Effects of Hybrid Engine Technology on Canadian Light Duty Vehicle Gasoline Demand

By

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A thesis submitted to the
Faculty of Graduate Studies and Research
in partial fulfillment of the requirements
of the degree of

Master of Arts in Economics

Department of Economics
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Ottawa, Ontario, Canada

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Your file Votre référence
ISBN: 978-0-494-52020-8
Our file Notre référence
ISBN: 978-0-494-52020-8

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Abstract

The effects of hybrid engine technology on the demand for gasoline in the Canadian passenger vehicle fleet are estimated. A demand model based on consumer choice and using 2006 data on Canadian driving patterns provided by Transport Canada and a market survey of hybrid vehicles is developed. The effects of elastic demand for vehicle kilometers traveled are considered. Steady state and transition demands are calculated. The social welfare effects of alternative environmental tax policies are estimated. The conclusion is reached that, while hybrid vehicles will provide substantial benefits to Canadian consumers, market intervention is not warranted on the basis of environmental concerns.

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List of Symbols

x_{km}	Annual km driven by the individual consumer
x_c	Annual quantity of the composite good consumed by the individual consumer
$\bar{x}_{car}$	Individual's choice of car, held constant
p_{km}	Price of driving a km
$\bar{p}_c$	Price of the composite good, held constant
p_{car}^a	Annualized price of a car
p_{car}	Price of a car
D	Discount rate
$\bar{I}$	Individual income, held constant
x_{km}^*	Individual optimal annual km driven
$\bar{x}_{km}^*$	Individual optimal annual km driven, held constant
x_{hv}	Quantity of hybrid vehicles consumed by the individual (0 or 1)
x_{ngv}	Quantity of new gasoline vehicles consumed by the individual (0 or 1)
p_{hv}^a	Annualized price of a hybrid vehicle
p_{ngv}^a	Annualized price of a new gasoline vehicle
p_{hp}^a	Annualized price premium of a hybrid vehicle
FE_h	Fuel economy of a hybrid vehicle
FE_{ngv}	Fuel economy of a new gasoline vehicle
x_{gh}	Quantity of gasoline consumed annually by a hybrid vehicle
x_{gngv}	Quantity of gasoline consumed annually by a new gasoline vehicle
$p_g^{\text{threshold}}$	The minimum price of gasoline for which a hybrid vehicle is cost effective
x_{hv}^*	Optimal quantity of hybrid vehicles consumed by the consumer (0 or 1)
x_{ngv}^*	Optimal quantity of new gasoline vehicles consumed by the consumer (0 or 1)
$d_{gasoline}$	Individual annual demand for gasoline
$f(x)$	Estimated density function of km driven
N	Number of pseudo-samples
h	Bandwidth
X_i	Pseudo-sample
s	Estimated standard deviation
a	Hill estimator variable
$D_{gasoline}$	Aggregate annual demand for gasoline
x_{kmBE}	Breakeven quantity of annual km driven
$x_{ngv\bar{x}_{km}^*}$	Quantity of new gas vehicles in the fleet that drive $\bar{x}_{km}^*$ annually

$x_{hv\bar{x}_{km}^*}$	Quantity of hybrid vehicles in the fleet that drive $\bar{x}_{km}^*$ annually
$x_{ogv\bar{x}_{km}^*}$	Quantity of old gasoline vehicles in the fleet that drive $\bar{x}_{km}^*$ annually
FE_{ogv}	Fuel economy of old gasoline vehicles
md_g	Marginal damage of gasoline
Δx_g^A	Annual aggregate fuel savings
t_g	New tax on gasoline
cv^A	Aggregate compensating variation in income
β	Lump sum benefit for every \$1.00 raised by the tax on gasoline
Δt^E	Change in existing tax revenue due to the imposition of a new tax
t_c^E	Existing tax on the composite good
Δx_c^A	Change in aggregate consumption of the composite good
t_g^E	Existing tax on gasoline
t_{hp}^E	Existing tax on hybrid vehicles
Δx_{hv}^A	Change in quantity of aggregate hybrids consumed
Δcs	Change in consumer surplus
s_h	Subsidy for hybrid vehicle

1.0 Introduction

The purpose of this study is to determine the effect of hybrid engine technology on the fuel consumption of the Canadian light duty vehicle fleet. This is done by first estimating the steady state technological makeup of the fleet in the face of a changing gasoline prices. 2006 data giving the distribution of km driven annually by Canadian drivers was provided by Statistics Canada. These data allow the determination of the number of vehicles for which replacement with a hybrid vehicle would be cost effective. This in turn is used to determine the technological makeup of the fleet. By combining the technological makeup of the fleet with the driving behaviour of Canadian drivers, the steady state demand for gasoline is determined. From the demand function the long term own price elasticity for gasoline that is attributable to hybrid engine technology is determined.

The effect of the long run elasticity of vehicle kilometers with respect to fuel cost per km on gasoline demand in the presence of hybrid vehicles is determined. A number of policy alternatives aimed at reducing CO₂ emissions are assessed.

2.0 Motivation

This thesis is motivated by two factors. The first is growing concern about greenhouse gas emissions and their links to global climate change. The second is the availability of new vehicle technology in the form of hybrid engines. This new technology gives consumers new choices and invites new policy alternatives.

Global climate change has been linked to CO₂ emissions. The Stern Review (2006) calls “Climate change is the greatest market failure the world has ever seen” and calls for “deep emission cuts in the transport sector”. This report was supported by Kenneth Arrow (2007) who says “I believe the fundamental conclusion of Stern is justified: we are much better off to act to reduce CO₂ emissions substantially than to suffer and risk the consequences of failing to meet this challenge”. While the Stern Review was called biased and had some of its policy recommendations questioned by Lomborg (2007), the underlying finding of a link between CO₂ emissions and global climate change was not disputed. The Intergovernmental Panel on Climate Change (IPCC) was awarded the Nobel Peace Prize in 2007. The IPCC 4th assessment report finds that climate change is unequivocal, and gives as proof the fact that eleven of last twelve years were among the twelve warmest since 1850 (IPCC 2007).

Canada ratified the Kyoto Accord (1997) in 2002 but has seen a 22% increase in greenhouse gas emissions since 1990 (Environment Canada 2008). Whether Canada should have signed Kyoto is a matter of debate. What is important is that while Canada officially stated that it would reduce CO₂ emissions, it increased them.

If Canada wants to reduce CO₂ emissions new policy alternatives must be considered. In fact the Canadian government has introduced a program aimed at encouraging Canadian drivers to purchase more fuel efficient vehicles (Transport Canada 2008 a). It has also announced a policy initiative that will require compliance to fleet fuel economy standards by 2011 (Transport Canada 2008b).

While CO₂ emissions from all sectors of the economy contribute to climate change, this thesis focuses on policies to reduce emissions from the personal transportation sector. Personal transportation accounts for a large proportion (12%) of CO₂ emissions in Canada (Environment Canada 2008, p12). It is a monolithic segment that can be addressed with targeted policy. Personal transportation is also simpler than freight to address with policy because international competition is less of an issue. There is also more possibility of unilateral action on the part of the Canadian government. Finally, this focus is consistent with the work in this area done by Jaccard (2004).

From an abatement policy perspective, the personal transportation sector has the advantage that the federal government already has programs in place in this area. A carbon tax could be applied at the pump to gasoline, diesel and propane for automotive and recreational (ATV, pleasure boat, snowmobile etc) use. As the federal government already applies a \$0.10 excise tax on gasoline at the pump, the implementation cost of the additional tax would be low. This tax could also be fine tuned to give credit for lower carbon emissions in the production process – but this is not explored here.

This work is also motivated by the introduction of hybrid vehicles into the Canadian market. More formally known as hybrid electric vehicles, these vehicles use regenerative braking to substantially reduce fuel consumption.

With the introduction of the Honda Insight in 1999 and the Toyota Prius in 2001, hybrid powered automobiles have been available in the Canadian market for some time. Hybrid automobiles now make up 1.5% of new car sales in the US and accounted for 3% of Toyota Canada's 2006 sales. While these early hybrid vehicles were focused on improving fuel economy, more recent vehicles such as the Lexus RXh SUV have instead offered somewhat improved fuel economy in a more appealing package (like an SUV). The popular Toyota Camry is available with both gasoline and hybrid engine technology. The price of a Toyota Camry hybrid is \$32,000 compared to \$28,000 for a 4 cylinder Camry. The hybrid model returns 5.7 l/100 km in combined city - highway driving while the 4 cylinder model returns 8.0 l/100 km in combined city – highway driving (General Motors Canada 2008).

This new technology changes consumer choices. Since the 1990s fleet fuel economy has not changed substantially. This has meant that if a consumer wanted to improve the fuel economy of their vehicle their only option was to purchase a vehicle that had less power or less space. As evidenced by the popularity of SUVs and minivans consumers often chose more space at the expense of fuel economy. This view is supported by Hughes (2006) who speculates that the fuel economy benefits of switching to a new vehicle are lower today than they were in the 1970's. "As more fuel efficient vehicles came to market, it was possible for consumers to realize a large improvement in fuel economy by trading in older vehicles for newer models. Today however, there is little difference in fuel economy between old and new vehicles. This is largely a result of Corporate

Average Fuel Economy (CAFE) standards that have not been significantly increased since the 1980's".

Consumers now have the option of spending more for a hybrid engine to improve their fuel economy. While this type of choice is new to North American consumers it is similar to the choice that European drivers have had since the 1990's. European drivers have the ability to choose either gasoline or more expensive but more economical diesel engines for a wide range of automobiles. The overall economies of this choice have been affected by policy decisions made by European governments, with some countries actively encouraging the use of diesel fuel for personal transportation with favourable tax rates. These policy initiatives were undertaken in varying degrees and with varying results across Europe including the major markets of France, Germany, the United Kingdom and Italy. This natural experiment involved 450 million individuals and 200 million automobiles in the European Union. As a result of these policies, diesel penetration in Europe ranges from 1% in Greece where the breakeven annual driving distance is 41,500 km to 43% in Belgium where the breakeven annual driving distance is 21,100 km (Mayeres, Proost 2001). The range in tax measures undertaken coupled with differences in other tax policy, national wealth and driving patterns provide robustness to the results. From the European experience it is learned that new technology choices coupled with abatement policy can result in a change in the technological makeup of the automotive fleet.

