to correspond with technologies in the electricity sector that I deemed as having similar characteristics and diffusion levels. I set the lag between R&D expenditure and knowledge stock to be five years as per Criqui and colleagues' (2000) assumption with respect to photovoltaic technology.

A summary of the vehicle characteristics as described above is found in Table 2. These characteristics are subjected to uncertainty analysis discussed in Section 2.5.

Table 2: Summary of Vehicle Characteristics for Cars

Technology	Intro. Year	Capital Cost (2000 USD)	Cost At Maturity (2000 USD)	F.E. (vmt/GJ)	LBD Single-factor	LBD Two-factor	LBS Two-factor
<i>Cars</i>							
Gasoline, Low Efficiency	1990	\$23,341		0.0061			
Gasoline, Mid Efficiency	1990	\$18,685		0.0051			
Gasoline, High Efficiency	1990	\$12,895		0.0039			
Diesel	1990	\$17,140		0.0043			
Ethanol	1995	\$17,174		0.0055			
Gasoline Hybrid Electric	2000	\$23,866	\$19,485	0.0028	0.95	-0.17	-0.05
Gasoline Plug-in Hybrid	2010	\$22,866	\$19,485	0.0022	0.9	-0.2	-0.07
Biofuel Plug-in Hybrid	2010	\$22,866	\$19,485	0.0023	0.9	-0.15	-0.07
Hydrogen Fuel Cell	2025	\$66,000	\$20,185	0.0037	0.75	-0.27	-0.11
Battery Electric	1995	\$37,776	\$20,685	0.0014	0.78	-0.25	-0.07

Examples of the single-factor and two-factor declining capital cost function for battery electric cars are shown in Figure 4 and Figure 5. The costs in the single-factor curve decline with increases in experience, expressed as cumulative vehicle stock. In the two-factor curve, costs decline with both cumulative experience (in Figure 5 cumulative production is assumed to be zero) and increases in knowledge stock, driven by cumulative R&D investment.

Figure 4: Declining Capital Cost (Single Factor Learning Curve) Battery Electric Cars

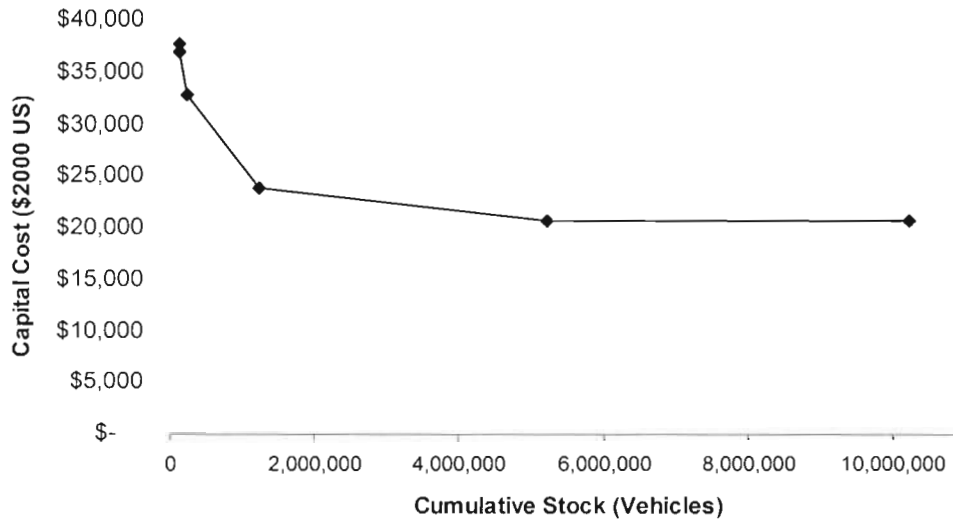
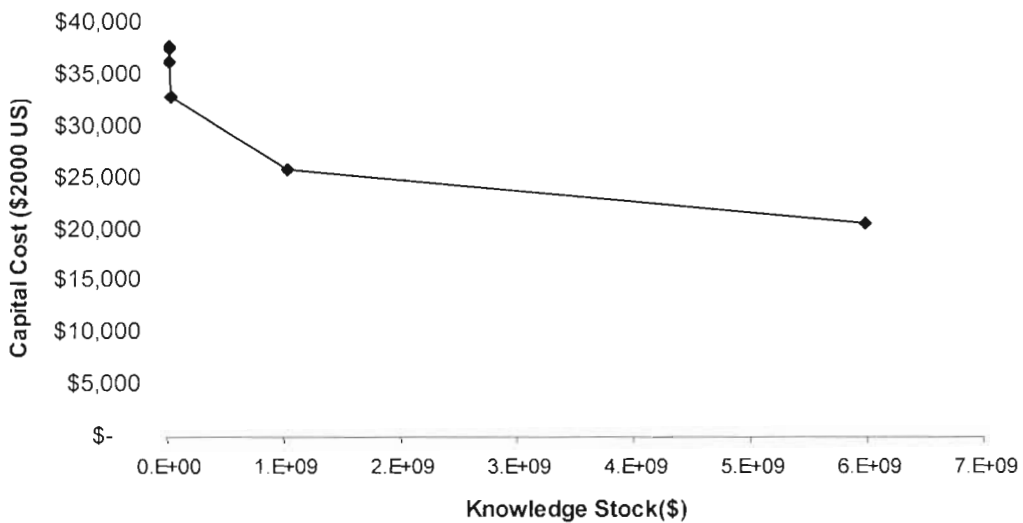


Figure 5: Declining Capital Cost (Two factor Learning Curve) Battery Electric Cars



A final element defining the vehicle technologies in the model is intangible costs and dynamics. The values of intangible costs and their dynamics for passenger vehicles has been the object of various research efforts (Axsen, 2006a; Mau, 2005; Eyzaguirre,

2004b). For the technologies used in the model, the intangible costs and their dynamics (i.e. the A and k parameters) were based on empirical research by Axsen (2006a) and an unpublished report by Axsen (2006b).

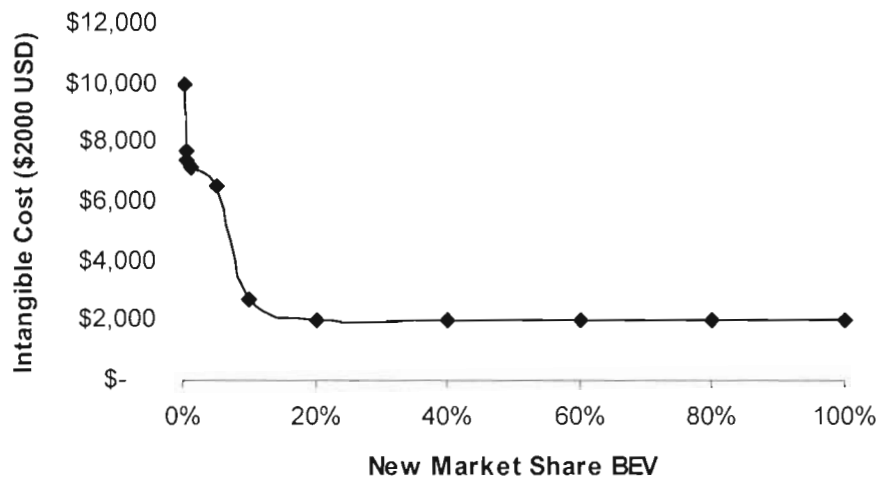
As previously discussed, the intangible costs are broken down into two components, first a fixed component that is not affected by market share of the technology and second, a dynamic component influenced by market share. This approach assumes that some elements of certain technologies, for example limited range or inconvenient fuelling, will always have an intangible cost associated with them independent of market share and the neighbour effect. Note that a negative number indicated for intangible cost represents a benefit consumers perceive from that technology. The intangible characteristics for trucks are similar to those of cars; however, a premium of -\$6750 was added to the fixed intangible costs of the trucks to account for the current preferences of consumers for trucks and SUVs. There remains a large range of uncertainty surrounding intangible cost characteristics, therefore these parameters were included in the uncertainty analysis discussed in Section 2.5.

Table 3: Summary of Intangible Vehicle Characteristics for Cars

Technology	Fixed Intangible Cost (2000 USD)	Variable Intangible Cost	A	k
<i>Cars</i>				
Gasoline, Low Efficiency	-\$6500	-		
Gasoline, Mid Efficiency	-	-		
Gasoline, High Efficiency	\$6000	-		
Diesel	\$2000	\$4000	0.4	65
Ethanol	\$1500	\$5000	0.4	65
Gasoline Hybrid Electric	-	\$4000	0.4	65
Gasoline Plug-in Hybrid	-	\$8000	0.4	65
Ethanol Plug-in Hybrid	-	\$8000	0.4	65
Hydrogen Fuel Cell	\$2500	\$13000	0.4	65
Battery Electric	\$2000	\$8000	0.4	65

The A and k parameters represent the shape and rate of change of the intangible cost curve in response to changes in new market share. An example of the declining intangible cost function for battery electric cars ($A = 0.4$, $k = 65$) is shown below in Figure 6.

Figure 6: Intangible Cost Curve for Battery Electric Cars



2.3.3 Other Key Model Parameters

In addition to the characteristics of specific vehicle technologies, a number of other factors influence the technology competition within the model. These parameters primarily shape the behavioural realism of the model.

The discount rate represents the trade-offs made by consumers between present costs and benefits and future costs and benefits. Studies examining vehicle purchase decisions found consumers' discount rate to be high (e.g. Horne, Jaccard, & Tiedemann,

2005). This high discount rate is attributed to a lack of information, limited time to make decisions, perceptions of risks of new products and the value of waiting for more information (Dixit & Pindyk, 1994; Hasset & Metcalf, 1994). I chose to use a discount rate of 25%, which was the value found for California in recent a study (Axsen, 2006a). This value falls within the range of other studies (Train, 1985; Horne et al., 2005).

The so-called variance (v) parameters used in this model enable a more behaviourally realistic allotment of market share to the various vehicle technologies. A high v means that the technology with the lowest life-cycle costs captures almost all of the new equipment stocks, whereas with a low v , equipment market shares would be distributed more evenly regardless of differences in life-cycle costs. I followed the recent report compiled by Axsen (2006b) and used a v of 15 for competition within class (i.e. between cars) and a v of 7 for competition between classes (i.e. between cars and trucks).

As discussed, the overall vehicle demand elasticity and the rebound effect provide important feedback effects of the model. The vehicle demand elasticity represents the response of consumers to changes in vehicle price. Once again, there is a range of vehicle demand elasticities found in the literature (e.g. McCarthy, 1996; Bordley, 1993). I used a value of 0.5, which is within the range found in the literature. A 1% increase in the average capital cost of vehicles will result in a 0.5% decrease in the demand for vehicles and vice versa.

Rebound effect represents the elasticity of the demand for vehicle miles travelled (VMT) with changes in the cost of driving. The rebound effect characterizes how increases in efficiency (in this case fuel efficiency) will generally reduce the cost of driving and thus stimulate some additional use. This phenomenon has considerable

implications for policy choice and thus is important to include in the model. I used a value of 0.2 taken from the survey completed by Greening and colleagues (2000). This means that a 1% decrease in the average cost of driving will result in a 0.2% increase in the demand for VMT and vice versa. A summary of the values discussed here is found below in Table 4.

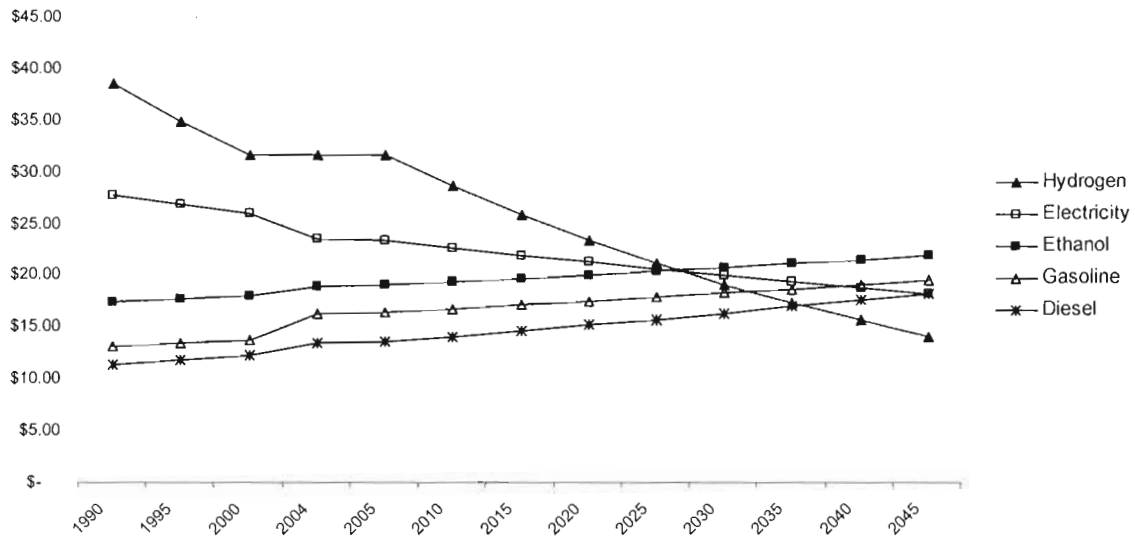
Table 4: Other Key Model Parameters

Parameter	Base Case Value
Discount Rate	25%
v – within class	15
v – between class	7
Vehicle demand elasticity	0.5
Rebound Effect	0.2

2.3.4 Fuel Costs and Characteristics

For the most part the fuel costs and forecasts were taken from Pacific data for Transportation Fuels from the U.S. Annual Energy Outlook (EIA, 2006a). Growth rates provided for the period 2004 to 2030 in the Annual Energy Outlook were assumed to continue for the period from 2030 to 2045. Because hydrogen was not included in these data, its costs were taken from the California Clean Fuels Assessment (California Energy Commission, 2003). The price of hydrogen is assumed to decline over time, corresponding to forecasts made by various researchers (National Research Council, 2004; Ogden et al., 2004). The fuel costs per gigajoule (GJ) over time are shown below in Figure 7.

Figure 7: Fuel Costs per GJ (2000 U.S.dollars)



The direct emission factors used in this analysis were taken from data contained in the CIMS model, which stem from a variety of sources. Ethanol has non-zero tailpipe emissions. However to depict the advantage of biofuels over fossil fuels, the full cycle emissions are provided, accounting for the CO₂ captured by the ethanol feedstock during its growing stage. Table 5 shows the factors used for direct emissions assumed for each fuel type.