Increasing concern over greenhouse gas emissions, new transportation technology offering new consumer choices combined with the European experience with new transportation technology establish the motivation for this thesis. The effect of this new technology on gasoline demand and the potential for new policy alternatives to reduce greenhouse gas emissions warrants investigation. Next, the relevant literature in greenhouse gas reduction in the personal transportation sector is reviewed.

3.0 Literature Survey

In this section the literature concerning Canadian greenhouse gas reduction and the literature concerning the migration to diesel powered automobiles in Europe are surveyed.

There are two main bodies of work in Canadian greenhouse gas reduction research. The first includes the work of Mark Jaccard at the Environmental Research Group at Simon Fraser University and the second includes the work of that of Randall Wigle at Wilfred Laurier University.

The work by Jaccard et al includes two books and numerous papers as well as two Master's Theses. It is all characterized by the use of a model of the Canadian economy called CIMS (Energy and Materials Research Group 2004). In the key paper Jaccard (2004) compares the use of market oriented regulation and tradable permits with the status quo to find the cost of reducing greenhouse gas emissions. Jaccard uses four criteria to assess each solution: effectiveness at achieving the environmental target,

administrative feasibility, economic efficiency and political feasibility. Jaccard breaks down the economy into five sectors; large industry, electricity generators, building and equipment for residential and commercial, upstream oil and gas production and transportation. In the transportation sector Jaccard focuses on personal transportation. Freight and air transport are ignored.

In the personal transportation sector, Jaccard proposes a vehicle emission standard targeted at automobile manufactures. This standard would require a certain percentage of the manufactures new car sales to be low, ultra low or zero emission vehicles according to a predetermined schedule. Manufactures would be susceptible to fines for non-compliance. A trading scheme is allowed to reward manufactures with more successful market offerings. This is similar to the approach currently being attempted by California. It is Jaccard's view that manufacturers would subsidize the price of LUZEV (low, ultra-low, zero emission vehicles) by increasing the price of SEV (standard efficiency vehicles) to encourage consumers to buy the LUZEV. The model predicts that the average vehicle price would increase by 8% in the least aggressive case and by 14% in the more aggressive case. Policy changes in the other sectors also result in a 3.3% (least aggressive) or a 15.5% (more aggressive) increase in the retail price of gasoline. Thus over time the installed base of personal vehicles is shifted from standard emission vehicles to low, ultra low or zero emission vehicles.

While the CIMS model incorporates a large number of factors and iterates over the supply and demand to find a solution to the reduction of greenhouse gases (GHG)

emissions, the rate of the reductions is largely determined by the price elasticity of gasoline, the retirement of the existing fleet and the schedule of LUZEV standard imposed on automobile manufacturers (an arbitrary input).

The study of the transport sector by Jaccard is augmented by the Master's Thesis work done by Rose Murphy (2000) (and supervised by Jaccard). In this work Murphy studies a wider range of solutions for greenhouse gas reduction in the transportation sector. An impressive behaviour based hybrid model is developed to predict consumer behaviour in the face of a number of policy alternatives. Included in these policy alternatives is a carbon tax that raises the price of gasoline by 50%. Using a simplistic elasticity model (-0.05 short term demand for light duty vehicle transportation and -0.2 long term, long term elasticities being used only after 15 years, the assumed lifetime of the fleet) this solution and one based on a fuel efficiency standard were found to cause the largest reduction in greenhouse gas emission for personal transportation. These results are based on a reduction in demand for light duty vehicle travel as calculated above and a shift toward higher efficiency gas vehicles and though fuel switching as calculated internally by CIMS. The magnitude of the substitutions is not published.

Wigle (2006) uses a computable general equilibrium (CGE) model to test the applications of two of the alternatives presented by Jaccard to meeting Canada's Kyoto protocol targets. Neither the least aggressive nor the most aggressive plans meet the Kyoto targets. Wigle augments the plans with international permits to meet the targets. He also analyses the use of an international tradable permits only option. In each of these cases he

finds the welfare costs to Canada, for meeting the Kyoto targets to be relatively small ranging from -0.54% to -0.59%. Next, the literature concerning the migration to diesel powered automobiles in Europe is surveyed.

The substitution by consumers from gasoline to diesel powered vehicles in Europe in the face of tax policy has been well documented (Pock 2007; Mayeres 2001; Orfeuil 2001). These papers find that with a high level of predictability, consumers substitute away from gasoline vehicles if there is an alternative that provides savings over the vehicle's lifetime. This substitution to diesel powered vehicles in Europe by high mileage drivers was triggered by tax policy, but it was also abetted by the introduction of new technology (such as turbo chargers and direct injection) that made diesel vehicles more attractive in the marketplace. An emphasis on small diesel vehicles by French manufactures in the early 1990's helped the migration of the automotive fleet from 17% diesel in 1990 to 35% in 2000 (and 45% in 2004).

Pock (2007) finds that the ongoing shift to diesel has distorted the estimates of gasoline elasticity. He finds that for Within estimators short range gasoline own price elasticity is unchanged but that long term own price elasticity of gasoline changes from -0.502 to -0.360¹. This change may reflect the fact that people who are willing to purchase a new vehicle and switch fuels to reduce their fuel bill have already done so. This is an interesting result for the Canadian situation in that it indicates that as fuel switching (or

¹ Polk tests nine common dynamic panel estimators to determine the effects of ignoring the migration to diesel powered vehicles from gasoline powered vehicles when estimating the short and long term own price elasticity of gasoline in Europe. He find that the "Within estimator (least square dummy variable), its bias-corrected version LSDVc, GLS with heteroscedastic, cross-sectional correlation and/or AR(1) error structure, and the Arellano-Bond estimator FD-GMM" provide the best results.

car technology switching) becomes an option for Canadian consumers the people who do not switch will demonstrate relatively lower long term own price elasticity for gasoline. Note also that the long term own price elasticity of gasoline in Europe is higher than the own price elasticity for gasoline in Canada (-0.2) used by Jaccard (2004).

Verboven (2002) uses the market for gasoline and diesel powered vehicles in Europe to investigate quality based price discrimination. In the course of his study he finds that the primary factor used by consumers when choosing between gasoline and diesel engines is the payback obtained from fuel cost savings from using diesel fuel offsetting the initial higher cost of a diesel powered car. Thus drivers with an annual predicted mileage greater than the payback distance will choose diesel. Other factors such as noise, maintenance costs or the emotional appeal of a gasoline powered vehicle do not appear to be relevant.

Verboven (2002) also finds that the differential tax treatment of diesel and gasoline fuels leads to monopolistic type price setting of diesel powered automobiles. Thus automobile manufacturers will seize part of the benefit derived from switching to diesel engines.

Mayeres (2001) uses an applied general equilibrium model to show that the current tax policy has caused a shift to diesel fueled cars and that when tax efficiencies and environmental damages are taken into account that this policy was misguided.

Orfeuil's (2001) findings support the view that it is more efficient to tax CO₂ emissions than to tax vehicles (as is the case indirectly in the Jaccard (2004) proposal) as there is a

more direct link between fuel consumption and CO₂ emission than there is between vehicle price and CO₂ emission.

From this literature we learn that given a choice, consumers will choose the most cost effective engine technology for their driving needs. From the Canadian literature survey we learn that abatement policies have the potential to reduce greenhouse gas emissions while incurring low social welfare costs.

This thesis extends the existing literature by using distributional data on driving behaviour instead of fleet wide averages, by developing new theory which allows individuals to choose the most cost effective technology for their personal driving situation and by considering hybrid vehicles that are currently available in the Canadian market. It also evaluates greenhouse gas abatement policy alternatives by estimating their effect on social welfare.

4.0 Theory

This section provides an overview of the approach taken. First the consumer choice problem is defined. This is a two stage problem where the consumer must choose which type of engine to equip their new vehicle with and then choose how much to drive. This problem is approached in the standard manner where the second stage is solved first. This problem, how many km to drive annually, is assumed to have been solved by Canadian consumers. (This solution is represented by a histogram of annual km driven for light duty vehicles in Canada, see Section 5). Once this stage has been solved the consumer

solves the first stage with a simple net present value (NPV) calculation based on the fuel economy advantage and price premium for a hybrid engine and their individual solution to the second stage problem of how many km to drive annually. With both stages of the consumer's choice problem solved the individual demand for gasoline for each vehicle in the fleet can be calculated.

Note that in this problem that the type and model of car chosen by the consumer is not considered. The theoretical model does not make any predictions about the consumer's choice of car model. Instead the assumption is made that all car models are available with a choice of either a hybrid or a gasoline engine. This is similar to the situation in the European market where many car models are available with a choice of diesel or gasoline engines. The model then uses a single factor for the fuel economy advantage and price premium for a hybrid engine².

Once the individual demands for gasoline have been determined the aggregate demand and own price long run elasticity for gasoline for both the steady state and transition are calculated. Finally by varying the price premium for hybrid engines and the price of gasoline a number of policy alternatives aimed at reducing CO₂ emissions are tested.

4.1 Consumer Choice and the Demand for Gasoline

² A survey of the vehicles available with a choice of gasoline or hybrid engines in the Canadian market was conducted to determine the value of this factor. In the Canadian market the price premium for hybrid vehicles ranges from -\$1,900 to \$32,700 with an average price premium of approximately \$7500. However this range is complicated by differences in vehicle trim levels and vehicle type. The improvement in fuel economy ranges from 0.505 liters per 100 km to 3.165 liters per 100 km, with the average improvement of 2.4 liters per 100km. – see Section 5 and Table 10 for details of this market survey.

When buying a new automobile, the consumer is faced with a two stage optimal choice problem. The consumer must decide which car to buy and how much to drive that car. First the consumer solves the problem of how much to drive versus how much to spend on other goods by maximizing utility while keeping the choice of car constant. This is given by

Equation 1

$$\text{Max } U(x_{km}, x_c; \overline{x_{car}})$$

Equation 2

$$\text{Subject to } \bar{I} = p_{km}x_{km} + \bar{p}_c x_c + p_{car}^a \overline{x_{car}}$$

Where x_{km} is the annual km driven by the consumer, x_c is the amount of a composite good. $\overline{x_{car}}$ is the choice of car which at this point is fixed. p_{km} is the price of driving a km and could include non-monetary costs such as time spent in traffic or perceived risk of a collision. $\bar{p}_c$ is the price of the composite good and is assumed to be constant. $\bar{I}$ is the consumer's annual income and is assumed to be constant. This is a multi-year problem, covering the life of the car which has been simplified to a single year problem by assuming that x_{km} and x_c are constant over time and by annualizing the price of the car p_{car}^a .

$$p_{car}^a = \left(\frac{D}{1 - \frac{1}{(1+D)^n}} \right) p_{car}$$

Where p_{car} is the initial purchase price of the car, D is the discount rate and n is the expected life of the vehicle. A similar approach is taken throughout this section.

Each individual consumer is assumed to have solved this problem with the aggregation of the solutions x_{km}^* forming the distribution function for annual km driven derived below.

Note that x_{km}^* is a function of income and prices. So

Equation 3

$$x_{km}^* = \bar{x}_{km}^*(\bar{I}, p_{km}, \bar{p}_c, p_{car}^a)$$

Once found, for each consumer, the solution $\bar{x}_{km}^*$ is assumed to be constant and unaffected by the subsequent changes in the price of gasoline or the choice of engine technology. Initially, it is also assumed that there is no rebound effect of purchasing a more fuel efficient car. That is buying a more fuel efficient car does not induce a customer to drive more. These assumptions are relaxed later.

Once the consumer has solved the problem of how much to drive the consumer must choose which vehicle to purchase and which engine type to equip the vehicle with.

Instead of attempting to explain the choice of model that each consumer will choose the assumption is made that all models are available with either hybrid or gasoline engines³.

Thus the choice for the consumer is determined by the most cost effective engine type.

³ The choice of vehicle model is given by

$$\begin{aligned} & \text{Max } U(x_{car}, x_c) \\ & \text{Subject to } \bar{I} = p_{car}^a x_{car} + \bar{p}_c x_c \end{aligned}$$

Where x_{car} represents the complete range of vehicles available in Canada and p_{car}^a is the annualized price for each car in that range. As the capital cost of a new car is large relative to income this problem is multi-year problem where the time value of money is considered. The solution to this problem x_{car}^* provides two components of utility $u_{car \text{ itself}}$ and u_{km} . Where $u_{car \text{ itself}}$ is the utility obtained from the car other than that which is derived from driving it and u_{km} is the utility derived by enabling the consumer to drive $\bar{x}_{km}^*$ annually. The utility of the car itself could be the utility of pride of ownership, social status, comfort or load carrying capacity among other things. It is assumed to be the same whether the car uses hybrid or new gasoline technology. This assumption is supported by Verboven (2002) who found that European drivers chose the engine type based on their estimates of annual km driven and future fuel costs. Here it is assumed that Canadian drivers will exhibit the same behaviour as European drivers when faced with a fuel saving

This choice is given by

Equation 4

$$\text{Max } U(x_{hv} + x_{ngv}, x_c)$$

Equation 5

$$\text{Subject to } \bar{I} = p_{hv}^a x_{hv} + p_{ngv}^a x_{ngv} + \bar{p}_c x_c$$

Where x_{hv} is one if the consumer chooses a hybrid vehicle and zero if the consumer chooses a new gas vehicle and where x_{ngv} is one if the consumer chooses a new gas vehicle and zero if the consumer chooses a hybrid vehicle. The price p_{hv} includes the annualized initial capital premium p_{hp}^a of a hybrid engine over a new gasoline engine and the annual expense of owning a hybrid vehicle p_{ha} . The variable p_{ngv} includes only the annual operating cost of the new gas vehicle. Hybrid and new gasoline powered vehicles are assumed to have equal annual maintenance, repair, licensing and insurance costs. Therefore these costs fall out of the technology choice problem. Annual operating costs reduce to the annual cost of fuel $p_g x_{gh}$ for the hybrid engine and to $p_g x_{gngv}$ the annual cost of fuel for the new gasoline engine. Where x_{gh} the amount of fuel is consumed annually by the hybrid powered vehicle and where x_{gngv} is the amount of fuel consumed annually by the new gasoline powered vehicle. p_g is the price of gasoline. These costs can be expressed as

technology. The model does not attempt to explain the choice of vehicle model. Instead, using the same approach as Verboven (2002), it assumes that each model is available with both types of power plants. While this assumption is not true today there are twelve different models available in Canada in 2008 with a choice of hybrid or gasoline technology. These models represent a range of vehicle types (see below). Therefore the choice for the Canadian driver is between hybrid powered and conventional gasoline powered for the same model of vehicle. Once x_{car}^* has been found it can be optimized by choosing the most cost effective engine type.

Equation 6

$$p_g x_{gh} = p_g FE_h \bar{x}_{km}^* x_{hv}$$

And similarly

Equation 7

$$p_g x_{gngv} = p_g FE_{ngv} \bar{x}_{km}^* x_{ngv}$$

Where FE_h and FE_{ngv} are the fuel economies of hybrid vehicles and new gas vehicles.

The consumer choice can now be re-written as

Equation 8

$$\text{Max } U(x_{hv} + x_{ngv}, x_c)$$

Equation 9

$$\text{Subject to } \bar{I} = p_{hp}^a x_{hv} + p_g FE_h \bar{x}_{km}^* x_{hv} + p_g FE_{ngv} \bar{x}_{km}^* x_{ngv} + \bar{p}_c x_c$$

As the consumer can choose **either** a hybrid engine **or** a new gasoline engine the maximization problem becomes a cost minimization problem with the consumer choosing the lesser of the annual costs of owning a hybrid or new gasoline vehicle

Equation 10

$$p_{hp}^a x_{hv} + p_g FE_h \bar{x}_{km}^* x_{hv}$$

Or

Equation 11

$$p_g FE_{ngv} \bar{x}_{km}^* x_{ngv}$$

Each consumer solves this problem individually according to their value of $\bar{x}_{km}^*$. Thus for each vehicle in the fleet there is a solution x_{hv}^*, x_{ngv}^* to the engine technology choice problem. The consumer will be at a corner solution, choosing a gasoline powered vehicle while the price of gasoline remains below the threshold price of gasoline

Equation 12

$$p_g^{\text{threshold}} = \frac{p_{hp}^a}{\bar{x}_{km}^*(FE_{ngv} - FE_h)}$$

and will switch to preferring a hybrid powered vehicle if the price of gas rises above $p_g^{\text{threshold}}$. Accordingly $x_{hv}^* = 0$ and $x_{ngv}^* = 1$ if the consumer chooses a new gasoline powered vehicle and $x_{hv}^* = 1$ and $x_{ngv}^* = 0$ if the consumer chooses a hybrid powered vehicle.

Once the individual's choice of engine technology is known, the individual annual demand for gasoline $d_{gasoline}$ is can be determined. Where

Equation 13

$$d_{gasoline} = x_g^* = FE_{ngv}\bar{x}_{km}^*x_{ngv}^* + FE_h\bar{x}_{km}^*x_{hv}^*$$

Note that while Equation 13 is not in the classic form of a demand function it has the advantage that values for all of the variables can be determined and therefore the demand for gasoline can be found. Note that this is done without knowing the utility function in either Equation 1 or Equation 4 although it does require the assumptions that the utility function is continuous, quasiconcave and exhibits constant elasticity. Also from above recall that $\bar{x}_{km}^*$ is a function of income and prices.

The task now is to determine the values of $\bar{x}_{km}^*$, x_{ngv}^* , x_{hv}^* , p_{hp} , FE_{ngv} and FE_h . This is done in the next section by examining the driving patterns of Canadian drivers and the vehicle technology available to them.

5.0 Data and Data Sources

To calculate the demand for gasoline the individual values $\bar{x}_{km}^*$ must first be determined. This is done by examining the driving patterns of Canadian drivers and then creating a distribution function for the annual km driven Canadian light duty vehicles.

Data on the driving patterns for Canadian drivers is obtained from Statistics Canada (2006a). Together with Transport Canada they publish The Canadian Vehicle Survey every quarter. This report, based on surveys of Canadian drivers, provides detailed data about the driving habits of Canadian drivers. One of the key pieces of data it provides is the average number of vehicle kilometers driven per quarter for light duty cars and trucks (less than 4500 kg). To date however no information about the distribution of vehicle km driven has been published. For this study a special extraction of distribution data was performed by Statistics Canada. This extraction provides a histogram of vehicle kilometers for light duty cars and trucks. This data includes one random quarter from each of 2004, 2005 and 2006 (Table 1).

The survey is based on a questionnaire sent to Canadian drivers. The drivers are chosen to provide coverage of the provinces and territories and of a range of vehicle classes. For

example, in the Q3 2007 survey, 9563 vehicles out of 19,539,924 from the survey population were drawn for the ten provinces and three territories. Weights are used to extrapolate from the actual questionnaire responses to the nationwide survey results.

The data for the distribution is in the form of an enhanced histogram. This histogram is unevenly spaced. The right hand tail of the distribution is described by a bin for vehicles that drive more than 15,000 km per quarter. No indication of the shape of the tail is given. Data is also included for the number of vehicles that drive zero km per quarter. The median and mean of each range of the histogram is given. This additional information is used to construct a probability density function for km driven per quarter. Having a probability density function provides much better resolution than using the histogram in its original form.