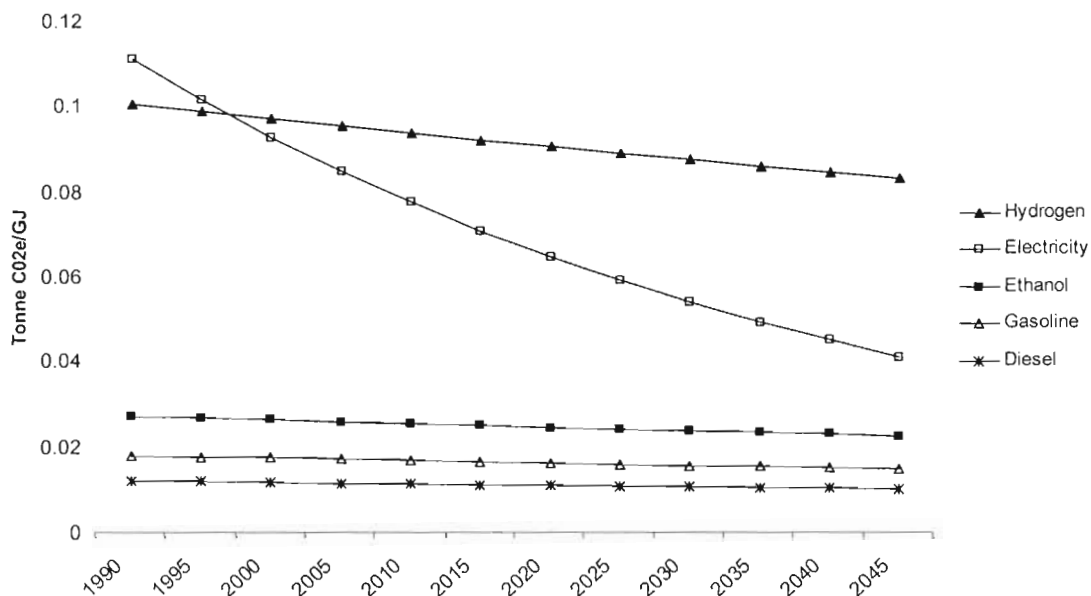
Table 5: Direct Emission Factors

Fuel	Direct Emissions (Tonne CO₂e/GJ)
Gasoline	0.0681
Diesel	0.0706
Ethanol ¹	0
Hydrogen	0
Electricity	0

¹The emission factor for ethanol is a full-cycle emission factor.

The indirect emissions for many of the fuels were derived from forecasts made by Weiss and colleagues (2000). The indirect emissions from California electricity generation were obtained from Bemis and Allen (2005). The indirect emissions were assumed to change exogenously over time. I assumed that a moderate economy-wide policy aimed at reducing greenhouse gas emissions would be in place during the forecasting period. Therefore, changes in the indirect emissions intensities of various fuels over time were based on a cap and trade scenario for the U.S. described in EIA (2006b). However, I assumed that the emissions factors for electricity and hydrogen decreased more rapidly than the EIA scenario based on California's recently announced commitment to reduce emissions by 80% by 2050 (Office of Governor, 2006). I assumed that California's targets would have less impact on the upstream emissions for fuels such as gasoline and diesel than the electricity sector. Figure 8 shows the indirect emissions scenario assumed for the forecast period.

Figure 8: Indirect Emissions Scenario



2.4 Policies Assessed

Section 1.3 in the opening chapter described in general terms the policies selected for this analysis. Four different policy types were considered. Each policy type was assumed to have been implemented beginning in 1995. The policies examined were:

- a tax on greenhouse gas emissions applied to the direct emissions of vehicle fuels,
- a standard mandating zero-emission vehicle market share requirements,
- a purchase subsidy applied to battery electric vehicles (BEVs),
- a R&D subsidy targeted at biofuel plug-in electric vehicles (BPHEVs).

The purchase subsidy was targeted at BEVs because of its availability in the 1990s as opposed to the other ZEV technologies. The R&D subsidy was targeted at

biofuel plug-in electric vehicles (BPHEVs), a technology currently unavailable, but which is considered to hold future promise.

Policy combinations were also tested, specifically a purchase subsidy combined with a tax and a standard combined with a tax. In addition, combining a R&D subsidy with a tax and a standard respectively was assessed. For these policy combinations, R&D subsidies were applied from 1990 to 2005 such that the cost of BPHEVs in their first year available (2010) was significantly lowered.¹⁴

Another part of the policy analysis included the assessment of a delay strategy. In the delay strategy, no action is taken until 2035 and then either a tax or a standard is put in place to meet the required target.

Finally, there has been debate on the validity of ZEV diffusion as a policy goal, particularly with respect to cost-effectiveness (Dixon et al., 2002). Therefore, to explore how removing ZEV diffusion as a policy goal may affect the results, I also assessed a ULEV-ZEV standard that allows ultra low-emission vehicles (ULEVs) such as hybrid electric, plug-in hybrids and ethanol vehicles, in addition to ZEVs, to meet its market share requirements. This enabled an understanding of some of the trade-offs involved in attaining a less prescriptive target than the target selected for this study. A summary of the policy alternatives assessed is provided in Table 6.

¹⁴ Battery electric and fuel cell vehicles would also likely benefit from R&D subsidies. However, because of the lack of data to characterize the impact of R&D investment on vehicle costs, testing R&D policies was limited. I targeted BPHEVs to understand how lowering the cost of BPHEV early in the policy run with a R&D subsidy may lower the costs of various policies.

Table 6: Summary of Policies Assessed

POLICY	POLICY LEVER
Tax	Tax applied to direct GHG emissions of fuels
ZEV Standard	ZEV new market share mandated
Purchase Subsidies	Subsidy is provided to consumer for each BEV purchased.
R&D Subsidies	R&D subsidy is provided for BPHEV research.
ZEV only Standard then Tax	ZEV new market share mandated from 1990 to 2010 followed by a tax applied to direct GHG emissions of fuels
Purchase Subsidies plus Tax	Purchase subsidy provided for consumers buying BEVs and a tax is applied to direct GHG emissions of fuels
R&D Subsidy plus ZEV Standard	R&D subsidy is provided for BPHEV research and ZEV new market share is mandated
R&D Subsidy plus Tax	R&D subsidy is provided for BPHEV research and a tax is applied to direct GHG emissions of fuels.
Delay then Tax	No policy until 2035 then a tax is applied to direct GHG emissions of fuels.
Delay then ZEV Standard	No policy until 2035 then ZEV new market share is mandated
ULEV-ZEV Standard	More flexible standard, both ULEVs and ZEVs qualify to meet a market share mandate.

Each policy presented in Table 6 was set such that the target of deep emission reductions and widespread ZEV diffusion described in Section 2.2 was reached. The stringency required for each policy to meet this target is detailed in the following chapter.

2.5 Incorporating Uncertainty

Explicit reporting of uncertainty is a key component of a credible and useful policy analysis (Morgan & Henrion, 1990). This model is a simplified version of reality that attempts to make predictions over a relatively long period. In particular, predicting the path of R&D activities and new technology diffusion is fraught with uncertainty.

Section 2.3 describes the input assumptions used in the model’s base scenario. While significant effort was expended to find the most appropriate parameters for this base scenario, there is inevitable uncertainty around the parameters and input

assumptions used in this analysis. Therefore, a range of high and low values around the base scenario assumptions was attributed to the key uncertain parameters. The ranges of the uncertain parameters were chosen based on subjective judgment in conjunction with consideration of the ranges provided in literature. I used two approaches for analyzing the effect of uncertainty on the results, namely, sensitivity analysis and Monte Carlo analysis.

Sensitivity Analysis

Sensitivity analysis can be used to highlight key areas of considerable uncertainty, serving two purposes. First, it demonstrates how results may change given changes in parameters. Second, sensitivity analysis can be used to prioritize uncertainties in the parameters to inform future research in an effort to narrow the range of results. Single value sensitivity analysis was performed to understand how single parameter changes influenced the results. The high and low values of key uncertain parameters are changed one at a time, the model is then run and the results are recorded. The results are then presented in a tornado diagram, which helps to evaluate and rank how each uncertain parameter affects the results. A limitation to this approach is that it does not capture the effect of multiple uncertainties on the results.

Monte Carlo Analysis

In many cases, using a model with the “best values” for each uncertain parameter will generate considerably different results than incorporating a more explicit probabilistic analysis (Morgan & Henrion, 1990). Monte Carlo simulation is a commonly used technique to capture the effects of uncertainty in large models with a

number of uncertain parameters. Unlike sensitivity analysis, this method may capture the effects of multiple uncertainties. Monte Carlo simulation was used to estimate a range of uncertainty in emissions and costs for each policy given a number of uncertain inputs.

I specified a normal probability distribution for each uncertain input. For each uncertain parameter, the base scenario assumption described in Section 2.3 was selected as the mean of this distribution and the range of high and low values, described above, was considered one standard deviation from the mean. The Monte Carlo simulation takes a random draw from the probability distribution of each uncertain parameter and runs the model. This was repeated 1000 times¹⁵. The distribution of the simulation outputs, emissions and costs, provides a characterization of the uncertainty of these outputs. The Monte Carlo simulation was developed using a Visual Basic Macro.

Finally, it should be noted that other sources of uncertainty in the results exist that are not fully captured by the sensitivity or Monte Carlo analysis described here. This is discussed in more detail in Chapter 4.

¹⁵ Running the model 1000 times was chosen to balance between model run-time and quality of results.

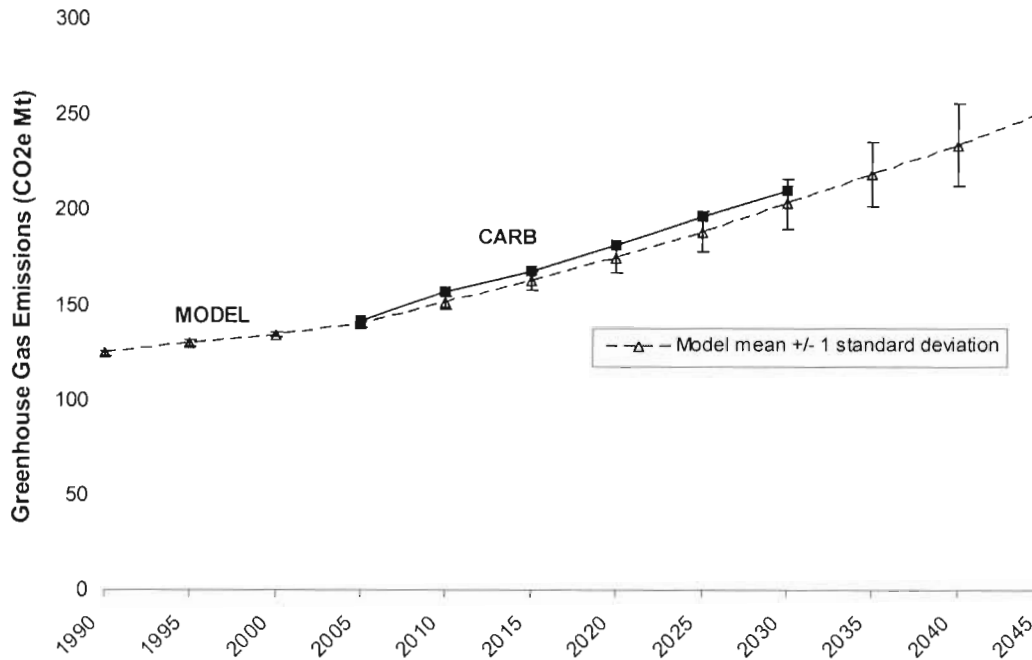
CHAPTER 3: RESULTS AND DISCUSSION

Using the model described in Chapter 2, this chapter presents the results of the policy analysis. To begin I describe the business-as-usual forecast generated by the model (Section 3.1). Next, the policy simulations are detailed (Section 3.2). First, I describe the stringency required for each policy to meet the two-fold target. Second, I examine the impact of these policies on greenhouse gas emissions and the diffusion of zero-emission vehicles. Third, I analyze key features of the policies and compare the costs of policy alternatives. A measure of the uncertainty of the results is provided using Monte Carlo analysis. Finally, I present sensitivity analysis to understand the significance of selected uncertain parameters on the results (Section 3.3).

3.1 Business as Usual Forecast

A business as usual (BAU) forecast for greenhouse gas emissions, representing a scenario in which no additional greenhouse gas (GHG) policy is applied, was generated. Monte Carlo analysis was used to produce this forecast. The forecast of California's passenger vehicle emissions, that includes both direct and indirect GHG emissions, was compared to a similar forecast produced by the California Air Resources Board (CARB, 2004) in Figure 9.

Figure 9: BAU Emissions Forecast (Direct and Indirect Emissions)



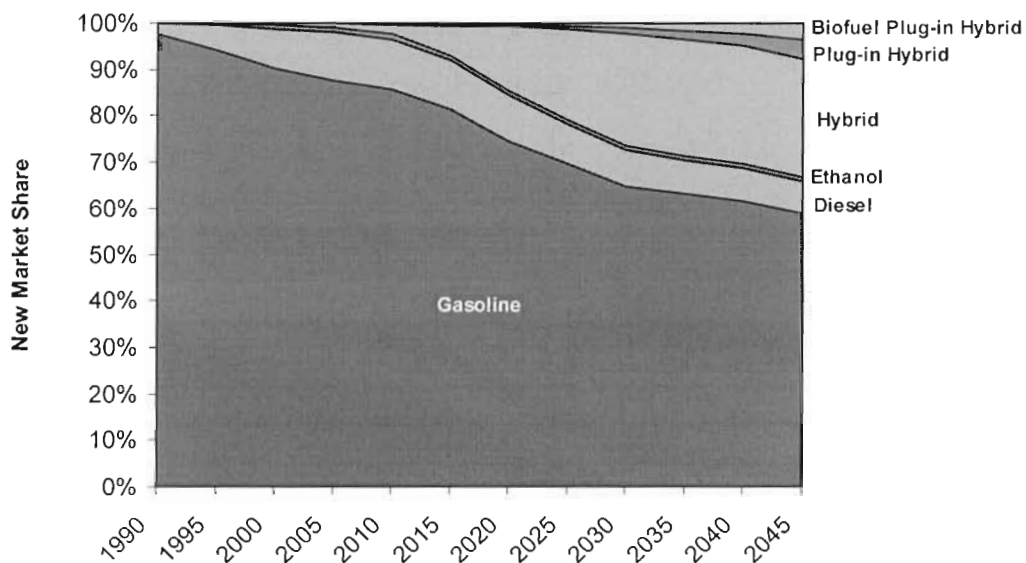
The model's forecast represents the mean of the Monte Carlo analysis and the error bars depict one standard deviation in each direction from the mean. The standard deviation around the mean of the forecast increases over time, indicating the increased uncertainty in predictions of technological change as the forecasting period lengthens.

The forecasts are within 5% of each other and follow a similar increasing trend. CARB's forecast is slightly higher than my forecast. This variation can be attributed to a number of possible factors, such as differing assumptions regarding indirect emission intensities, the policy efforts assumed to be included in the BAU, and assumptions about the market acceptance of various vehicle types.

The model's BAU forecast for new market share of vehicle technologies is shown in Figure 10. In the BAU scenario, conventional gasoline vehicles begin to lose market share over time, as diesel, hybrid electric vehicles, biofuel and plug-in hybrid electric

vehicles gain varying amounts of market share. The model predicts that hybrid electric vehicles will have the largest gains in market share, reaching up to 25% market share by 2045. Zero-emission vehicles, in the form of biofuel plug-in vehicles, are predicted to capture less than 4% of new market share in the year 2045.