Table 1 Quarterly km driven histogram

Estimates of number of vehicles in scope for Canada by distance driven per quarter, vehicles up to 4.5 tonnes

Source: Statistics Canada, Canadian Vehicle Survey custom tabulation

	2004			2005			2006		
	Count	Mean	Median	Count	Mean	Median	Count	Mean	Median
0km	2,170,954	-	-	2,105,521	-	-	2,392,740	0	0
1-500	579,114	281	300	815,642	288	301	769,040	301	319
500-999km	1,244,796	754	743	1,274,693	778	796	1,233,225	768	767
1,000-1,999km	2,668,827	1,522	1,500	2,932,176	1,487	1,483	2,722,536	1,490	1,487
2,000-2,999km	2,346,064	2,459	2,444	2,505,347	2,489	2,486	2,517,988	2,469	2,467
3,000-3,999km	2,017,534	3,478	3,466	2,075,767	3,494	3,488	1,978,328	3,470	3,452
4,000-4,999km	1,585,755	4,454	4,428	1,511,718	4,463	4,446	1,724,330	4,467	4,453
5,000-5,999km	1,232,483	5,520	5,535	1,269,175	5,465	5,436	1,332,625	5,462	5,444
6,000-6,999km	933,552	6,462	6,432	843,609	6,493	6,492	940,753	6,487	6,466
7,000-7,999km	1,280,160	7,899	7,891	1,182,215	7,852	7,819	1,217,927	7,848	7,765
9,000-9,999km	405,708	9,482	9,507	334,053	9,474	9,460	319,895	9,490	9,482
10,000-11,999km	514,267	10,836	10,787	404,268	10,936	10,923	410,874	10,935	10,940
12,000-15,000km	364,205	13,161	12,859	374,101	13,401	13,382	392,719	13,336	13,308

15,000 km and over	439,301	21,683	18,847	506,454	23,248	20,352	583,976	22,734	19,688
	17,782,720			18,134,739			18,536,956		

The probability density function for km driven per quarter is constructed in the following manner. A non-parametric density estimation technique is employed (Green 2003).

Normally this technique begins with samples from a population and then uses an arbitrary kernel to create the probability density function. In this case however no samples were available - only the histogram described above. The approach taken was to use the histogram to create a set of pseudo-samples for the population and to use these pseudo-samples to complete the nonparametric density estimation. In order to create the pseudo-samples three issues with the data were resolved. These issues were; the uneven bin spacing, the large number of vehicles with zero km per quarter driven and the open ended upper tail.

Two algorithms to resize the bins were tested. The first assumed that the distribution in each original bin was smooth and even. The samples were then split into each new bin. This approach was tested by examining the median and the mean of the resized bins. The second algorithm was to assume even spacing of the population below the median of the original bin and even (but different) spacing above the median in each of the original bins. The samples were then split into each new bin. This approach was also tested by examining the median and mean of the new bins. The second approach was found to have to have a better match and was therefore the one employed.

The open ended upper tail was modeled in the same manner except that the upper limit of the second block was set so that the mean of the two blocks equaled the mean of the original bin. First, the population in the bin greater than 15,000 km driven per quarter was assumed to be one of two blocks. These blocks were from 15,000 km driven per quarter to 18,847 km, the median for this bin and 18,848 km driven per quarter to an upper limit of 35,000 km driven per quarter. The spacing within each block is assumed to be even. The upper limit of the second block was set so that the mean of the two blocks equaled the mean of the original bin. Thus the count, median and mean of the original bin are preserved.

The large count at zero km driven per quarter was removed from the data. The rationale for this was the fact that the probability distribution is to be used to calculate the fuel consumed by the fleet. As the vehicles that are not driven do not consume fuel they have no impact on the absolute amount of fuel consumed by the fleet. Also zeros might in fact be non-responses.

Once the three issues with the histogram data were resolved the set of pseudo-samples was created (X_i). This was done by dividing the number of vehicles in each of the corrected bins by 20,000. This was done to reduce the computational load while still retaining a whole number of samples in most bins. See Table 9 for a list of pseudo-samples for 2004.

These pseudo-samples are then used to estimate the density function using a Gaussian non-parametric density estimation technique. The estimated density function is given by

Equation 14

$$f(x) = \frac{1}{N} \sum_{i=1}^N \frac{1}{h} K(z)$$

where

Equation 15

$$K(z) = \frac{1}{\sqrt{2\pi}} e^{-\frac{z^2}{2}}$$

and

Equation 16

$$z = \frac{x - X_i}{h}$$

$f(x)$ is calculated for a range of x from 0 to 20,000km in increments of 100km and 20,000km to 35,000km in increments of 300km. Where x is the quarterly km driven, X_i is the pseudo-sample and h is the bandwidth, N is the number of pseudo-samples which for the quarter in the year 2004 was 780.

The choice of h is somewhat arbitrary. A large h results in over smoothing and a small h results in under smoothing. Greene (2003) suggests setting $h=0.9 \times s/N^{1/5}$ where s is the estimated standard deviation of $f(x)$. Following this suggestion results in $h = 1025$; however this resulted in a curve that on inspection appears slightly over smoothed. Setting h to 800 results in a curve that on inspection seems to balance between over and under smoothing, hence I used this value in what follows.

The shape of the tail was investigated through the use of two kernels (Gaussian and Logit). The Gaussian kernel produces a normal distribution. The Logit kernel produces a distribution with a fat tail. Both of these tails were compared to a tail created using Hill estimation. This estimation assumes that the tail varies with x^{-a} and then estimates the value of a (Drees 2000). The tails produced by utilizing each of these methods are plotted in Figure 1. For reference the histogram of pseudo-samples is also shown. Note that the histogram of pseudo-samples jumps up and down due to granularity effects resulting from the bin re-sizing described above. Once these tails were created they were used to calculate the number of samples expected across the range. This output was then compared to the number of pseudo-samples used as input. It was found that the Gaussian kernel produced results where the output was close to the input (Table 2). The Logit kernel over estimated the number of samples expected. The Hill estimation gave similar results to those of the Gaussian kernel. Therefore the Gaussian kernel was chosen as it produced a good fit. The Logit kernel and Hill estimation were not used.

Table 2 Comparison of the number of pseudo-samples (an input) to the number predicted by using different kernels (an output)

Quarterly km	Pseudo samples	Gaussian	Logit	Hill
14,000 -14,999 km	4.00	4.102679	5.041330	4.0705037
15,000 -20,000 km	12.00	12.972859	14.133572	11.9808902
20,000 -35,000 km	10.00	10.312739	10.944227	10.3977126

Figure 1 Quarterly km driven tail detail

With the issue of which kernel to use resolved, the quarterly km driven distribution for one quarter in 2004 was plotted (see Figure 2). For reference this plot includes the input histogram (raw histogram). It also includes a histogram of the pseudo-samples generated using the median preserving scheme outlined above. Both histograms have had their y axis re-scaled to be consistent with the probability distribution. This was done by dividing the count in each bin by the total number of samples and by the width of each bin. As a check the area under the under the probability density curve was integrated and found to be 0.964. The expected value is 1.0. The discrepancy is explained by the cut off left side tail.

Figure 2 Quarterly km driven distribution 2004

This process was repeated for the data from 2005 and 2006. Once the probability density function had been created for each quarter a combined probability function was created. This was done by combining the pseudo-samples from each of the individual quarters and then performing the Gaussian non-parametric density estimation described above. The probability density functions for each quarter and for the three quarters produced consistent results and there is no obvious trending. The combined probability function was then multiplied by four to give an estimate of the number of km driven annually.

As an aside, to gain more insight into the problem of fuel consumed, a curve showing vehicle km versus annual km driven was generated. This curve is generated by multiplying the number of vehicles that drive a certain number of annual km by the

annual number of km driven and then plotting that versus the number of annual km driven. This curve is shown below (Figure 3). Fuel consumption is a function of vehicle km driven and so the insight gained from this curve is that policy that addresses high mileage vehicles will have more impact than the number of vehicles alone would seem to indicate.

Figure 3 Annual vehicle km driven

The probability of driving a certain number of km annually was multiplied by the number of vehicles in the fleet to produce Figure 4. This probability density function is assumed to represent the aggregation⁴ of each individual solution $\bar{x}_{km}^*$ to the problem of how much to drive each vehicle versus how much to spend on other goods (see Equation 1 and Equation 2). Together with p_{hp} , FE_{ngv} and FE_h it is used to solve the problem of which engine technology to buy (and hence to determine the values of x_{ngv}^* and x_{hv}^*) for

⁴ Note that this aggregation is based on the number of vehicles in the fleet and not on the number of individuals. Individuals are assumed to have chosen how much each vehicle is driven and as a result of that decision which engine technology it should have. Individuals may own multiple vehicles or may share a single vehicle. No mapping between individuals and vehicles beyond that stated above is required.

each vehicle (see Equation 4 and Equation 5) and from there to determine the demand for gasoline. The values of p_{hp} , FE_{ngv} and FE_h are determined next.

Figure 4 Annual km driven distribution

5.1 Derivation of Fuel Economy Parameters

In order to calculate the penetration of hybrid vehicles and the demand for gasoline, the values of the price premium (p_{hp}) of hybrid power over a new gas power for the same model of vehicle and the values for the fuel economy (FE_h , FE_{ngv}) of both hybrid and gasoline powered vehicles must be determined. These values were estimated in the following manner.

A survey of the 2008 Canadian automobile market was performed. All vehicles that are available with a choice of hybrid or new gas power were selected. One vehicle model, the

Toyota Prius, was available only with hybrid power. It was therefore excluded from the study. It was found that twelve different models were available with a choice of hybrid or new gasoline power. Three of these were available in more than one trim level. This gave a total of 15 different vehicles to be compared. These vehicles were compared on a model by model basis at the most comparable trim level to find the price difference between hybrid and new gas power. In general car manufacturers do not offer the same model with the only difference being power type. There are minor differences in trim level between hybrid and new gas power as well. These minor differences in trim level, such as 16 inch vs. 17 inch alloy wheels, were ignored. For example the Toyota Camry Hybrid was compared to the Toyota Camry SE 4cylinder with automatic transmission. Pricing information was obtained from GM Canada's comparison tool and is the manufacturer's suggested retail price (General Motors Canada 2008). Fuel economy information was obtained from Natural Resources Canada (2008). City and Highway fuel economies were combined using Natural Resource Canada's figure of 55% city 45% highway⁵. See Table 10 for the results of this survey.

Once the price and fuel economy differences were obtained for these 15 models the fleet wide numbers were calculated. This was done using two approaches. The first was to take the simple average of the price difference and the fuel economy difference, excluding the data for the Lexus LS600h and the Chevy Malibu. These vehicles are outliers. The LS600h is positioned as the top of the line Lexus and has a MSRP of \$125,000. The gasoline powered LS460L has a significantly lower trim level and has a MSRP of \$92,700. The Malibu hybrid provides almost no improvement in fuel economy. The

⁵ This assumption is tested below.

result of this averaging is a price premium for hybrid power of \$7,421 and a fuel economy improvement of 2.41 liters per 100km.

The second method used the vehicles as a proxy for different vehicle classes. For instance the Chevy Tahoe was used as a proxy for large pickups, large SUVs and large vans. While GM does not offer hybrid power in a pickup or van model the use of the proxy is justified by the fact that the Tahoe is built on the same platform (GMT900) as GM's large pickups and vans. The sports car class was assumed not to have a hybrid option. Next the breakdown of new vehicle sales by type in Canada was introduced (DesRosiers 2008). Applying the proxy data to this breakdown yields a price premium for hybrid power of \$7596.60 and fuel economy improvement of 2.45 liters per 100km (see Table 11). Comparing these two methods yields a price difference for hybrid power in the range of \$7421 to \$7596 and a fuel economy improvement of 2.4 liters per 100 km. For this study p_{hp} is set to \$7500 as it is a round number between the values determined by each method. The proxy method was used to estimate the absolute fuel economy of hybrid and new gasoline powered vehicles. FE_{ngv} is set to 9.2 liters per 100km and FE_h is set to 6.8 liters per 100km.

The absolute fuel economy for old gasoline powered vehicles was estimated using data from Statistics Canada, which for 2004 found the average fleet fuel economy for light duty vehicles to be 10.8 liters per 100km.

Several of the scenarios investigated below make use of a reference price for the price of gasoline. This reference was established by reviewing the average at the pump price for gasoline across Canada from 2004 to 2008 (GasBuddy.com 2009). These data show that the average price for gasoline was \$0.99 per liter with a median price of \$1.00 per liter with prices ranging from \$0.73 to \$1.35 per liter. Therefore the reference price for gasoline of \$1.00 per liter was chosen.

6.0 Demand Estimation

With the determination of the driving patterns of Canadian drivers and the vehicle technology available to them the individual demands for gasoline can be determined. This is done for three scenarios which vary the assumptions around the long term elasticity of vehicle km traveled with respect to the fuel cost per km and the elasticity of vehicle km travelled with respect to the price of a new vehicle. Two reference cases that do not include hybrid vehicles are also included. All of the scenarios and reference cases assume an 11 year vehicle life and a discount rate set at the market interest rate of 5%.

6.1 Scenario 1 - *inelastic*

This scenario maintains the assumptions as stated in the consumer's choice problem described above. These assumptions are that the long term demand for vehicle kms is unaffected by the price of gasoline and that the improved fuel economy offered by a hybrid vehicle does not induce the consumer to drive more. Thus the change in demand for gasoline is solely due to a change in engine technology. A sample of individual

demands is given in Figure 5 below. These sample consumers drive 37,621 km, 25,081 km and 19,801 km annually. Hybrid engine technology is cost effective for these drivers when gasoline exceeds \$1.00 per liter, \$1.50 per liter, and \$1.90 per liter respectively. Note that, other than the jump in the demand curve when the hybrid technology breakeven point is reached, the demand for gasoline is inelastic. Note also that the change in demand for gasoline is greater for the high mileage driver than for the low mileage driver.

Figure 5 Individual demand for gasoline - Scenario 1 inelastic

6.2 Scenario 2 - elastic

In this scenario the assumption of inelastic long run demand for vehicle kms is removed. Instead the long run elasticity for vehicle kms traveled with respect to the fuel costs per km is introduced. This elasticity affects drivers of both new gasoline vehicles and hybrid vehicles. Drivers of both new gas and hybrid vehicles will reduce their driving when the price of gasoline increases. Drivers who purchase hybrid vehicles take advantage of the improved fuel economy offered by their hybrid vehicle and increase the number of km

they drive annually. This increase in driving is referred to as the rebound effect by Small and Van Dender (2007). The value for the long run elasticity for vehicle kms traveled is set at -0.1066 as reported by Small and Van Dender (2007). Using this value and those established for fuel efficiency in section 5 above generates a rebound effect of approximately 3% of vehicle kms when a hybrid vehicle is purchased. For this scenario the reference annual km is assumed to be at a price of gasoline of \$1.00 per liter. Thus for p_g less than \$1.00 per liter consumers will increase their driving above that given in scenario 1 and for p_g greater than \$1.00 per liter consumers will decrease their annual driving.

6.3 Scenario 3 – vehicle price

This scenario makes the same assumptions as scenario 2 – elastic but also adds the assumption that the demand for vehicle kms is sensitive to the price of the vehicle. The value for the elasticity of vehicle km travelled with respect to the price of a new vehicle is set at -0.0876 also as reported by Small and Van Dender (2007). This elasticity works to reduce the rebound effect of purchasing a hybrid vehicle. (An increase in the price of a vehicle works to reduce the number of vehicles per person which in turn reduces the number of km driven per person.) Using the values determined for fuel efficiency and the price premium for hybrid vehicles in section 5 above results in almost complete elimination of the rebound effect. This can be seen in figure 6, which shows the demand for gasoline under the three scenarios, when the price of gasoline is above \$1.00 per liter. For a price of gasoline below \$1 per liter, individuals choose new gas vehicles in all three scenarios. There is no rebound effect for new gas vehicles. Further the price of a new gas vehicle is the reference vehicle price for the elasticity of vehicle km

travelled with respect to the price of a new vehicle. Therefore the curves for scenario 2 - elastic and scenario 3 - vehicle price below \$1 per liter are the same.

Figure 6 Individual demands for gasoline - Three scenarios

6.4 Reference Cases

In order to further assess the impact that hybrid vehicles will have on the demand for gasoline two reference cases without hybrid vehicles are considered. They are reference - no hybrid inelastic which is equivalent to scenario 1 - inelastic, where demand for vehicle kms traveled is inelastic, but where no hybrids are offered in the marketplace and reference - no hybrid elastic which is equivalent to scenario 2 - elastic, where vehicle kms traveled has elastic long run demand, but where no hybrid vehicles are offered in the market place.

7.0 Steady State Aggregate Demand

Once the individual choice problem has been solved, the technological composition of the fleet and the annual aggregate demand for gasoline $D_{gasoline}$ can be determined. This is done for both the steady state and the transition.

The steady state aggregate demand for gasoline is found by assuming that all existing vehicles in the fleet have been replaced with either new gas vehicles or hybrid vehicles according to the consumer choice problem outlined above. By setting Equation 10 and Equation 11 equal to each other and setting both x_{ngv} and x_{hv} equal to one (the consumer is indifferent) the breakeven number of km driven annually x_{kmBE} can be calculated.

Equation 17

$$x_{kmBE} = \frac{p_{hp}D}{\left(1 - \frac{1}{(1+D)^n}\right)(P_g(FE_{ngv} - FE_{hv}))}$$

Vehicles that are driven greater than x_{kmBE} are replaced with hybrid vehicles. Vehicles that are driven less than x_{kmBE} are replaced with new gas vehicles. The model then sums the fuel consumed across the entire range of vehicles (Equation 18). This is done by first summing the product of the number of new gas vehicles that travel $\bar{x}_{km}^*$ annually ($x_{ngv_{\bar{x}_{km}^*}}$) and the number of km they travel annually ($\bar{x}_{km}^*$) across the range of km travelled annually by new gas vehicles ($0km$ to x_{kmBE}). This yields the total number of km driven annually by new gasoline vehicles. This value is then multiplied by the fuel economy of new gas vehicles FE_{ngv} to find the total fuel consumed by new gas vehicles. This procedure is then repeated for hybrid vehicles.

Equation 18

$$D_{gasoline} = FE_{ngv} \sum_{\bar{x}_{km}^*=0}^{\bar{x}_{km}^*=x_{kmBE}} x_{ngv\bar{x}_{km}^*} \bar{x}_{km}^* + FE_{hv} \sum_{\bar{x}_{km}^*=x_{kmBE}}^{\bar{x}_{km}^*=max} x_{hv\bar{x}_{km}^*} \bar{x}_{km}^*$$

The Canadian market constitutes a small part of the world market for petroleum.

Therefore it is assumed that the price of gasoline is independent of domestic demand and that there is no feedback between rising fleet fuel economy (lower domestic demand) and the domestic price of gasoline.

The Canadian aggregate steady state demand for gasoline under scenario 1 – inelastic is shown in Figure 7. The shape of the demand curve is driven by the distribution of annual km driven and by the breakeven point for hybrid technology. This breakeven point is a function of the price of gasoline. At low prices of gasoline only a small number of vehicles exceed the breakeven point. As the prices increases the number of hybrid vehicles increases but the average number of km driven annually by hybrid vehicles decreases. As the price of gasoline rises above \$2.29 per liter the incremental number of additional hybrid vehicles km decreases. With a high enough price for gasoline all vehicles would be hybrid powered and the demand curve would become vertical.

Figure 7 Steady state aggregate demand for gasoline – Scenario 1 inelastic

Next the demand under scenario 2 – elastic and scenario 3 – vehicle price is calculated. This is done using the same methodology as in scenario 1 – inelastic with the exception that the breakeven distance for hybrid vehicles is no longer based on a simple npv calculation.

When the assumption on the rebound effect is relaxed, the choice of buying a hybrid vehicle or a new gasoline vehicle becomes more complicated than described in section 4.1. This is addressed graphically in Figure 8 by seeking the utility maximizing bundle of the composite good and vehicle km traveled subject to the budget curve of either the new gas vehicle or the hybrid vehicle. From this figure we can see that the decision of whether to purchase a hybrid vehicle or a new gas vehicle depends on the vehicle km initially driven, on the shape of the individual's utility function, on the price of gasoline, on the relative fuel economy of hybrid and new gasoline vehicles and on the price premium of hybrid vehicles. In the case shown the consumer is indifferent. Note that as the price of gasoline changes the individual might jump from one solution to another. This is

consistent with the discontinuity in the demand for gasoline shown in Figure 7. Without knowing the individual's utility function the exact breakeven distance for a hybrid vehicle cannot be determined. However, if the breakeven distance is defined as the minimum number of vehicle kms, before considering the rebound effect, where a driver would prefer a hybrid vehicle over a new gas vehicle then a range of breakeven distances can be found. They are the high boundary, where the cost of the hybrid and the new gas vehicle are equal for the pre-rebound vehicle kms and the low boundary where the cost of the hybrid vehicle and the new gas vehicle are the same for the post-rebound vehicle kms. The model arbitrarily uses a point half way between the high and low boundaries for calculating the costs and benefits of different scenarios.