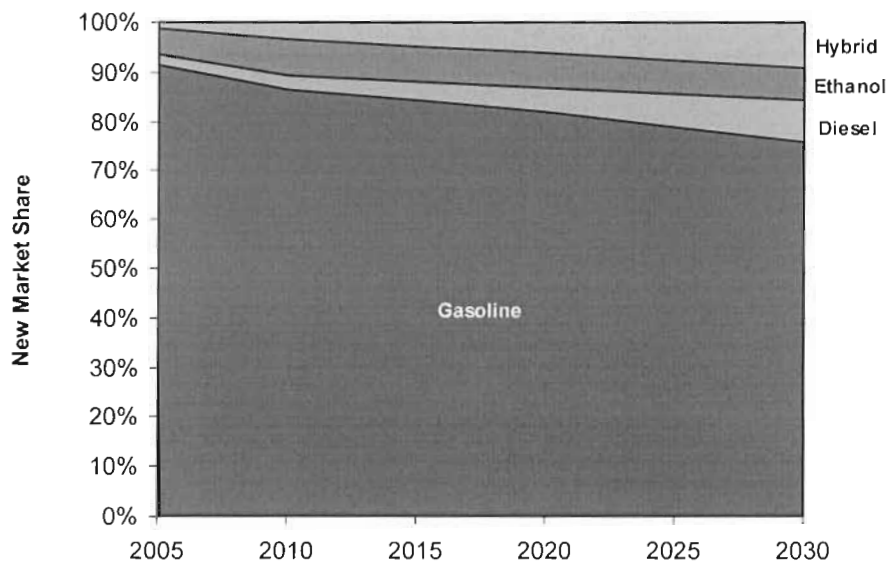
Figure 10: BAU New Market Share Forecast



This forecast was compared to a similar forecast generated by the EIA for the period 2005 to 2030 (EIA, 2006a) in Figure 11. Early in the forecasting period there are variations between the two forecasts for diesel vehicles; however, their forecasts align by 2030. The EIA predicts that alternative vehicles will gain a smaller share of the market by 2030 (20% versus the model’s 30%). Additionally, the EIA predicts a larger share of the alternative vehicle market will go to ethanol vehicles, while my BAU scenario depicts a larger share going to hybrid electric vehicles. Variations in these forecasts likely arise

from different assumptions regarding the projected costs and market uptake of hybrid and ethanol vehicles as well as the incorporation of the outcomes of various policy efforts in the BAU. Uncertainty analysis will in part account for such variations in BAU assumptions.

Figure 11: EIA Forecast



3.2 Results of Policy Comparison

As discussed, the selected policies were set to meet the following two-fold target:

1. *Deep Emissions Reductions*: Reduce (direct) emissions to 60% below BAU 1990 levels by 2045.
2. *Widespread ZEV diffusion*: One-half (50%) of all vehicle stock is ZEVs by 2045.

The policies were adjusted using the base scenario parameters to be as stringent (or as large in the case of incentives) as necessary to meet the target. For simplicity, the stringency of most of the policies were simply increased (or decreased) linearly over time as required to meet the target.

3.2.1 Policy Details

The specifics of the policy simulations are detailed in Table 7. The percentage provided for the ZEV standard is the minimum new market share for zero-emission vehicles mandated by the policy. For the purchase subsidy, the amount indicated is the subsidy per battery electric vehicle purchased.

Table 7: Policy Details

	Policy Lever	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045
Tax	<i>\$/tonne CO₂</i>	0	295	310	326	342	360	378	398	418	439	462	485
ZEV Standard	ZEV (%)	0	2	5	10	15	20	30	50	60	70	80	90
Purchase Subsidies	<i>\$k/BEV</i>	0	15.8	15.5	15.1	14.7	14.3	14.0	13.7	13.3	13.0	12.6	12.3
ZEV only Standard then Tax	ZEV (%)	0	2	5	10	15	25	-	-	-	-	-	-
	<i>\$/tonne CO₂</i>	-	-	-	-	-	-	425	425	425	425	425	425
Purchase Subsidies plus Tax	<i>\$k/BEV</i>	0	15.0	14.6	14.3	13.9	13.6	13.2	12.9	12.6	12.3	12.0	11.7
	<i>\$/tonne CO₂</i>	0	20	24	30	36	44	53	65	79	96	117	142
Delay then Tax	<i>\$/tonne CO₂</i>	-	-	-	-	-	-	-	-	-	800	800	800
Delay then ZEV Standard	ZEV (%)	-	-	-	-	-	-	-	-	-	60	86	100

In addition to the policies described in Table 7, the use of a research and development (R&D) subsidy as a policy lever was explored. Combining a R&D subsidy with a tax or a ZEV standard was also examined. For these policy combinations, R&D subsidies were applied in the first period (from 1990 to 2005) such that the capital cost of biofuel plug-in vehicles in their introduction year, 2010, decreased from \$22,866 to \$20,170, which is 80% of their maximum possible reduction in cost. I assumed that cumulative experience and learning-by-doing is required, in addition to R&D, to reach the lowest possible cost of a technology.

The stringency of the tax and ZEV standard policies remained the same as denoted in Table 7. This simplification was chosen because of the lack of empirical evidence relating to the size and impact of automaker R&D on vehicle capital costs. This approach allowed for a comparison of the cost-effectiveness of a policy (tax or standard) with and without the effects of R&D investment, thus providing a crude estimate of the possible value of R&D investment in meeting the target.

Interestingly, it was found that solely subsidizing R&D (that is not combining the subsidy with other policies) results in minimal change from the BAU, and does not meet the target. In the model, R&D investment affects capital costs of a technology but does not provide any incentive to consumers to adopt the technology. Therefore, few consumers adopt the new technology and its intangible costs remain high. Since intangible costs are a significant hurdle for new technologies entering the market, lower capital costs garnered from R&D investment do not necessarily equate to substantial gains in market share.

The stringency of the policies should be noted. The tax reaches \$485/tonne of CO₂ by 2045, translating into an over \$4.00/gallon increase in the cost of gasoline. This equates to an over 150% increase in California's current price of gasoline. The standard eventually requires 90% ZEV new market share by 2045. Moreover, the subsidy required for battery electric vehicles is over \$10,000 per vehicle, just under one third the vehicle's capital cost in its first year of availability. As would be expected, the policies that delay action until 2035 necessitate even higher incentives and more stringent regulations than those that are applied beginning in 1995.

The stringency of the regulations and size of the market-based incentives required to meet the target reflect the extent of the challenge in inducing technological change in the passenger vehicle sector. Stringent policies are necessary even when declining capital and intangible costs from increases in market share have been endogenized in the model. However, a number of caveats must be considered when interpreting Table 7.

First, the model does not allow for vehicle technologies that have significantly decreased in market share to "die out" and become unavailable for the technology competition. Therefore, the model lacks the ability to depict how a technology could begin to dominate the market as other technologies become unavailable (Pratt & Hoffer, 1990). More importantly, because R&D investment is not endogenous to the model, additional innovation and the resulting cost improvements likely motivated by various policies are not captured. Nevertheless, the caveats described above should have minimal effect on the comparison of policy alternatives, a key objective of this study.

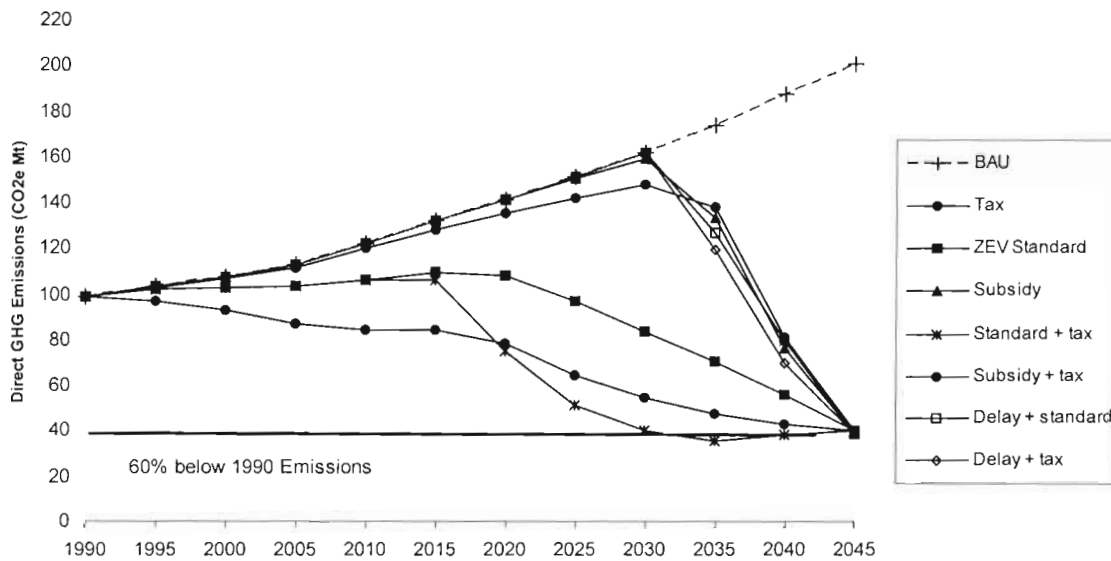
Next, I present the impact of the policies described above on direct and indirect emissions and ZEV diffusion.

3.2.2 Greenhouse Gas Emissions

Direct GHG Emissions

Direct emissions must reach 40Mt by 2045 in order to be 60% below 1990 levels. All policies reach this goal in a base scenario, when model parameters are set to their mean values (Figure 12). Business-as-Usual (BAU) direct emissions reach 201 Mt by 2045, 20% lower than the combined indirect and direct emissions considered in Figure 9. Note that subsidy here refers to a purchase subsidy and not an R&D subsidy.

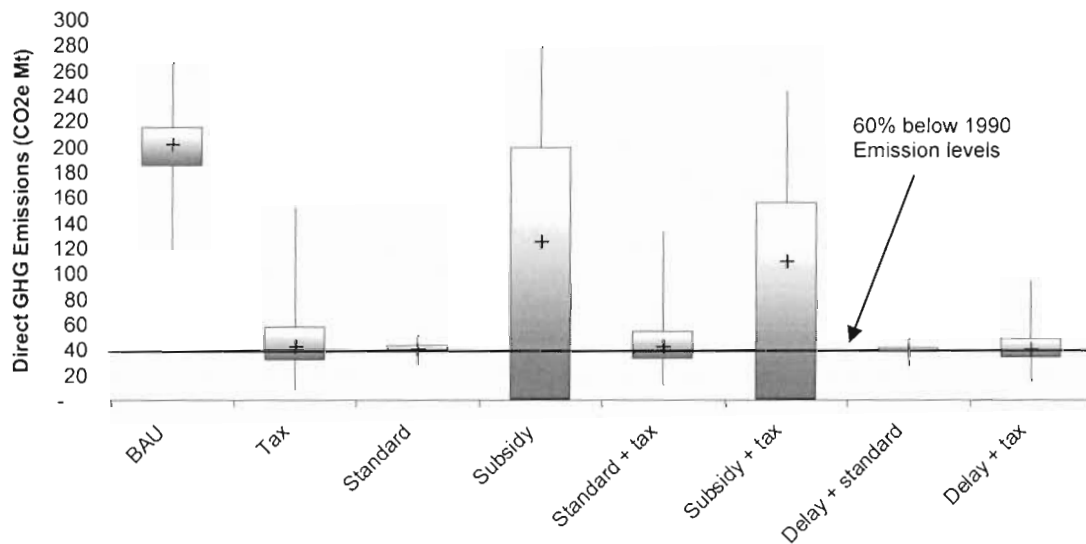
Figure 12: Direct GHG Emissions for Simulated Policies



As noted, the stringency of each policy measure was defined using the base scenario parameters. Subsequently, Monte Carlo simulation was used to analyze how GHG emissions may be impacted given uncertainty in these parameters (Figure 13). These data are presented in box-plot form indicating the median, shown with the symbol +; the interquartile range, which provides a measure of the dispersion of the Monte Carlo

results; and the minimum and maximum values resulting from the Monte Carlo runs. In the box-plot, the interquartile range, represented by the box, depicts the range between the 25% and the 75% quartile. About half of the data fall within the interquartile range (hereafter referred to as the “range”). The lines outside the boxes indicate the possible spread of data up to the data’s minimum and maximum values.

Figure 13: 2045 GHG Emissions Levels



Given uncertainty in the model parameters, all of the policies’ median 2045 emissions, except the subsidy, hover around the 40 Mt target. The subsidies have a wide range and their median emissions do not meet the target. These results indicate that the emission levels resulting from the subsidies are much more sensitive to changes in model parameters than the other policies. Moreover, while it is possible to reach very low

emissions with subsidies, overall, these policies are less likely to meet stipulated emission reductions.

Policies incorporating a standard have the narrowest range. Therefore, their resulting emission levels can be considered the most resilient to change in the uncertain parameters. This is due to the compulsoriness of standards where technological change is mandated through regulation. Of the two types of market-based policies assessed, taxes and subsidies, the taxes have a much narrower range and their resulting emission levels are thus considered more resilient to uncertainty.

The higher uncertainty of the subsidies can be attributed to their reliance on a single lever for inducing technological change, that is, consumers' acceptance of a subsidy towards the purchase of battery electric vehicles (BEVs). If the market conditions change slightly, for example a change in the predicted cost of BEVs relative to other vehicles, then consumer acceptance varies widely. All or very few consumers may be compelled to collect the subsidy and purchase BEVs, resulting in two extremes, either very low or very high GHG emissions.

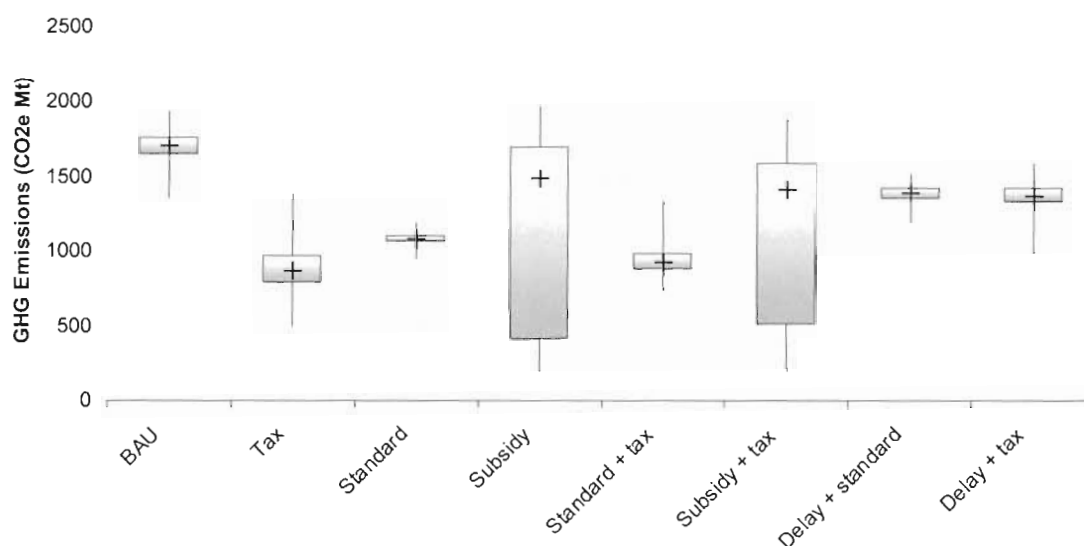
The emissions resulting from a tax are less uncertain because of the tax's inherent flexibility for the decision maker. For example, under a high tax, if the capital cost of an alternative technology like the BEV is higher than predicted, other competing low-emission technologies will be adopted in place of the BEV and/or consumers will reduce their demand for vehicle use.