Figure 8 Breakeven distance for hybrid vehicles

The aggregate demand for gasoline for all three scenarios and the two reference cases is shown in Table 3 and Figure 9. A comparison of the demand for gasoline in scenario 1 -

inelastic with the demand for gasoline for the reference case - no hybrid inelastic shows steady state savings in gasoline across the range of gasoline prices tested. A comparison of the scenario 2 - elastic curve in Figure 10 with the reference no hybrid - elastic curve shows that in the long run the presence of hybrid vehicles in the fleet will have a significant effect on the demand for gasoline. This is also shown in Table 3 in the left most column where the differences in the demand for gasoline between the reference case – no hybrid elastic and scenario 2 – elastic are calculated. The conclusion that having widespread availability of hybrid vehicles in the market place has a large effect on the demand for gasoline is reached.

As expected the inclusion of long run elasticity of vehicle kms with respect to fuel cost per km in scenario 2 - elastic flattens the demand curve relative to scenario 1 – inelastic (see Figure 9). The inclusion of the elasticity of vehicle kms relative to the price of the vehicle in scenario 3 – vehicle price reduces the rebound effect and reduces the demand for gasoline at a given price. However the effect is small and the overall conclusion remains unchanged.

Table 3 Steady State Demand for Gasoline

Steady State Aggregate Demand for Gasoline (000,000 liters)						
Price Gasoline (\$/liter)	Scenario 1 - inelastic	Scenario 2 - elastic	Scenario 3 - vehicle price	Reference - no hybrid inelastic	Reference - no hybrid elastic	Reference - no hybrid elastic minus Scenario 2 - elastic
0.8	25,800	26,470	26,358	27,480	28,137	1,779
0.9	25,487	25,852	25,754	27,480	27,788	2,034
1	25,176	25,291	25,151	27,480	27,480	2,329
1.1	24,825	24,783	24,629	27,480	27,203	2,574
1.2	24,503	24,264	24,094	27,480	26,953	2,859
1.3	24,194	23,830	23,647	27,480	26,725	3,079
1.4	23,912	23,397	23,199	27,480	26,516	3,317
1.5	23,609	23,016	22,807	27,480	26,322	3,515
1.6	23,351	22,639	22,416	27,480	26,142	3,726
1.7	23,150	22,322	22,089	27,480	25,975	3,886
1.8	22,945	22,011	21,768	27,480	25,817	4,050
1.9	22,735	21,767	21,451	27,480	25,669	4,218
2	22,593	21,469	21,206	27,480	25,530	4,324

Figure 9 Steady state demand for gasoline – comparison

Figure 10 shows the number of km driven by hybrid vehicles versus the breakeven distance for hybrid technology assuming inelastic demand for vehicle kms. The reference point for a gasoline price of \$1/liter is shown.

Figure 10 Number of hybrid vehicle km vs. breakeven distance

7.1 Calibration

The results in the previous section are calibrated by comparing the predicted total number of vehicle km from the model (2.9835×10^{11} km) with the actual number of vehicle km for 2004 reported in the Canadian vehicle survey (2.8409×10^{11} km). The Canadian vehicle survey also reports an average fuel economy of 11.1 liters per 100 km for light duty vehicles for 2004, with quarterly variations ranging from 12.64 liters per 100 km to 10.38 liters per 100 km. Using these inputs to calculate the total demand for gasoline in 2004 for light duty vehicles yields 3.153×10^{10} liters. This compares to 2.580×10^{10} liters at $p_g = \$1.00$ for the study. These results are consistent with the difference in demand being

explained by the difference in average fuel economy for 2004 (11.1 l/100km) and for the study (8.74l/100km at $p_g=\$1.00$).

7.2 Sensitivity

The results above are based on the assumption that the mix of city and highway driving is fixed at 55% city. Hybrid vehicles provide more benefit in city driving than in highway driving and it could be argued that high mileage drivers drive proportionally more highway miles. To test the effect that this would have on the results the following sensitivity analysis was performed. The assumption that the mix of city and highway driving is fixed was replaced with the assumption that the first 4800 km driven annually are all city km, the next 75,200 km driven annually are assumed to be at a 30% city, 70% highway split and all km driven above 80,000 km annually are assumed to be highway. The overall mix remains the same at 55% city. The resulting demand for gasoline is shown in Figure 11. At a price of gasoline of \$1.00 per liter the breakeven distance increases from 37,600 km to 46,800 km which results in the number of hybrid vehicles being reduced from 1.830 million to 0.970 million. Gasoline consumption remains largely unchanged as additional new gas vehicles operate at 70% highway and are therefore operating in a more efficient mode. The savings of gasoline versus the no hybrid case is reduced from 2.3 billion liters to 2.0 billion liters annually. The demand for hybrid vehicles is sensitive to the assumption of city / highway mix, but the overall conclusion that the widespread availability of hybrid vehicles will result in significant benefits for Canada is unchanged.

Figure 11 Gasoline demand sensitivity to city / highway mix

8.0 Long Run Own Price Elasticity

The long run own price elasticity for gasoline is also determined for each of the scenarios (Figure 12). The long run own price elasticity for gasoline varies with the price of gasoline. This is due to the breakeven distance changing with the price of gasoline and a resulting change in the number of km driven by hybrid vehicles. For the scenario 1 - inelastic the low point in the point elasticity corresponds to a breakeven distance of 23,513 km.

The long run steady state own price elasticity for gasoline is also shown for scenarios 2 and 3. In scenario 2 – elastic the long run own price elasticity of gasoline is not the simple sum of the long run elasticity of vehicle km with respect to fuel cost per km and the long run elasticity calculated in scenario 1 - inelastic. This is due in part to the rebound effect which increases the number of km driven by hybrid vehicles, and hence the amount of fuel they consume, and to the fact that hybrids breakeven at a lower price

of gasoline than in scenario 1 – inelastic which reduces the demand for gasoline at a given price. In general the estimated elasticity has a lower absolute value than the simple sum.

In scenario 3 - vehicle price the long run elasticity of vehicle kms to vehicle price reduces the rebound effect and therefore reduces the amount of fuel used by hybrid vehicles. This in turn results in slightly higher (absolute) elasticity than in scenario 2 – elastic.

Figure 12 Own price steady state elasticity for gasoline

9.0 Transition Aggregate Demand

As seen in the steady state aggregate case described above, the effect of having widespread availability of hybrids in the market is large. However to fully realize this effect the entire existing fleet of vehicles must be replaced. This is obviously a very long term undertaking. In order to understand the impact of hybrid vehicle availability in the medium term the transition case is examined.

By combining the individual technology solutions from above with the retirement schedule for the existing fleet, the technology composition of the fleet can be determined for each year of the study.

Once the breakeven number of annual km has been calculated, the model then calculates the technology makeup of the fleet for each year of the study. This is done by assuming that all vehicles in the fleet at the start of the study are of the type old gas. Once a vehicle reaches the end of its life it is replaced. Vehicles are assumed to have an eleven year life. The age distribution of vehicles in the fleet is assumed to be uniform. Further the age of the vehicle is the only factor used to determine if a vehicle is to be replaced. Annual km driven is assumed not to effect vehicle replacement. Therefore 1/11 of the vehicles in the fleet are replaced each year⁶. If the vehicle has anticipated annual km greater than or equal to the annual breakeven distance for hybrid technology then the new vehicle will be

⁶ This is a conservative assumption. If high mileage vehicles were replaced earlier than low mileage vehicles then the transition to the steady state would be accelerated.

a hybrid vehicle. If not, then the old gasoline vehicle will be replaced with a new gasoline vehicle.

Once the technology composition of the fleet has been determined the model then calculates the annual fuel consumption of the fleet. This is done by calculating the total km driven annually for each technology and then multiplying this number by the average fuel economy for each technology type.

Equation 19

$$\begin{aligned}
 D_{gasoline} = & FE_{ngv} \sum_{\bar{x}_{km}^*=0}^{\bar{x}_{km}^*=x_{kmBE}} x_{ngv\bar{x}_{km}^*} \bar{x}_{km}^* \\
 & + FE_{hv} \sum_{\bar{x}_{km}^*=x_{kmBE}}^{\bar{x}_{km}^*=max} x_{hv\bar{x}_{km}^*} \bar{x}_{km}^* \\
 & + FE_{ogv} \sum_{\bar{x}_{km}^*=0}^{\bar{x}_{km}^*=max} x_{ogv\bar{x}_{km}^*} \bar{x}_{km}^*
 \end{aligned}$$

Where $x_{ngv\bar{x}_{km}^*}$ is the number of new gas vehicles in the fleet that drive $\bar{x}_{km}^*$ annually,

$x_{hv\bar{x}_{km}^*}$ is the number of hybrid vehicles that drive $\bar{x}_{km}^*$ annually and $x_{ogv\bar{x}_{km}^*}$ is the

number of old gas vehicles that drive $\bar{x}_{km}^*$ annually. FE_{ogv} is the fuel economy of an old gas vehicle.

This consumption is a function of the technology make up of the fleet (old gasoline, new gasoline, or hybrid), the fuel economy of each technology and the distribution of km driven for each technology.

Once again the reference case of “no hybrid” is considered. In this case old gasoline vehicles are replaced with new gasoline vehicles at the end of their life. For this part of the study the assumption that there is no elasticity of vehicle km driven is reinstated.

As expected when we take into account the transition time required for new hybrids to penetrate the fleet, the effect of having hybrid vehicles available is reduced. Figure 13 shows the total demand for gasoline for the 11 year transition period. For reference both the “no hybrid” case and the steady state demand multiplied by 11 are shown.

Figure 13 Transition demand for gasoline

Figure 14 shows the annual gasoline consumption by technology for each year of the transition at the reference price of gasoline of \$1 per liter. Notice that, while fuel consumption drops by 20% from year 1 to year 11 of the study, 48% of that savings is due to the shift to new gasoline engines. By year 11 hybrid powered vehicles account for 10% of the vehicles, 31% of the vehicle km driven and 52% of the fuel saving. Note that the fuel economy factor for old gas vehicles was determined from the Canadian Vehicle Survey (2006) and thus is based on measurement of real vehicles in real driving situations. The fuel economy factors for hybrid and new gas vehicles were determined through the market survey and are based on Transport Canada laboratory tests. This difference in methodology likely results in some of the savings attributed to new gas vehicles but does not change the overall conclusions.

Figure 14 Transition gasoline consumption per year by technology

Figure 15 shows the fuel consumed in the hybrid scenario and “no hybrid” reference case. It also shows the difference between the two cases. At \$1.0 per 12.7 billion liters of gasoline would be saved or 3.9%. At \$2.0 per liter this amounts to a savings of 26.9 billion liters or 8.2%.

Figure 15 Transition fuel savings

10.0 Policy

Three policy approaches⁷ aimed at reducing greenhouse gas emissions in the personal transportation sector are considered here. They are a tax on gasoline⁸, a subsidy (tax) on fuel efficient (inefficient) vehicles and fleet fuel economy standards. The first two approaches are evaluated by determining their effect on social welfare. The third, fleet fuel economy standards, involves trade-offs not captured by the model and is therefore only commented on.

The reference case, called *hybrid substitution*, for evaluating the policy alternatives is scenario 3 – vehicle price outlined above with the price of gasoline set to \$1.00 per liter.

⁷ More drastic policies that have been put in place such as gasoline rationing, banning driving on odd or even days, charging a congestion charge or closing sections of a city to vehicular travel or indirect policies such as subsidizing public transport or encouraging urban redesign have not been considered.

⁸ The tax on gasoline would presumably be part of a more comprehensive carbon tax.

The elasticity of vehicle kms to both the price of vehicle kms and to the price of the vehicle is considered.

10.1 Policy – Tax on gasoline

Three levels of the tax on gasoline are investigated in detail. The first two assume a Pigouvian tax where the tax is set at the marginal damage of gasoline (md_g). Two values for the marginal damage of gasoline are tested. The first is \$50.00 per tonne of carbon. This value is published by Tol (2005) and is based on a literature survey of 28 studies. \$50.00 per tonne of carbon translates to \$0.03 per liter of gasoline. The second value is \$314 per tonne of carbon (\$0.20 per liter of gasoline). This value is used in the “Stern Review” but is challenged by Tol (2006) as being not widely supported by peer reviewed literature. The third level of the tax on gasoline considered is a larger tax on gasoline. This tax would be larger than the marginal damage of gasoline but could be justified by the need to raise tax revenue. Hybrid vehicles themselves may have a higher marginal damage than new gasoline vehicles. This could be due in part to the large batteries used in this type of vehicle. This potential marginal damage is ignored.

The tax on gasoline tested in this section would in fact be an increase to existing taxes on gasoline. At the reference price of \$1.00 per liter of gasoline approximately \$0.33 is made up of existing provincial and federal taxes (Department of Finance, Government of Canada 2005). Furthermore, both the composite good and hybrid vehicles are subject to existing consumption taxes. Therefore the effect of introducing a new tax on existing taxes is considered. Revenue raised by a tax on gasoline could also be used to offset a tax

cut in other areas such as personal income tax. The marginal cost of funds becomes important in this case. The marginal cost of funds for the gasoline tax is already included in the model. The Canadian Department of Finance (Baylor 2004) reports that the welfare gains per dollar of lost present value government revenue are \$0.32 for personal income taxes and \$0.13 for consumption taxes. Assuming that the government chose to reduce personal income taxes and the GST with the income generated by the gasoline tax and assuming that it did so keeping the relative proportion of revenue collected by each tax the same, then a shift to a gasoline tax would have tax efficiency gains of \$0.27 per dollar of present value revenue collected from gasoline taxes⁹. The impact of the gasoline tax on social welfare is compared to the reference both with and without considering marginal costs of funds and the changes to existing tax revenues. The gasoline tax alternative is less progressive than income tax and could have significant distributional effects. It could for instance penalize high mileage drivers, who could end up paying more tax than they do today, and reward high income people, who could end up paying less tax than they do under the current tax system. These effects are ignored.

The gasoline tax alternatives are evaluated on the basis of social welfare compared to the reference case. Social welfare is the sum of all benefits minus all costs across all of society. The change in social welfare due to each alternative over the reference case is expressed by:

Equation 20

$\Delta social\ welfare$

$$= NPV(md_g \Delta x_g^A + t_g x_g^A - cv^A) + \beta NPV(t_g x_g^A - \Delta t^E) - NPV(\Delta t^E)$$

⁹ 73% collected from personal income taxes, 27% collected from the GST (Statistics Canada 2008)

Each term in this equation is examined in detail. The superscript A indicates the aggregate of the value across society. The term $NPV(md_g \Delta x_g^A + t_g x_g^A - cv^A)$ represents the change to social welfare without considering the effects of the tax on other taxes. The term $md_g \Delta x_g^A$ represents the reduction of damage to the environment due to burning less gasoline, where md_g is the marginal damage of gasoline and Δx_g^A is the annual aggregate fuel saved by the alternative. The compensating variation of income cv^A is the income that a driver would need to receive in order to be fully compensated for the imposition of the new tax. It is introduced by drivers substituting away from driving due to the tax and the elastic demand for vehicle km. The loss of welfare by individuals due to the compensating variation is partially offset by the revenue raised by the tax $t_g x_g^A$. The compensating variation is calculated using the following method. Drivers are considered individually. They are divided into two groups; those who change technology as a result of the tax and those who do not.

Those drivers who **do not** change technology as a result of the tax consume less gasoline due to substitution effects only. This results in an individual excess burden, which is calculated using the demand curve for gasoline¹⁰, by finding the dotted area in Figure 16.

¹⁰ A rigorous treatment requires that consumer surplus is first converted to compensating variation because the demand curve here is uncompensated. This is done according to

$$CV = y^0 \left[\frac{-\Delta CS}{y^0} (1 - \rho) + 1 \right]^{1/(1-\rho)} - y^0$$

Where CV is the compensating variation and y^0 is income. ρ is the income elasticity of vehicle km which is assumed to be independent of price Willig (1976) and Jehle (2001). Note that when the tax is small in comparison to income consumer surplus and compensating variation are nearly equal and this is true for a broad range of values for ρ and y^0 . Supply is assumed to be completely elastic so there is no producer surplus.

The shaded rectangle shows the reduction in damage due to gasoline. Ignoring the marginal cost of funds momentarily yields the net gain in social welfare equal to the reduction in environmental damage minus the excess burden. The diagram illustrates a case where the tax is set below the marginal damage of gasoline.

Figure 16 Change in social welfare for drivers who **do not** change engine technology

Some insight into the change in social welfare for those drivers who **do** change technology as a result of the tax can be gained by examining the demand curve for gasoline for a sample driver (Figure 17). These drivers consume less gasoline due to two factors, the fuel saved through the use of hybrid technology and the fuel saved as a result of substitution effects induced by the tax. The total fuel saved times the marginal damage of gasoline equals the reduction in environmental damage, shown as the shaded rectangle, and is a benefit. The gasoline not consumed due to substitution effects results in a compensating variation, which is only partially offset by tax revenue. The difference is part of the excess burden of the tax, shown as the sum of the shaded areas, and is a cost.

The fuel saved due to the use of hybrid technology results in a discontinuity in the demand curve. This discontinuity causes difficulty in calculating the total excess burden of the tax so instead a different approach is taken.

Figure 17 Change in social welfare for drivers who do changes engine technology

Instead of using the gasoline demand curve alone to calculate the excess burden, a combined utility curve – budget curve and gasoline demand curve approach is used. Figure 18 shows the utility and budget lines for an individual consumer faced with a tax on gasoline. Here it is assumed that there is no income effect of a tax on gasoline and that therefore the utility curves maintain a constant vertical separation. It is also assumed that the price, including consumption taxes, of the composite good x_c is \$1.00. The consumer is at point a before the tax. The diagram shows that this consumer prefers a new gas vehicle at the initial prices and distance driven. When the tax t_g is imposed the consumer is indifferent to a hybrid or new gasoline vehicle. The loss to the individual consumer is shown as segment bc or segment ef which is the compensating variation of the tax. From

the assumption that the utility curves maintain a constant vertical separation it follows that segment $\underline{bc}$ is equal to segment $\underline{ef}$. The value of the compensating variation $\underline{bc}$, when the consumer does not choose a hybrid vehicle, is calculated using the same methodology used in Figure 16. This demand curve methodology can be used because, when the consumer chooses a new gas vehicle, no discontinuity in the individual demand curve is introduced. The compensating variation is composed of two elements - the tax revenue, shown as segment $\underline{cd}$ if the consumer chooses a new gas vehicle or as segment $\underline{fg}$ if the consumer chooses the hybrid vehicle¹¹ and the excess burden shown as segments $\underline{bd}$ or $\underline{eg}$ respectively. The change in social welfare, introduced by substitution effects, of a consumer choosing a hybrid vehicle at this point is the excess burden $\underline{eg}$. Note that the excess burden of the tax is greater when the individual chooses a hybrid vehicle. The compensating variation for choosing either type of vehicle is the same. However because the hybrid vehicle consumes less gasoline the tax revenue is lower. Consumers are spending money on hybrid technology to avoid paying tax and thus reducing social welfare.

¹¹ The tax revenue generated when a consumer chooses a hybrid is found according to $\text{tax revenue} = t_g x_{vkm} FE_h$

Figure 18 Change in social welfare due to a tax on gasoline for drivers who do change technology

Once the individual compensating variation and tax revenues due to the tax has been found for all individual drivers they are summed across the fleet and added to the reduction in damage due to gasoline to find the aggregate change in social welfare ignoring the effect of the new tax on existing taxes.