These results highlight the importance of careful policy design, particularly with respect to subsidies. For example, creating more options for consumers by broadening the scope of the subsidy to include all zero-emission technologies would likely reduce its

uncertainty. Similarly, a performance-based subsidy providing financial incentives for technologies based on their GHG emissions per mile would provide increased flexibility to the consumer and increased certainty in the subsidy’s resulting emission levels.

The relative impact of uncertainty on the policies 2045 emissions are echoed when examining their cumulative emissions (Figure 14).

Figure 14: Cumulative Direct GHG Emissions

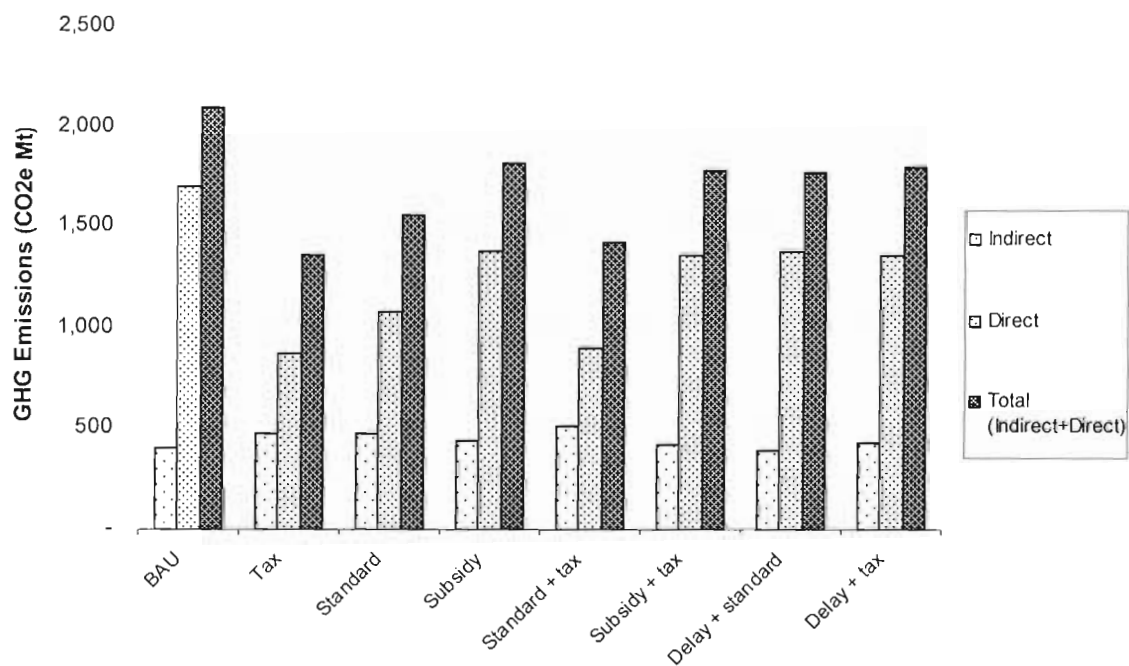


Relative to the BAU, the tax results in the largest median decrease in cumulative emissions, followed by the standard combined with tax. The subsidies have the lowest median reduction in cumulative emissions. Note that when policy action is delayed, reductions in cumulative emissions are significantly diminished. Compared to implementing a tax in 1995, by delaying action until 2035, over 500Mt of emission reductions are foregone.

Indirect GHG Emissions

The target stipulated reducing direct GHG emissions from the passenger sector. However, to fully capture the effect of the selected policies on emissions, indirect GHG emissions must also be considered (Figure 15).

Figure 15: Breakdown of Cumulative GHG Emissions – Direct and Indirect Emissions



Indirect emissions make up 20% of cumulative emissions in BAU and between 25-35% of cumulative emissions of the various policies. Due to the high penetration of zero-emission vehicles resulting from the policies, when total (indirect and direct) emissions are considered, the policies' 2045 emissions levels only reach between 19% and 25% below 1990 levels (rather than 60%). Zero-emission vehicles have zero direct

emissions but do contribute to indirect GHG emissions from the production of alternative fuels, for example electricity generation.

As discussed in Chapter 2, the indirect emission intensities of the various fuel types, particularly electricity, were assumed to be decreasing over time. Nonetheless, it was found that these emission sources play a significant role in overall GHG emissions for all of the policies. This highlights the importance of considering the upstream emissions of fuels in policy proposals targeted at reducing emissions from the passenger vehicle sector.

3.2.3 ZEV Diffusion

The target set out in this study was to reduce GHG emissions while also increasing the diffusion of zero-emission vehicles (ZEVs) to at least 50% of the total vehicle stock by 2045. The vehicle stock is made up of several vintages of vehicles, therefore to meet the goal, ZEVs must be purchased over several periods. The level of ZEV diffusion varied depending on the policy (Table 8).

Table 8: ZEV Diffusion in Policy Alternatives Tested

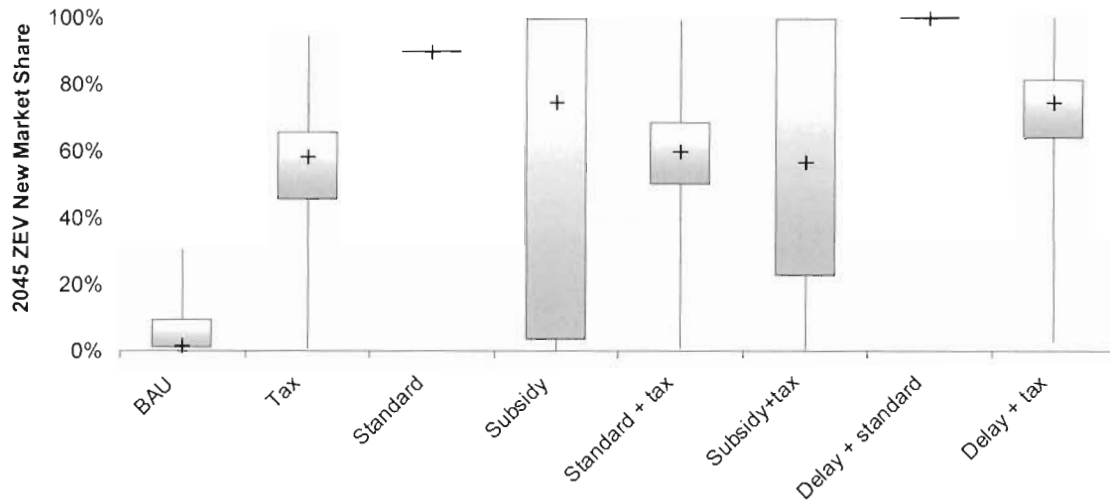
	BAU	Tax	Standard	Subsidy	Standard + tax	Subsidy + tax	Delay + standard	Delay + tax
2045 New ZEV MS	4%	60%	70%	75%	60%	98%	100%	75%
Share of ZEV in 2045 Stock	3%	55%	79%	77%	62%	78%	75%	55%

Using the base scenario parameters, all policies result in ZEVs contributing to over 50% of the stock in 2045 (the target level) and at least 60% ZEV new market share in 2045. The tax is predicted to have the lowest amount of ZEV diffusion. The tax

results in more diverse means, for example low-emission vehicles and reductions in vehicle use, being employed to reach the emissions goal. The lower ZEV diffusion resulting from the tax may be in part attributed to the model's inability to fully capture all of the aspects of technological change, particularly how one technology may gain momentum and begin to dominate the market as other technologies "die out". It is highly uncertain a tax would result in a diverse set of technologies and approaches used to reduce emissions, as depicted by the model, rather than in a single technology dominating the market.

Figure 16 shows the Monte Carlo simulation results for 2045 ZEV new market share for each policy assessed. As expected, by mandating ZEV market share through regulation, the standard has a high amount of certainty associated with its results. The market-based policies, particularly the purchase subsidies, have a considerable uncertainty in their resulting ZEV market share, depicted by their wide range.

Figure 16: 2045 ZEV New Market Share (%)



3.2.4 Key Characteristics of Policy Alternatives

While each policy results in ZEVs making up over 50% of the vehicle stock by 2045, the mix of ZEV technologies that gain share in the market varies by policy. As expected, the subsidized battery electric vehicle (BEV) dominates the ZEV market share in the subsidies, whereas the tax induces increases in the market share of the biofuel plug-in electric vehicle (BPHEV). The ZEV standards result in a split in market share over time between BEVs and BPHEVs. In the standard, BEVs increase in market share early in the forecast period, but upon BPHEV introduction, BPHEVs gradually gain and eventually dominate ZEV market share. These variations in ZEV market share highlight the potential for policy type, as well as its timing and design, to influence technological change.

Hydrogen fuel cell vehicles (HFCVs) do not penetrate the market in any policy simulations. Some analysts predict that if deep GHG emission reductions are mandated, mass-produced HFCVs will be competitive with other vehicle technologies (Odgen et al, 2004). However, in my modelled scenario, HFCVs cannot compete because of their high initial capital and intangible costs in combination with their late introduction year. HFCVs never establish market share by which capital and intangible costs may decline. Because biofuel plug-in electric vehicles have lower initial capital and intangible costs, in part because of their relative similarity to conventional vehicles, their transition to a niche market and then broader adoption is much easier than HFCVs. Thus, early niche markets are important for increasing the competitiveness and, thus, diffusion of a ZEV technology. HFCVs will require lower initial costs, perhaps through increased R&D investment, to begin to compete in niche markets.

Table 9: Highlighted Characteristics of Policy Alternatives

	BAU	Tax	Standard	Subsidy	Standard + tax	Subsidy + tax	Delay + standard	Delay + tax
% Cars 2045 (vs. Trucks)	50%	72%	68%	70%	75%	70%	70%	70%
Overall VMT Demand (relative to BAU)	-	-4%	1%	1%	-0.4%	-0.1%	0.8%	-2%
Capital Cost Reduction by 2045 ¹								
BPHEV	15%	15%	15%	15%	15%	15%	15%	15%
BEV	0%	0%	45%	45%	45%	45%	0%	0%
HFCV	0%	0%	0%	0%	0%	0%	0%	0%
Intangible Cost Reduction by 2045 ²								
BPHEV	30%	100%	100%	29%	100%	30%	100%	100%
BEV	0%	0%	60%	80%	80%	80%	0%	0%
HFCV	0%	0%	0%	0%	0%	0%	0%	0%

¹ Reductions in 2045 capital cost relative to cost in the first year available.

² Reductions in 2045 intangible cost relative to cost in first year available.

As illustrated in Table 9, in the BAU scenario, the split between cars and trucks remains relatively constant, hovering around 50% in 2045. However, in all of the policies, cars gain market share over trucks, taking 68-75% of new market share. The policies cause a decrease in the weighted average cost of cars relative to trucks resulting in more consumers choosing cars over trucks.

Table 9 also shows that all policies result in a change in overall vehicle use (demand for VMT) relative to BAU. These changes are driven by changes in the cost of driving, which include fuel costs and any emission charges. The tax on emissions increases the cost of driving and thus results in decreased demand for vehicle use. In contrast, the standard and subsidies result in an increase in vehicle use relative to BAU. This rebound effect results from consumers switching to more fuel-efficient vehicles, effectively lowering the cost of driving and increasing vehicle use. Note that the rebound effect, which has implications for GHG emissions, is tempered when the standard and subsidy are combined with a tax.

The impact of free-riders is also an important consideration for policy design, particularly with respect to subsidies. The battery electric vehicle subsidies result in very few free-riders as there is a negligible amount of these vehicles purchased in business-as-usual. However, it is expected that there would be a number of consumers who would purchase battery electric vehicles for a lower subsidy than what is provided because of heterogeneity in the consumer base, thereby causing an unnecessary cost to taxpayers. Further, as costs in BEVs decline with increased market share, the expected number of free-riders will increase.

Finally, the impact of various policies on the capital and intangible cost of ZEVs is also depicted in Table 9. A policy that results in lower costs for ZEVs early in the forecasting period will similarly enable a lower cost of ZEV diffusion. In the BAU, the capital cost of the biofuel plug-in vehicle (BPHEV) reaches its lowest value, a 15% reduction from its initial cost, by 2045. In contrast, due to increased BPHEV market share, all policies except the subsidies result in BPHEVs attaining their minimum capital cost by 2020 (versus 2045 in BAU). The intangible costs of BPHEVs represent an even larger variation between the BAU and the policy scenarios. In the BAU, BPHEV intangible costs are reduced from their initial value by 30% by 2045. The tax and the standard policies result in the intangible costs of BPHEVs reduced by 100% by 2025.

The standard and the subsidies also result in increases in battery electric vehicle (BEV) market share and thus significant reductions in the capital and intangible costs of BEVs. Because hydrogen fuel cell vehicles (HFCVs) do not penetrate the market in any policy simulations, no reductions in their costs are observed. As noted the path of ZEV costs relative to BAU plays a significant role in the cost of policies, discussed in the following section.

3.2.5 Costs of Policy Alternatives

This analysis uses expected resource costs to estimate the cost of the policies relative to BAU. The expected resource cost of a policy is comprised of the cost associated with consumers switching from technologies that they would have otherwise adopted in the BAU and the costs associated with shifts in demand for vehicles and/or vehicle use (VMT). As described in Section 2.2.2, the expected resource cost assumes a heterogeneous consumer base and includes financial costs, some portion of intangible

costs and premium for risk, to the extent that these values are real and not a result of market failures. Monte Carlo analysis was performed to estimate uncertainty in policy cost.

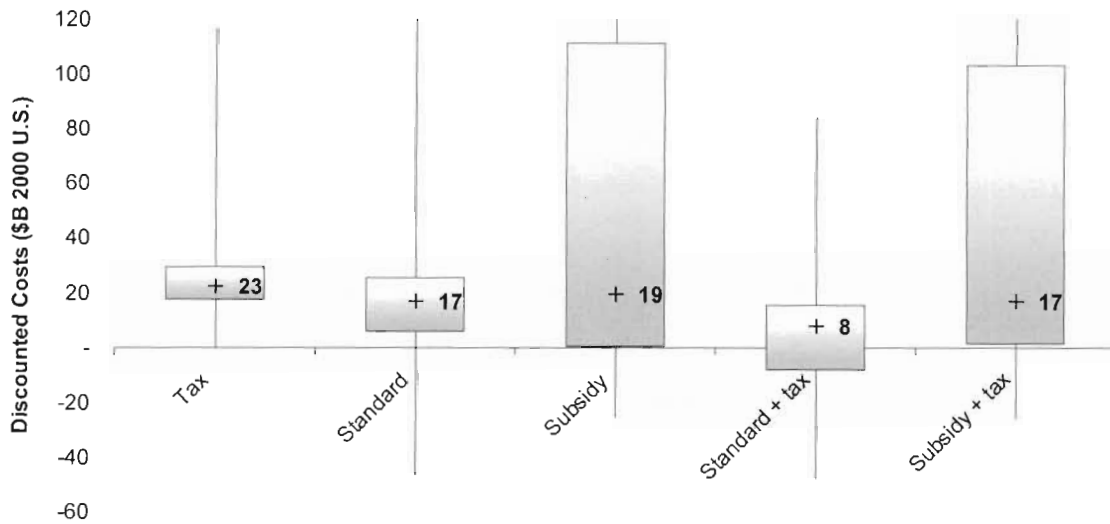
First, I compare the cost of policy alternatives implemented in 1990. Next, I examine how an injection of R&D investment for both the tax and the standard affects their costs. Finally, I explore the impact of delaying action until 2035 on policy cost.

Policies Implemented in 1990

The costs of policies implemented in 1990 are presented in Figure 17. The costs are discounted back to 1990 at the rate of 3% per year and presented in year 2000 U.S. dollars. Discounting costs attempts to capture society's preferences for present versus future consumption.¹⁶ The social discount rate (opportunity cost of capital) was chosen to fall between the range of 0.5% and 6% per year observed in the literature (IPCC, 1995). The sensitivity of the results to the selected discount rate are explored in Section 3.3. Once again, a box-plot is chosen to present the results. Positive numbers represent a cost, whereas negative numbers represent benefits derived from the policy. Negative costs or welfare improvements may occur when the intangible and capital costs of a new technology decline such that consumers benefit from adopting a vehicle with lower operating costs (generally fuel costs).

¹⁶ Note that the discount rate used here is different from that used in the model to capture how consumers value present and future costs when purchasing a vehicle.

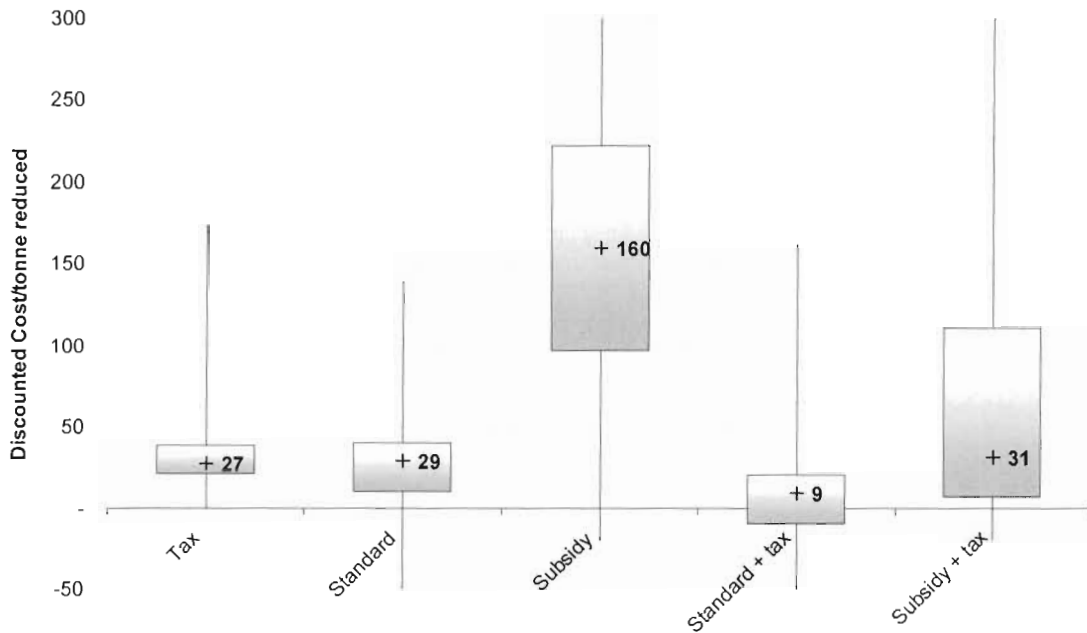
Figure 17: Cost of Policy Alternatives – discounted to 1990 at 3%/year, 2000 U.S dollars



The standard then tax has the lowest median cost, followed by the standard alone and the combination of a purchase subsidy with a tax. The tax and the subsidy implemented on their own have the highest median costs. Once again, the purchase subsidy policies have the widest range of their costs, indicating more uncertainty in their results.

Because of differences in their cumulative emission reductions, examining the cost of the policies per tonne of CO₂ reduced, allows a more informative comparison between the policy alternatives. This so-called cost-effectiveness analysis will remove the differences in cumulative emission reductions between policies, allowing a determination of the lowest cost option for meeting the target. Figure 18 shows the cost-effectiveness or average expected resource cost of the policies per tonne of CO₂ reduced. Note that while costs are discounted in these results, emissions are not.

Figure 18: Cost-Effectiveness of Policy Alternatives per tonne CO₂ reduced – costs discounted to 1990 at 3%/year, 2000 U.S dollars



The cost-effectiveness analysis presents a different rank order of the policies than that based on total costs. The standard and tax combination still has the lowest median cost per tonne of CO₂ reduced. The tax, standard and the combination of subsidy and tax are comparable in terms of their median cost-effectiveness.¹⁷

The combination of subsidy with tax has a much wider range than the tax or the standard policies. The range of the subsidy-tax combination is \$105 whereas the range for the tax is \$18 and standard is \$31. The subsidy is the least cost-effective as it has the

¹⁷ For a linear marginal abatement curve, we would expect the average cost/tonne of the tax policy to be half the tax rate applied. For the tax policy, the average cost presented here (\$27/tonne) is much lower than the applied tax (tax increases over time to \$425/tonne) for several reasons. First, the cost presented here is discounted while the emissions are not (this will lower the average cost/tonne). Second, the tax rate changes over time, however the cost presented here is over the entire forecasting period. Upon adjusting for these factors, it was noted that the average cost/tonne in a single period was about one third of the tax rate applied in that period. Thus, the shape of the marginal abatement curve for emission reductions in this sector is not linear but likely quadratic.

highest median cost per tonne of CO₂ reduced. Its costs also have the highest uncertainty. The relatively poor cost-effectiveness of the subsidy is due to its unpredictable emission reductions and its reliance on battery electric vehicles, a relatively expensive technology, to reduce GHG emissions. Note the substantial improvement in the cost-effectiveness of the subsidy when it is combined with a tax.

The standard and tax policy is most cost-effective as it induces gains in the market share of ZEVs early in the forecasting period resulting in reductions in the capital and intangible costs of ZEV technologies. Then, when the tax is implemented, ZEV market share continues to grow at relatively low cost to the consumer while other cost-effective methods of reducing emissions are also introduced, namely the growth in hybrid electric vehicle market share. Further, the tax neutralizes increases in the demand for vehicle use caused by the adoption of more fuel-efficient vehicles (rebound effect).

In contrast, while a simple tax results in reductions in the demand for vehicle use and increases in the penetration of ZEVs, it also relies on a more diversified response and therefore less early concentration of ZEVs. Thus, the cost savings in the ZEV technologies are not gained early in the forecasting period. The standard forces consumers to adopt ZEVs even when more cost-effective reductions could be garnered by adopting low emission technology or reducing demand. The standard then tax policy provides the benefits of both the tax and standard by balancing between reducing the costs of ZEVs for emission reductions in the future and using other cost-effective means to reduce emissions in the present.

A number of caveats should be highlighted in extrapolating these results from the modelled environment. First, these simulations assume that both government and the

firm are myopic and thus unable to predict and act on the lowest cost path for present and future emission reductions. That is, both the policy-maker and the firm cannot foresee the potential reductions in both intangible and capital costs of the various technologies to be garnered from experience. If one assumes that firms and governments have some foresight, the results presented here likely overestimate the costs of the policies. This is particularly relevant for the tax policy as the standard automatically captures many of the cost savings from experience by forcing the adoption of ZEVs. Second, as previously discussed, the model does not take into account innovation induced from policy, which would likely affect the policy costs. In the following section, I present results comparing the most cost-effective policy discussed above, the standard then tax, with a delay then act strategy.

Act Early versus Delay Strategy

There remains controversy around the optimal timing of policy to reduce GHG emissions (Grubb, 1997). To explore how this debate might influence the policy comparison performed here, I compared the costs of implementing policy in 1990 (with the cost-effective standard then tax policy) with delaying action until 2035. As discussed above, a key difference between taking early action and delaying is the large variation in cumulative emissions between the two strategies. Here I evaluate both the median costs of the policies (Figure 19) as well as the median cost-effectiveness of the policies (Figure 20). Because of the significance of discount rate in analyzing act now versus delay strategies, all of these results are shown with varying assumptions of the discount rate.

Figure 19: Median Costs by Discount Rate (2000 U.S. dollars)

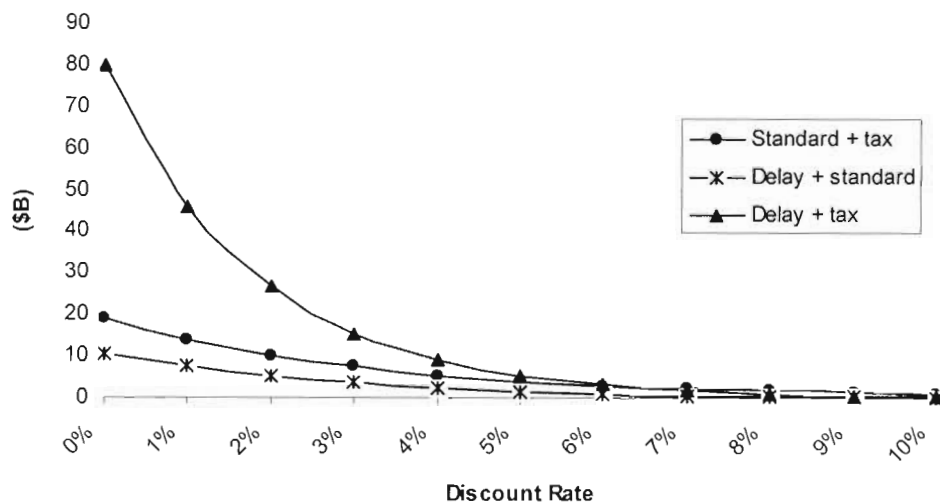


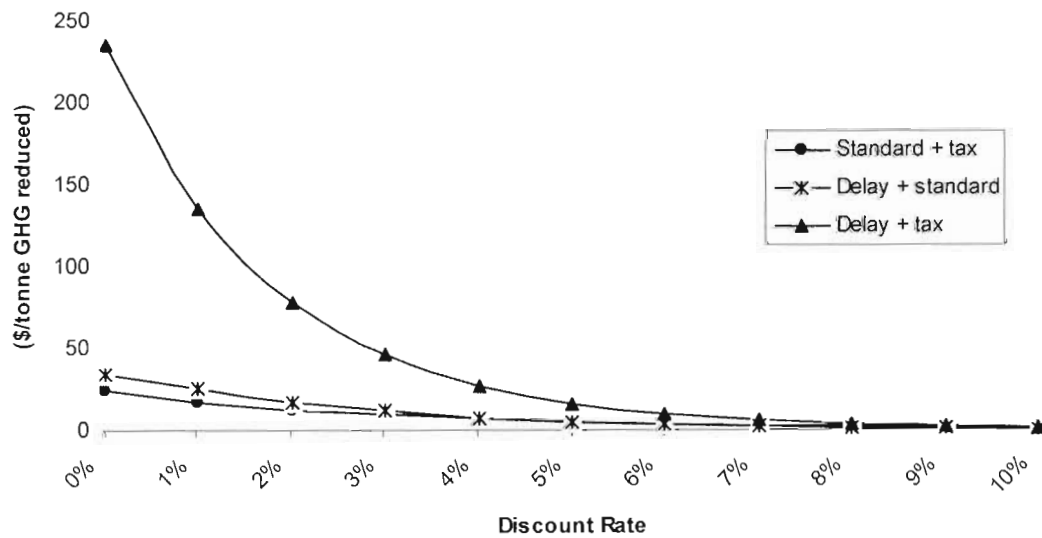
Figure 19 illustrates that independent of the discount rate, the delay plus standard strategy always has the lowest total cost. Even with a discount rate of 0%, the standard plus tax policy has higher costs than the delay then standard strategy. This is because by 2035 the biofuel plug-in vehicle (BPHEVs) has begun to get a very small amount of market share even without policy intervention. Implementing a standard in 2035 quickly forces large increases in the market share of BPHEVs, which then lowers the intangible costs of the technology, allowing a significant portion of the market to adopt the BPHEVs at a substantially reduced cost. Therefore, in this scenario, implementing a standard policy in 2035 provides enough time for BPHEVs to gain market share and thereby reduce their capital and intangible costs. On the other hand, delaying and then implementing a tax results in higher costs as the efforts are spread out with some consumers adopting hybrid electric vehicles, some lowering their demand for vehicle use

and some adopting ZEVs. Thus, by scattering the market among these differing options, costs for ZEV technologies do not decrease as substantially.

However, these results are based on the uncertain assumption that biofuel plug-in hybrids (BPHEVs) will be available at a relatively low entry cost in the future without any policy intervention. If BPHEVs are not available and an alternative ZEV technology is required to meet the prescribed target in 2035, the cost of the delay strategies would be expected to rise substantially.

As discussed a large difference between the act now versus delay strategies is in their total cumulative emissions. The cost-effectiveness of these policies per tonne of CO₂ reduced is shown in Figure 20.

Figure 20: Median Cost-effectiveness by Discount rate (\$/tonne GHG reduced)



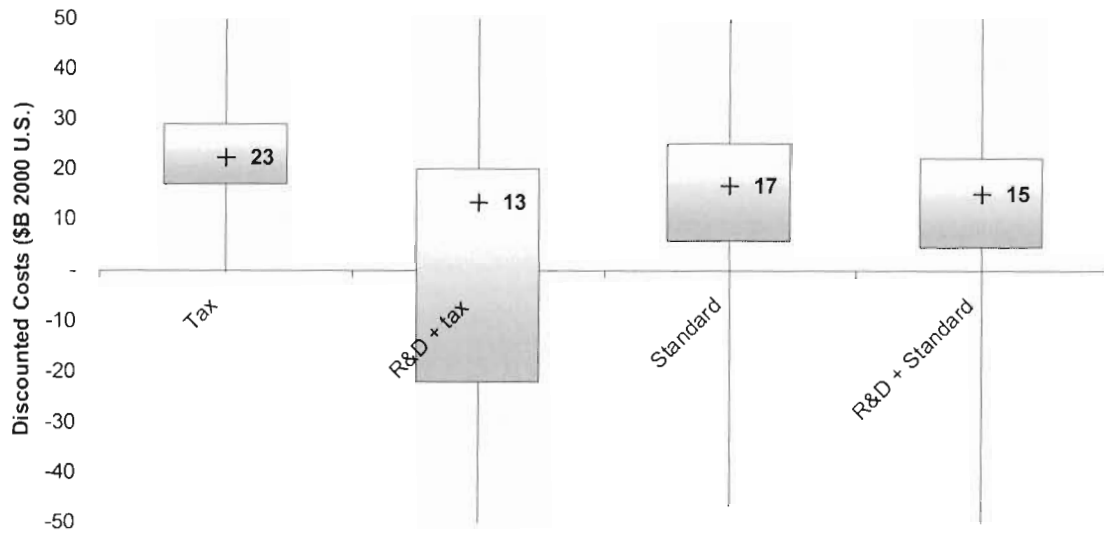
Based on their median results, for a discount rate from 0-6%, the standard then tax is the most cost-effective policy, followed by the delay plus standard strategy. This is because the cost of the standard then tax is divided over its large cumulative emission reductions. However, if the discount rate is increased to 7%, the delay plus standard strategy becomes the most cost-effective policy. This illustrates the power of discounting, particularly when examining act now versus delay strategies.

Therefore, if decision-makers can foresee that the cost of BPHEVs will decline without a policy *and* they can forego the cumulative emission reductions lost by deferring action, delaying may be the lowest-cost strategy. However, there is risk involved as the technological pathway of BPHEVs is uncertain, meaning that delay could involve significant costs. In a future study, one could account for such risks by determining the probabilities associated with the technological pathway of ZEVs, such as their costs and their availability. Using probabilities to establish the expected costs of policies, the risks of these approaches could be compared.

Potential Impact of R&D Investment on Policy Cost

The potential impact of R&D investment on the discounted costs of select policies is depicted in Figure 21. For these simulations, it is assumed that the R&D subsidy is targeted at the biofuel plug-in vehicle (BPHEVs) technology from 1990 to 2005. This R&D subsidy results in a substantial reduction in the capital cost of BPHEVs. The cost of the policy with and without this R&D investment is compared. Note that the R&D investment is not included in the cost of the R&D policies shown here.

Figure 21: Impact of R&D Investment on Discounted Costs of Policy – discounted at 3%



As expected the R&D subsidy results in lowering the median cost of both the tax and the standard policy. It is interesting to note that the R&D investment has a substantially larger impact on reducing the costs of the tax policy. The standard policy already has lower BPHEV costs gained through experience without the R&D investment.

In essence, what this exercise is telling us is that if the discounted R&D subsidy is less than the cost difference between the policy with and without the R&D investment, it is cost-effective to invest in R&D. Therefore, for the standard, the discounted R&D subsidy would have to be less than \$2B. For the tax, a greater R&D subsidy, up to \$10B, is warranted. Comparing these findings relative to previous government R&D subsidies targeted at clean vehicle technology shows that over a long period it is not unrealistic to assume that R&D subsidies could amount to \$2B. For instance, the R&D budget for Partnership for a New Generation of Vehicles (PNGV), a consortium made up of U.S.

government agencies and automakers dedicated to alternative vehicle research, was \$950M in the period from 1997-2000 (Burke, Kurani, & Kenney, 2000). However, a state acting alone would likely have more limited resources.

It may also be useful to interpret these results through the lens of a firm whereby they would invest in R&D if it were profitable under a policy scenario. For example, if firms are required to subsidize BPHEVS so that consumers purchase the vehicles under a ZEV standard, firms may choose to invest in R&D to lower the cost of BPHEVs and increase their profit. Alternatively, if firms under the tax policy observe that reducing the cost of BPHEVS will increase their sales and their profit, they will be motivated to invest in R&D. Both of these figures presented above are within the realms of the R&D budgets of the big five automakers. For instance, Ford and Toyota spent just over \$7B and \$6B on R&D in 2004 respectively (Technology Review, 2005). Additionally, GM is reported to have spent \$1B on the development of an electric car (Shnayerson, 1996).

Note that this is a very rudimentary treatment of R&D investment and is meant only to begin the process of exploring how R&D investment may affect policy cost. First, there is significant uncertainty around predicting the success and effect of R&D investment. Second as discussed, this treatment does not incorporate endogenous R&D induced by policy or the effect of spillover.

3.2.6 Are ZEVs Required?

To understand the emission and costs trade-offs involved in prescribing ZEV diffusion as part of the target, two additional scenarios were examined. First, I examined whether the GHG target could be met without the adoption of ZEVs. I calculated the

GHG emissions of a stock entirely comprised of ultra-low emission vehicles (ULEVs), specifically hybrid electric, plug-in hybrids and ethanol vehicles, all of which have lower initial capital and intangible costs than ZEVs. It was found that a vehicle stock of 100% ULEVs would result in significant reductions in GHG emissions over time, but unlike ZEVs, ULEVs eventually plateau in their capability to reduce GHG emissions. Thus, a vehicle stock comprised of ULEVs does not result in emissions reaching 60% below 1990 levels by 2045. A stock comprised of 100% ULEVs has 2045 median GHG emissions almost 60 Mt higher than the 40 Mt target.

Unless vehicle usage is significantly constrained, the diffusion of ZEVs are required for deep GHG reductions. The next scenario explores the cost and emission trade-offs if the goal of ZEV diffusion is removed. To this end, a standard policy with the same market share requirements as the ZEV standard detailed in Section 3.2.1 was simulated. However, in this more flexible policy, ULEVs, in addition to ZEVs, are allowed to qualify in meeting the mandated market share (ULEV-ZEV standard).

Table 10 compares the median results of this ULEV-ZEV standard with both the ZEV only standard and those of the most cost-effective ZEV policy, the standard then tax.

Table 10: ULEV-ZEV Standard Compared with ZEV Standard and Standard plus tax

	ULEV-ZEV Standard	ZEV Standard	Standard + tax
Cumulative GHG Emission Reductions (CO₂e Mt)	220	618	773
2045 GHG Emissions (CO₂e Mt)	155	40	42
Average Cost/tonne reduced (\$)¹	20	29	9

¹ Costs discounted at 3%/year to 1990 in year 2000 U.S. dollars.

As expected, the ULEV-ZEV standard results in much more moderate emission reductions than the other policies. However, the ULEV-ZEV standard has a lower average cost/tonne than the ZEV standard. Thus, by allowing ULEVs to meet the market share requirements of the standard, it improves the standard's cost-effectiveness. However, even with this increased flexibility, the ULEV-ZEV standard remains less cost-effective than the ZEV standard plus tax policy. The significant emission reductions of the standard and tax policy over the forecasting period, as well as its ability to capitalize on the dynamics of technological change, contribute to its cost-effectiveness.

ULEV technology has lower initial costs, less infrastructure requirements and more certainty about future costs and performance. Thus, depending on the policy design, if more moderate emission reductions are required, adding an objective of ZEV diffusion may increase costs. Combining a ULEV policy with a policy that reduces demand for vehicle use or reduces the GHG intensity of fuels would have even more impact on emissions (but also on costs). However, for very deep reductions in GHG emissions from the passenger vehicle sector, ULEV technology is unlikely to be sufficient and a transition to ZEVs is likely required.

3.3 Single Parameter Sensitivity Analysis

3.3.1 Sensitivity of Cost Comparisons to Social Discount Rate

As noted, there is a considerable range in the discount rates used in policy analysis. While the social discount rate has particular implications in the debate surrounding whether we should act now or delay action, it also may affect the results of the other policy comparisons. A sensitivity analysis was completed to understand the

effect of the discount rate on median policy costs (Figure 22) and cost-effectiveness (Figure 23).

The rank order of policies in terms of cost and cost-effectiveness is only marginally sensitive to discount rate. The standard and tax combination has the lowest total cost over a social discount rate of 0% to 8%. With a discount rate of 9% and 10%, the subsidy policies become slightly less expensive than the standard plus tax. The subsidies' costs are generally consistent over time, whereas the standard plus tax's costs decline over time. Since a higher discount rate emphasizes near-term costs, it favours the subsidies. The costs of the standard and the subsidy are most sensitive to discount rate illustrated by the steepness of their curves in both figures. Both of these policies are predicted to have higher median costs out in time making their results more sensitive to the chosen discount rate. The standard then tax is the most cost-effective policy over all tested values of the discount rate.

Figure 22: Sensitivity of Median Policy Costs to Social Discount Rate

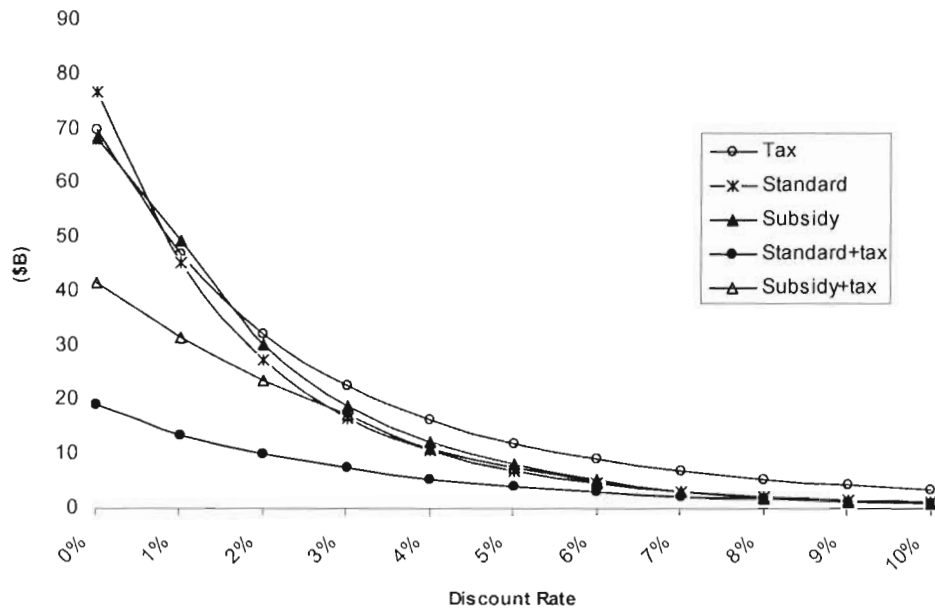
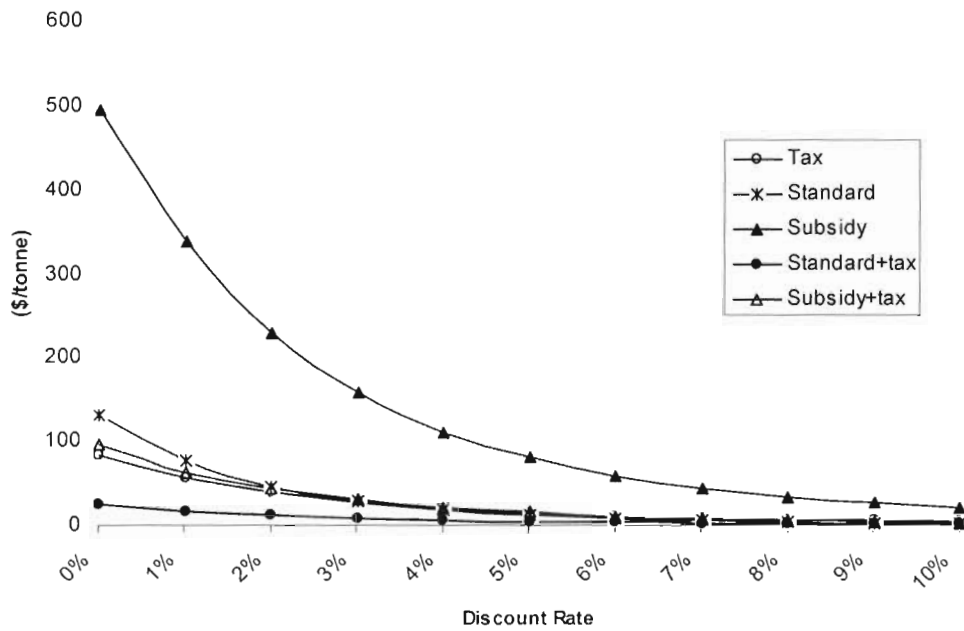


Figure 23: Sensitivity of Median Cost-effectiveness to Social Discount Rate



3.3.2 Determining Key Uncertain Parameters

While Monte Carlo simulation provides an aggregated depiction of the influence of uncertainty on the results, it cannot be used to differentiate between the effects of one uncertain parameter over another. In this section, I perform single parameter sensitivity analysis, quantifying the fluctuation of selected results by a change in a single parameter in the model. This analysis allows for a better understanding of where key uncertainties lie and may help to inform future research and modelling endeavours, for example by prioritizing efforts in narrowing the uncertainty of certain parameter values.

The following results are broken up into two parts. First, I examine the sensitivity of the 2045 GHG emission levels of the selected policies (Figure 24). Second, I explore the sensitivity of 2045 ZEV new market share (Figure 25). For this analysis, the high and low values of key uncertain parameters were changed one at a time. For each scenario, the results from the five parameters that contribute to the most fluctuation from the base scenario are presented, from highest deviation from the base scenario to lowest deviation, in a tornado diagram.

The bars of the tornado diagram represent the change in output with a change in the corresponding parameter. The value of the changed parameter is written beside the bar. For example, Figure 24 – BAU, analyzes the sensitivity of BAU 2045 emission levels to changes in uncertain parameters. The BAU base parameter emissions are 201 Mt, represented by the vertical line in the diagram. The discount rate shown here represents the value used in the model to capture vehicle purchase decision-making, not the social discount rate discussed in the previous section. Decreasing the discount rate, from its base value, 25%, to 20% reduces the emissions to 179 Mt; similarly increasing

the discount rate to 30% increases the emissions to 211 Mt. The BAU emissions are most sensitive to the variance parameter characterizing the heterogeneity of consumers within a class of vehicles (within class v). Decreasing v to 11, making consumers more sensitive to life-cycle costs of technologies, decreases emissions to 173 Mt. On the other hand, decreasing consumers' sensitivity to life-cycle costs by increasing v to 19, increases emissions to 213 Mt.

Figure 24: Single Parameter Sensitivity –2045 CO2e Emissions (Mt)

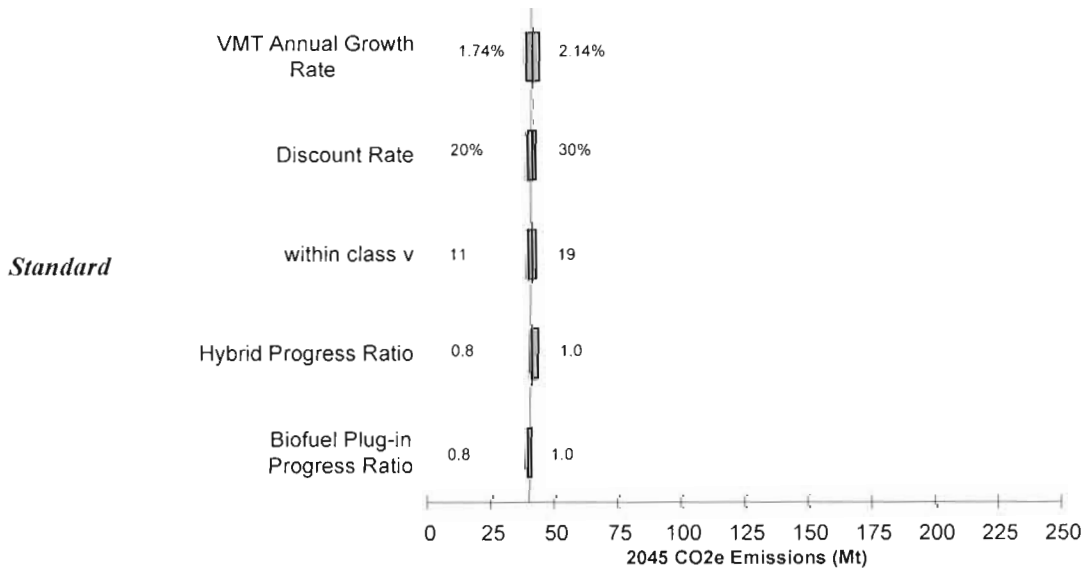
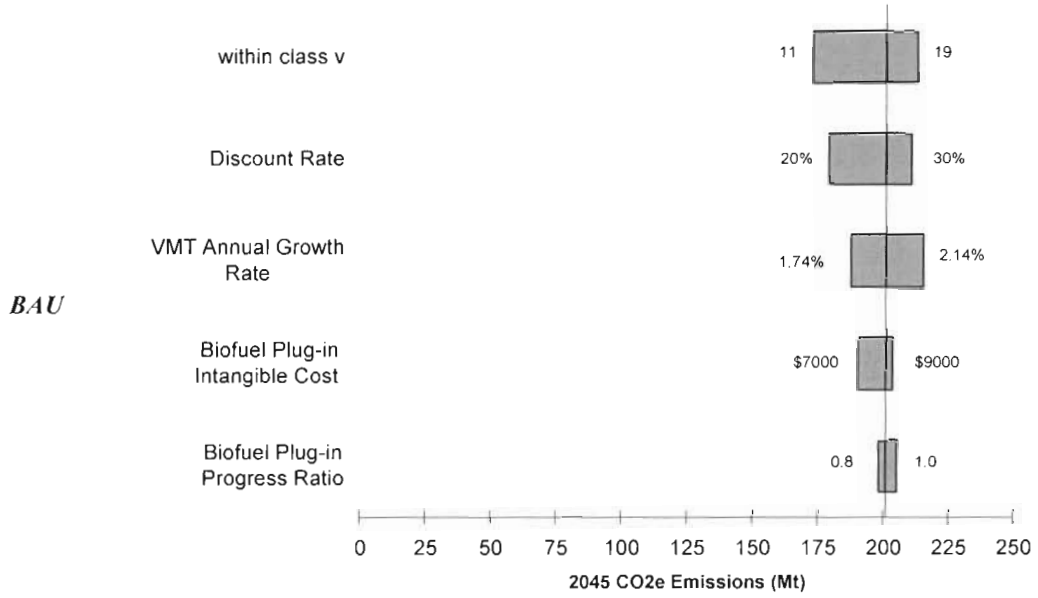
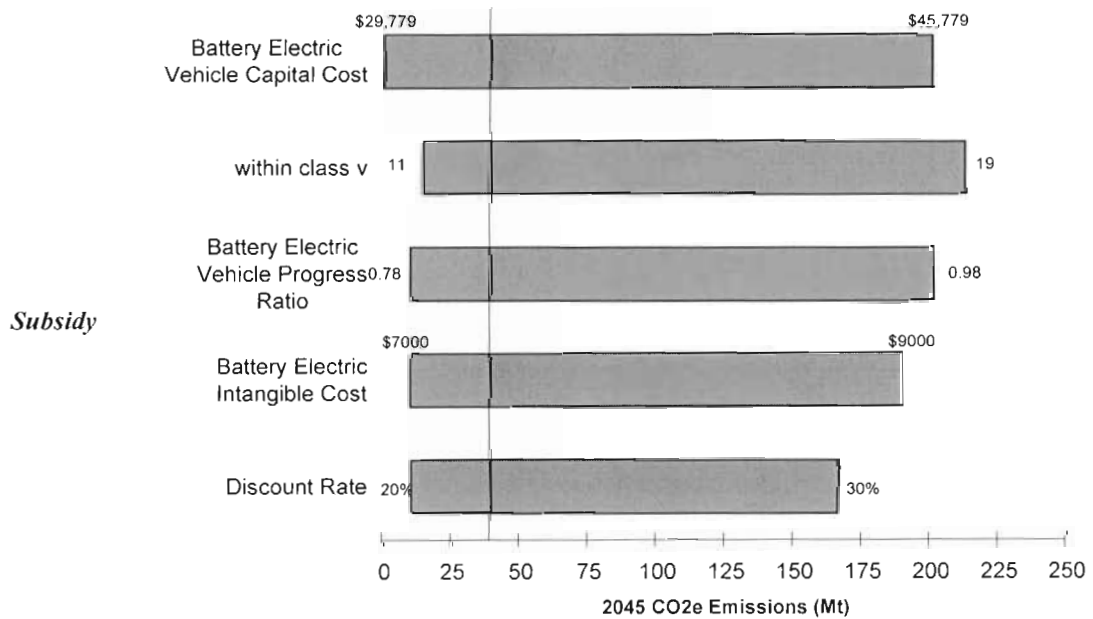
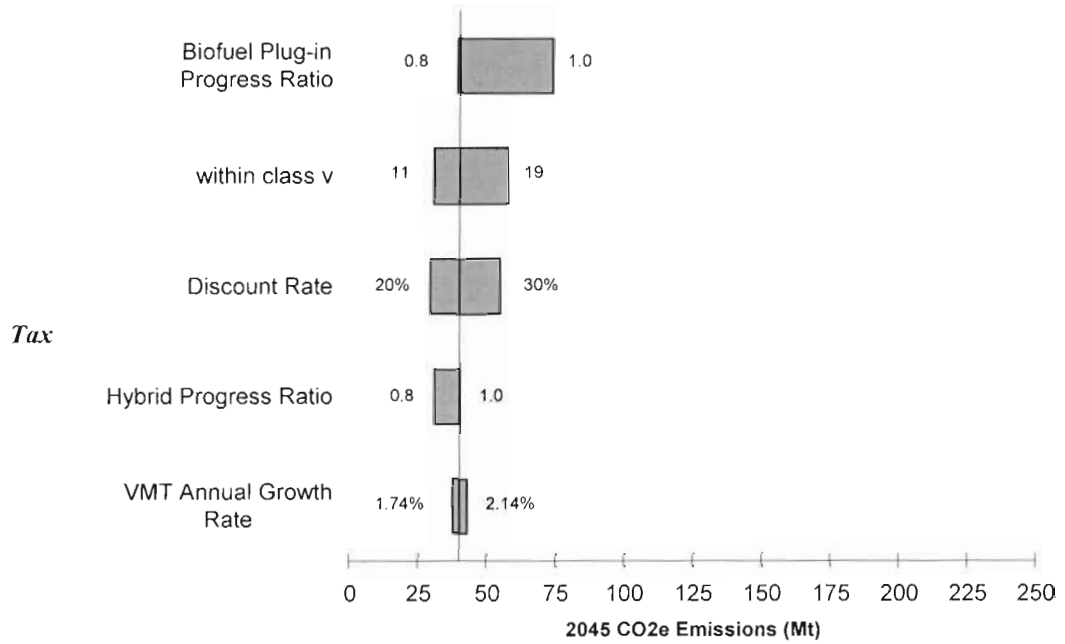


Figure 24 continued.



As in the case of the Monte Carlo analysis, the purchase subsidy emissions are most sensitive to changes in uncertain parameters. For example, a shift in the starting capital cost of battery electric vehicle from the base value of \$37,779 to \$29,779 decreases 2045 emissions from 39 Mt to only 1 Mt. A similar increase in the capital cost results in an increase in emissions to 201 Mt. The subsidy is also very sensitive to the v parameter and the discount rate. As expected, the subsidy is highly sensitive to the parameters characterizing the battery electric vehicle (BEV) technology, such as capital and intangible costs and the progress ratio, which dictates how quickly costs of electric vehicles will decline with experience.

The standard is the least sensitive to uncertainty because of its compulsory nature. Therefore, its emissions change only very slightly with changes in the parameter values. The BAU and policy runs are sensitive to a number of common parameters. The BAU, the tax and the standard results are all sensitive to the discount rate, the within class v parameter and the annual growth rate for vehicle use (VMT). While the subsidy is most sensitive to changes in the characteristics of battery electric vehicles, the BAU, standard and tax are more affected by changes in the parameters of the biofuel plug-in and the hybrid electric vehicles.

Figure 25 shows the sensitivity of 2045 ZEV new market share to changes in the parameters.¹⁸ For the most part these results echo those found in Figure 24. Once again, the subsidy is the most sensitive to uncertain parameters. Again, both the BAU and the policies are sensitive to the within class v parameter and the discount rate. The ZEV diffusion of the tax is sensitive to the plug-in vehicle progress ratio. For the market-

¹⁸ The standard was not included in Figure 25 as it mandates ZEV market share. Thus, changes in uncertain parameters will not affect the standard's 2045 ZEV new market share.

based policies, ZEV penetration is sensitive to the relative costs of other competing technologies.

Figure 25: Single Parameter Sensitivity – Selected Policies 2045 ZEV New Market Share

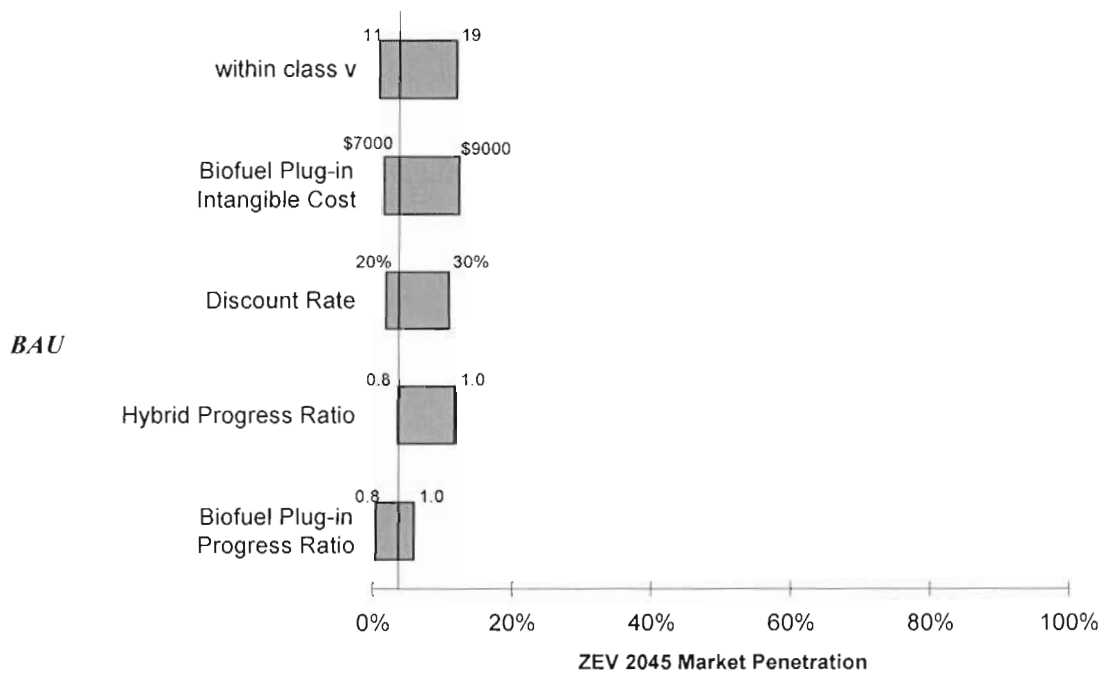
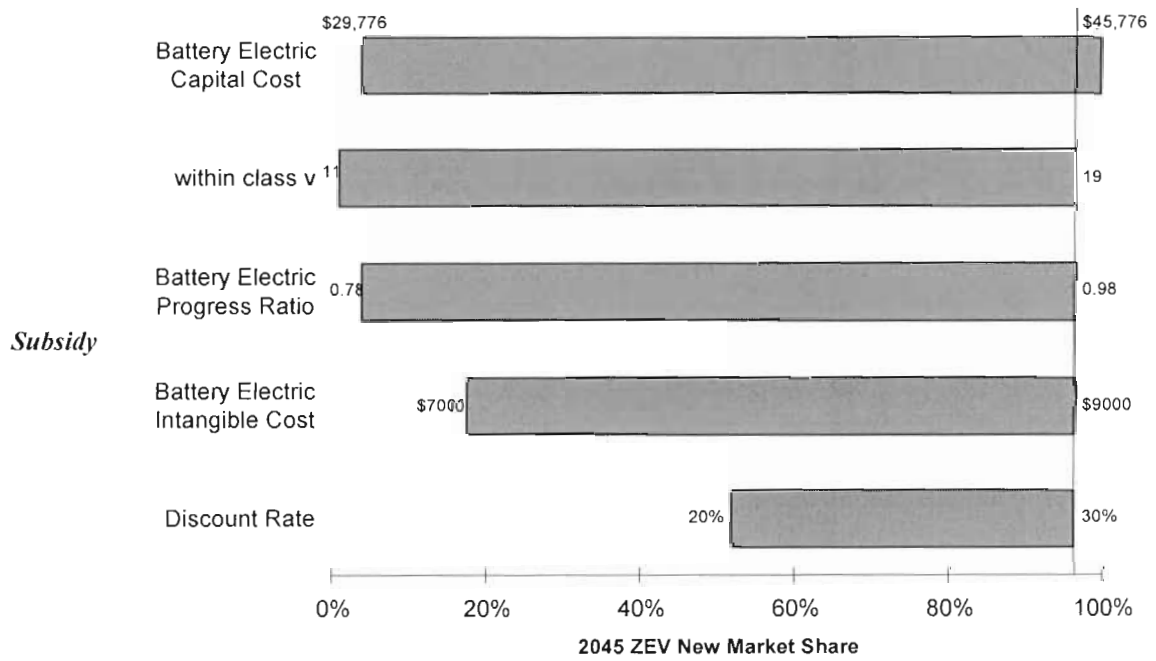
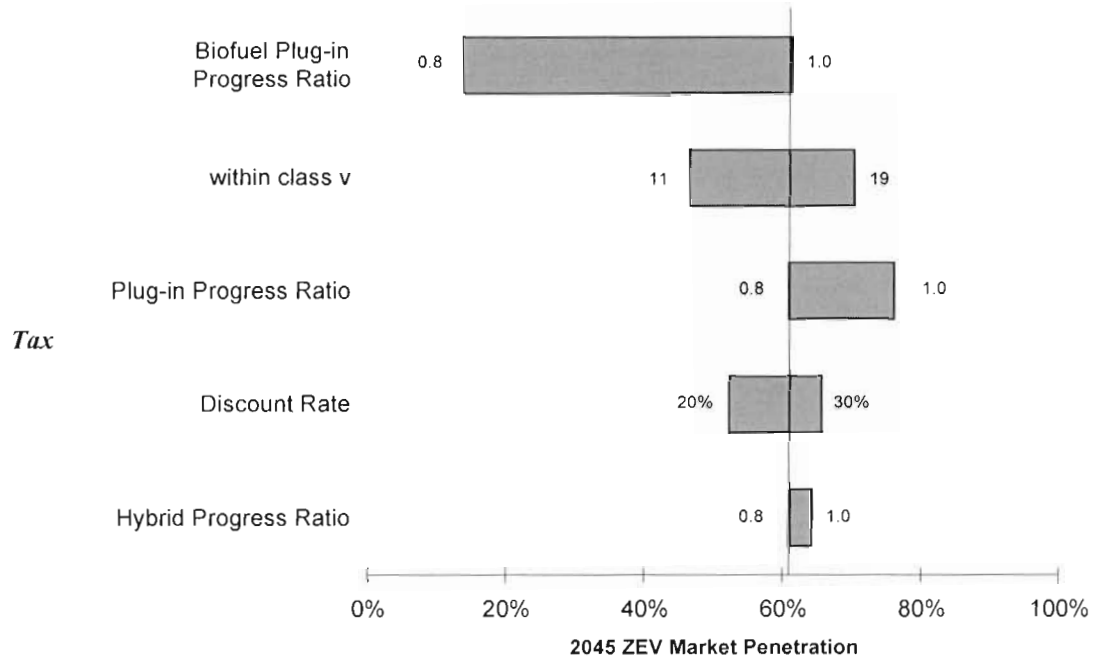


Figure 25 continued.



To summarize, results presented here are most sensitive to changes in the following:

- the variance parameter, which characterizes the heterogeneity of consumers purchasing within a vehicle class, such as cars,
- the discount rate used to characterize vehicle purchase decisions,
- the forecast for vehicle use,
- zero-emission vehicle characteristics, specifically their capital and intangible costs and the rate in which costs decline with increases in market share and experience,
- ultra-low-emission vehicle specifications, such as hybrid electric vehicles and plug-in electric vehicles.

CHAPTER 4: SUMMARY AND CONCLUSIONS

4.1 Summary

The objective of this research was to assess various policies for increasing the market penetration of zero-emission vehicles and reducing greenhouse gas emissions in the passenger vehicle sector. Policies evaluated included a tax on GHG emissions, a standard mandating ZEV market shares and a purchase subsidy for battery electric vehicles. Combinations of these policies were examined, as was the potential for research and development investment to lower the cost of meeting these objectives.

In order to assess the policies, I built a model of the passenger vehicle sector and applied it to California. It incorporated both widely accepted dynamics of technological change, such as learning-by-doing, as well as more novel concepts, such as a declining intangible cost function to capture the neighbour effect and a two-factor learning curve to explore R&D effects. The model was used in tandem with a cost-accounting tool in order to estimate the expected resource costs of selected policies. Monte Carlo simulation was used to assess how policies may be affected by uncertainty.

Policy alternatives were assessed in meeting a two-fold target of reducing GHG emissions from the passenger vehicle sector to 60% below 1990 levels in 2045 while increasing ZEV diffusion to at least 50% of vehicle stock by 2045. For each policy, I reported the direct and indirect GHG emissions, the ZEV diffusion and the cost of the policy. In addition, the impact of uncertainty on each of these factors was presented.

The policies differed in their cumulative GHG emission reductions. The tax resulted in the largest cumulative reduction in emissions. The tax not only induced technological change but also had the largest impact on consumer demand for vehicle use, lowering overall demand for vehicle-miles-travelled (VMT) by 4%. The standard and purchase subsidy both resulted in a 1% increase in the total demand for VMT, a rebound effect resulting from the lowered cost of driving induced by these policies.

Indirect emissions from upstream fuel production were found to be an important contributor to overall emissions in both the BAU and policy simulations. Indirect emissions were estimated to make up 20% of total GHG emissions in BAU, and from 25-35% of total GHG emissions of various policy alternatives. When indirect emissions were included, the 2045 GHG emissions were found to reach only 19-25% below 1990 levels, rather than the target of 60% below 1990 levels.

The standard then tax policy, which consisted of a relatively conservative standard (reaching 25% ZEV market share in the period from 1990 to 2015) followed by a strong tax (\$425/tonne of CO₂) for the remainder of the forecasting period, had the lowest median total cost and was found to be the most cost-effective policy per tonne of CO₂ reduced.¹⁹ The standard then tax policy had a median average expected resource cost of \$9/tonne CO₂ reduced, three times less than the second most cost-effective policy, the tax alone, at \$27/tonne CO₂. Three of the policies tested were comparable in terms of cost-effectiveness, the standard, the purchase subsidy combined with tax and the tax alone. The purchase subsidy was estimated to be the least cost-effective policy, having

¹⁹ Unless otherwise noted, all policy cost information refers to a case when costs are discounted at 3%/year back to 1990.

the highest median cost/tonne reduced at \$160/ tonne CO₂. The standard then tax policy was the most cost-effective alternative over discount rates of zero to ten percent.

The standard then tax policy was found to be the most cost-effective policy for two reasons. First, this policy forces market concentration in ZEV technology early in the forecasting period, resulting in declining ZEV capital and intangible costs. Second, by implementing a tax when the standard is removed, a signal is sent for consumers to lower their demand for vehicle use tempering any rebound effect from the increased fuel-efficiency of the vehicle fleet. Additionally, the tax portion of this policy also increases cost-effectiveness as it allows more flexibility in how consumers respond (for instance purchasing a hybrid electric vehicle rather than a ZEV). A standard or a tax, implemented on its own, provides a portion of these benefits but not all of them, resulting in higher costs relative to the combination of a standard then tax.

Given a successful R&D program targeted at reducing the capital cost of biofuel plug-in hybrids (BPHEVs), R&D investment could lower the cost of a policy. R&D investment was estimated to lower the expected resource cost of the tax and the standard policies by approximately \$10B and \$2B respectively. These findings can be interpreted as an estimate of the maximum expected resource cost savings to be gained from successful R&D investment in meeting the prescribed target. In the context of this study and its assumptions, the benefits of R&D investment *over* \$10B and \$2B for a tax and standard do not outweigh the resulting savings in their expected resource costs. However, the depiction of R&D in this analysis is rudimentary and further work in this area is required.

Further, it was observed that the prescribed target could be met even if policy action was delayed until 2035. However, by delaying, over 500 Mt of cumulative emission reductions would be lost. Implementing a standard then tax policy in 1990 was found to be more cost-effective than delaying action until 2035 for a discount rate of less than 6%. Because of the long forecasting period, the results of this comparison are particularly sensitive to the assumptions regarding the discount rate.

It was observed that in order to meet the target, the policy alternatives had to be relatively stringent. The size of the tax, subsidy or market share mandate of the policies suggests that the challenges involved in transitioning the passenger vehicle sector to zero-emission technology are substantial. Finally, the diffusion of ZEV technology was found to be required to reduce 2045 emissions to 60% below 1990 levels. Ultra-low-emission vehicles, while providing moderate reductions will not result in this level of deep emission reductions. In the near term, ULEVs have lower life-cycle costs than ZEVs. Therefore, there may be a trade-off between attaining cost-effective GHG emissions reductions in the present versus transitioning the vehicle stock to zero-emission technology to achieve deep emission reductions in the future.

Uncertainty analysis was reported for all of the major findings. While all of the predictions made for the selected policies are subject to uncertainty, the results estimated for the purchase subsidies are particularly uncertain. The parameters that have the most influence on the results are assumptions regarding the heterogeneity of consumers purchasing within a specific class of vehicles, the discount rate characterizing vehicle purchase decisions, the forecast for vehicle use and the costs of zero-emission and ultra low-emission vehicles.

4.2 Model Limitations and Areas for Future Research

This study used a model of the passenger vehicle sector to assess a variety of policy alternatives in inducing ZEV diffusion and reducing GHG emissions in the sector. While this model provides a satisfactory representation of the vehicle sector and of technological change, it also has a number of limitations. In particular, I identify four caveats in extrapolating the results from the modelled environment. These limitations in the model may provide good areas for future research. Areas in which this analysis could be further extended are: (1) full-equilibrium analysis (2) firm-level representation (3) evaluation of other policy measures (4) treatment of technological change.

4.2.1 Full-Equilibrium Analysis

The model used in this analysis represents a partial equilibrium system. While demand changes due to shifts in the price of vehicles and the cost of driving were endogenous in the model, the cost of fuels and the indirect emissions intensity of fuel types were exogenous. Further, macro-economic effects such as changes in GDP or income due to a policy are not included in the model's cost results.

Therefore, changes in the cost of fuel from variations in fuel demand due to policies were excluded from this analysis. In general, the policies assessed resulted in a decrease in the demand for gasoline while the demand for electricity and/or biofuel increased significantly. Such changes in the demand for fuels would likely influence the costs of these fuels thereby altering the results. Enabling a full-equilibrium analysis would account for any of these supply-side effects.

Further, a full equilibrium analysis would enable a more thorough depiction of how shifts in the indirect emissions intensities of various fuels may be influenced through policy. This would allow a more accurate assessment of policies targeted at both indirect and direct vehicle emissions, such as an economy-wide tax on greenhouse gas emissions or a low-carbon fuel standard. Finally, a model that moves towards full-equilibrium would enable more complete cost results by capturing any macro-economic effects of the policies such as changes in economic activity, government revenues and employment. The model used in this study is based on CIMS-T, a component of the economy-wide model CIMS. Building a California CIMS, and incorporating the model, would enable modelling efforts to move toward full equilibrium.

4.2.2 Firm-level representation

The decision-agent in the model is the consumer. When there is demand for new vehicles, the market share of vehicle technologies is determined by an algorithm based on the life-cycle costs, discount rate and heterogeneity of vehicle consumers. This approach operates under the assumption that vehicle technologies appear to supply consumer demand. How firms (in this case automakers) supply this demand is represented in the model in two ways.

First, when market share in a technology increases, the costs of a new technology may decline with learning-by-doing in part as the firm gains experience with the technology. Likewise, an influx of R&D investment may reduce a technology's capital costs through firm-level research. This provides a representation of many elements that influence vehicle stock turnover and technological change. However, there are a number of potentially significant factors regarding the firm that are not incorporated in this

analysis. Therefore, the model is unable to fully capture how firms may affect (or be influenced to affect) technological change.

First, the analysis does not incorporate how policies may drive innovation through greater R&D investment and how spillovers may influence the firms' R&D decisions. Second, this analysis assumes that firms have no foresight with respect to future policies and the outcomes of R&D and experience. Varying assumptions regarding firm foresight would affect the policy results. Third, this study does not analyze the concept of cross-subsidization, where a firm may subsidize the sale of clean vehicle technologies using profits from other vehicle sales in order to meet a regulation or influence the market. While this may be implicit in the model when simulating a standard, quantifying cross-subsidization would require further research.

Enhancing firm-level representation, whether incorporated into the model used here or by linking this model with a firm-level model, would enable many of these effects to be incorporated into the policy assessment. Future studies should seek to endogenize firm-level decisions in their analysis, particularly with respect to spillover and foresight.

The impact of cross-subsidization and R&D investment on vehicle technology is not well documented in the literature. A significant hurdle to this research is a lack of data, which are rarely released by automakers for competitive reasons. Creative methods will be required to analyze these areas, perhaps forming partnerships with automakers to exchange information or using estimates to create scenarios for analyzing how these effects may influence policy.

4.2.3 Further Policy Alternatives to be Assessed

In this analysis, a subset of policy alternatives was selected based on their relevance in meeting the goal of deep emission reductions and increased ZEV diffusion. The policy alternatives were then determined using trial and error to meet these goals. Because of modelling complexity and programming limitations, none of these policies was optimized for the lowest cost path for the prescribed target. Therefore, a so-called optimal policy was not determined. Such an optimal policy would provide a good a basis from which to compare the policy alternatives tested here. Note that an optimal policy is not exempt from uncertainty; therefore, uncertainty analysis must also be incorporated into such an evaluation. This could be considered in future studies.

Further, to maintain a reasonable scope, the number of policies assessed were limited. However, future research efforts could include evaluation of policies that influence indirect emissions, such as the low carbon fuel standard recently introduced in California. Additionally, it was found that policies used in combination were proven to be a cost-effective method of reducing GHG emissions and inducing technological change. This research could be extended to include additional policy combinations with varying stringencies to better understand the mechanics of how policies act in combination. Finally, policies were simulated to begin in 1990 and while it is expected that the findings can be extended to the present, it warrants performing further analysis to confirm this assumption. The model developed for this study is capable of simulating additional policies.

4.2.4 Treatment of Technological Change

While the model attempts to capture a large portion of the dynamics of technological change, there remain areas in which the representation of technological change could be further enhanced. For instance, it was observed that relatively stringent policies were required to induce substantial technological change. The rigidity of the model to relatively strong policy signals may be attributed to a number of factors that could be investigated. First, as discussed above, the model does not endogenize innovation resulting from R&D investment driven by policy. Second, the model does not allow for technologies that see a sharp decrease in market share due to a policy to become unavailable for competition. Implementing a so-called “sunset” function, described in Peters (2006), would likely result in requiring less stringent policies for inducing technological change.

The results are sensitive to a number of uncertain parameters. The results were found to be most sensitive to the assumptions regarding consumer heterogeneity, the discount rate and selected technology characteristics such as capital costs. Because of their potential impact on policy assessment, these areas warrant further empirical study to reduce the uncertainty about these values.

Further, while working with the model, I observed that both the BAU and the policy forecasts were very sensitive to the initial intangible costs selected for the various vehicle technologies. Research into the intangible costs of vehicle technologies is relatively limited, and given their importance in the results in hybrid models, I recommend that empirical research in the non-financial costs of vehicles be continued.

At a minimum, research incorporating vehicle intangible costs must undertake considerable uncertainty analysis on these parameters.

4.3 Conclusions

Understanding the limits of this model and inherent uncertainties in forecasting over a fifty-year period, there remain lessons for both the researcher and policy-maker. In the following, I present a number of conclusions that can be reached from this analysis.

First, relying solely on technological change to meet a reduction of 60% below 1990 levels by 2045 in the passenger vehicle sector will require a transition to zero-emission vehicles. This transition will require strict regulations and/or strong market-based signals.

Second, a policy combination of a standard then a tax cost-effectively leverages key aspects of technological change such as learning-by-doing and the neighbour effect. The standard lowers capital and intangible costs of targeted technologies by forcing their adoption. Once technology costs are lowered, implementing a tax tempers any rebound effect and allows consumers more flexibility to cost-effectively reduce their emissions. Such combinations hold promise for minimizing the cost of inducing technological change towards zero-emission vehicles and reducing GHG emissions.

Third, intangible costs are likely to play a vital role in technological change and therefore policies should aim to induce both declining capital and intangible costs. For instance, R&D policies on their own may not affect intangible costs of technologies and therefore may be more successful when combined with other policies.

Fourth, the impact of indirect GHG emissions will become increasingly significant with the adoption of ultra low and zero-emission vehicles. Therefore, in addition to policies aimed at reductions in direct GHG emissions from the passenger vehicle sector, policies that target indirect emissions should be explored.

Fifth, the cost of deep GHG emission reductions in the passenger vehicle sector should be compared to the cost of reducing emissions in other sectors in the economy. To meet economy-wide emission targets, it may be less costly to reduce GHG emissions from other sectors while seeking more moderate emission reductions from the passenger vehicle sector. Depending on the policy design, if only moderate GHG emission reductions are required from the passenger vehicle sector, abandoning zero-emission technology for ultra-low emission technology may provide more cost-effective GHG reductions. The emission reductions available from the diffusion of ultra-low emission technology are limited compared to those available from zero-emission technology.

Sixth, uncertainty analysis has important implications for policy comparison. The robustness of a policy's expected results varies by policy type. Market-based policies that are not flexible, such as purchase subsidies targeted at a single technology, are subject to the most uncertainty.

Finally, future research of a similar nature should consider the following areas:

- moving to full-equilibrium analysis
- increasing firm-level representation
- enhancing the treatment of technological change, particularly endogenizing R&D.

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