The terms $\beta NPV(t_g x_g^A - \Delta t^E) - NPV(\Delta t^E)$ in equation 19 above are introduced to capture the effect the new tax has on existing taxes. The change to existing tax revenue Δt^E is expressed as:

Equation 21

$$\Delta t^E = p_c t_c^E \Delta x_c^A + p_g t_g^E \Delta x_g^A + p_{hp}^A t_{hp}^E \Delta x_{hp}^A$$

Where $p_c t_c^E \Delta x_c^A$ is the change in tax revenue generated by existing consumption taxes on

the composite good. The imposition of the new taxes reduces the amount consumers spend on the composite good. To estimate the consumption tax rate on the composite good it is assumed that the composite good is represented by the Consumer Price Index (CPI) basket of goods. Statistics Canada (2006b) estimates that 60% of the goods in the CPI basket of goods are subject to the GST. The total value for the consumption tax is assumed to be 11.67%¹². Therefore the tax rate on the composite good used is 6.5%. The term $p_g t_g^E \Delta x_g^A$ is introduced because the price of gasoline at the pump already includes existing taxes t_g^E . Imposing the new tax reduces the revenue raised by the existing tax. The term $p_{hp}^A t_{hp}^E \Delta x_{hv}^A$ is introduced because the imposition of the new tax induces consumers to spend more on hybrid technology. Existing tax revenue is increased by the tax raised on the annualized price premium paid p_{hp}^A on the incremental number of hybrid vehicles Δx_h^A . The existing average consumption tax rate on hybrid technology t_{hp}^E is 11.67%. The term $\beta NPV(t_g x_g^A - \Delta t^E)$ is the benefit gained by returning the net revenue raised by the new tax on gasoline to consumers by reducing marginal personal income tax rates and the GST as described above. This causes a \$0.27 lump sum benefit β for every \$1.00 of present value of new net gasoline tax raised ($t_g x_g^A - \Delta t^E$). In the case where tax revenues are assumed to be returned in a lump sum then the value of β is zero.

The reference case, called *hybrid substitution*, for evaluating the policy alternatives is scenario 3 – vehicle price outlined above with the price of gasoline set to \$1.00 per liter.

¹² This value is the average total consumption tax including GST and PST across Canada when weighted by the provincial retail sales. The GST rate is 5%. Actual PST rates range from 0% in Alberta to 10.5% in P.E.I. The PST and GST have somewhat different application rules. For this study it is assumed that as with the GST they apply to 60% of the CPI Basket of goods.

Note that this case itself provides significant benefit compared to the case where hybrid vehicles are not available and the fleet is composed entirely of new gas vehicles. Hybrid substitution would result in an annual saving of 2329 million liters of gasoline over the no hybrid case. This is an 8% saving. It would also result in 1.6 million hybrid vehicles being put on the road. The change social welfare over the no hybrid case is:

Equation 22

$$\Delta social\ welfare = NPV(md_g \Delta x_g^A + p_g \Delta x_g^A - \Delta t^E) - p_{hp} \Delta x_{hv}^A$$

This amounts to \$2.4 billion over the life of the hybrid vehicles. The additional cost of the hybrid technology $p_{hp} \Delta x_{hv}^A$ would be \$12.1 billion. This would be offset by lifetime fuel savings $NPV(p_g \Delta x_g^A)$ worth \$19.3 billion and a reduction in damage due to gasoline $NPV(md_g \Delta x_g^A)$ worth \$580 million. The reduction in gasoline consumption would result in a loss of existing tax revenues $NPV(\Delta t^E)$ worth \$5.4 billion. These benefits would be achieved without any direct policy initiatives.

The change in social welfare assuming a marginal damage of gasoline of \$0.03 per liter and both with and without considering the effect on existing taxes is shown in Figure 19 . Without considering the effect on existing taxes the results show a mild maximum when the tax is \$0.05 per liter. This is close to the expected Pigouvian result (where the maximum should be found when the tax is equal to the marginal damage). However when the effects on other taxes are considered the change in social welfare continues to increase across the range of taxes tested. These results are examined in detail below.

Figure 19 Social welfare

The change in social welfare for each of the tax levels assuming the marginal damage of gasoline is \$0.03 per liter and without considering the impact of the different marginal cost of funds or the loss of tax revenue due to the increase to an existing tax is shown in Table 4.

Table 4 Change in social benefit for three gasoline tax scenarios

Change in social benefit for three gasoline tax levels without considering other tax implications (,000,000.)			
Marginal damage of gasoline	\$0.03	\$0.03	\$0.03
Tax on gasoline	\$0.03	\$0.20	\$1.00
Social benefit	\$37.8	\$263.2	\$983.0
NPV change in damage due to gasoline	\$37.8	\$263.2	\$983.0
Lump sum benefit of tax shift	\$0.0	\$0.0	\$0.0
Social cost	\$14.0	\$348.2	\$4,406.6
NPV tax revenue lost due to incremental tax	\$0.0	\$0.0	\$0.0
NPV excess burden	\$14.0	\$348.2	\$4,406.6
Change in social benefit	\$23.8	-\$85.0	-\$3,423.6

The change in social welfare for each of the tax levels assuming the marginal damage of gasoline is \$0.2 per liter and without considering the impact of the different marginal cost of funds or the loss of tax revenue due to the increase to an existing tax is shown in Table 5. At tax rates of \$0.03 per liter and \$0.20 per liter the change in social welfare is positive. A tax on gasoline may be justified in this case. However because the increase in social welfare is small compared to outlays (for instance total spending on hybrid vehicles when the tax is \$0.03 is \$55 billion) and thus likely sensitive to other factors, the optimal tax might be better set by distributional or political concerns.

Table 5 Change in social benefit for three gasoline tax scenarios

Change in social benefit for three gasoline tax levels without considering other tax implications (,000,000.)			
Marginal damage of gasoline	\$0.20	\$0.20	\$0.20
Tax on gasoline	\$0.03	\$0.20	\$1.00
Social benefit	\$251.9	\$1,754.9	\$6,553.3
NPV change in damage due to gasoline	\$251.9	\$1,754.9	\$6,553.3
Lump sum benefit of tax shift	\$0.0	\$0.0	\$0.0
Social cost	\$14.0	\$348.2	\$4,406.6
NPV tax revenue lost due to incremental tax	\$0.0	\$0.0	\$0.0
NPV excess burden	\$14.0	\$348.2	\$4,406.6
Change in social benefit	\$237.8	\$1,406.7	\$2,146.7

The change in social welfare for each of the tax levels assuming the marginal damage of gasoline is \$0.03 per liter and considering the impact of the different marginal cost of funds is shown in Table 6. Notice that the benefit is dominated by the difference in the marginal cost of funds between gasoline and income taxes.

Table 6 Change in social benefit for three gasoline tax scenarios

Change in social benefit for three gasoline tax levels considering other tax implications (,000,000.)			
Marginal damage of gasoline	\$0.03	\$0.03	\$0.03
Tax on gasoline	\$0.03	\$0.20	\$1.00
Social benefit	\$1,528.3	\$9,810.6	\$43,462.9
NPV change in damage due to gasoline	\$37.8	\$263.2	\$983.0
Lump sum benefit of tax shift	\$1,490.5	\$9,547.4	\$42,479.9
Social cost	\$723.4	\$5,030.4	\$23,500.9

NPV tax revenue lost due to incremental tax	\$709.0	\$4,666.6	\$18,810.9
NPV excess burden	\$14.4	\$363.8	\$4,690.0
Change in social benefit	\$804.9	\$4,780.2	\$19,962.0

Table 7 Change in social benefit for three gasoline tax scenarios

Change in social benefit for three gasoline tax levels considering other tax implications (,000,000.)			
Marginal damage of gasoline	\$0.20	\$0.20	\$0.20
Tax on gasoline	\$0.03	\$0.20	\$1.00
Social benefit	\$1,742.4	\$11,302.3	\$49,033.3
NPV change in damage due to gasoline	\$251.9	\$1,754.9	\$6,553.3
Lump sum benefit of tax shift	\$1,490.5	\$9,547.4	\$42,479.9
Social cost	\$723.4	\$5,030.4	\$23,500.9
NPV tax revenue lost due to incremental tax	\$709.0	\$4,666.6	\$18,810.9
NPV excess burden	\$14.4	\$363.8	\$4,690.0
Change in social benefit	\$1,019.0	\$6,271.9	\$25,532.4

The change in social welfare for each of the tax levels assuming the marginal damage of gasoline is \$0.20 per liter and considering the impact of the different marginal cost of funds is shown in Table 7. Again the benefit is dominated by the difference in the marginal cost of funds between gasoline and income taxes. Whether the marginal damage due to gasoline is small or large it appears that the environmental and excess burden considerations are of minor importance compared to the marginal cost of funds and the change to existing tax revenues. The best approach may be to design the tax system considering tax efficiency first and environmental concerns second. Also, as noted above the widespread availability of hybrid technology provides a social welfare benefit of \$2.4 billion without any tax on gasoline.

These results were found to be robust when tested using sensitivity analysis. Specifically, the elasticity of vehicle kms with respect to fuel cost per km was increased to -0.2221¹³ while the elasticity of vehicle km with respect to vehicle price was reduced to zero. These changes maximize the rebound effect. The discount rate was lowered from 5% to 2%. Neither of these changes had any meaningful impact on the results. See appendix b for the details of this work.

10.2 Policy – Subsidy for fuel efficient vehicles

The next policy alternative investigated is a subsidy for fuel efficient vehicles. Such a subsidy is currently offered by the federal government. This subsidy provides \$2000 for fuel efficient vehicles. A list of eligible vehicles is published by Transport Canada (2008a). To have a significant impact on CO₂ emissions this subsidy would require a significant level of funding. The assumption is made that this program would be self funding and that the subsidies would be paid for by a tax on fuel inefficient vehicles. To test this policy with the model the assumption is made that the subsidy is available to all purchasers of hybrid vehicles and that a tax is applied to all new gasoline vehicles. By setting the sum of the subsidy and the tax to \$2000 a rough assessment of the effect of extending the existing program to cover a wide deployment of hybrid vehicles is achieved.

The subsidy alternative is compared to the hybrid substitution reference case on the basis of change to social welfare. The subsidy alternative generates a benefit due to the

¹³ Small, Kenneth A, Van Dender. Kurt (2007) give a range of -0.1066 to -0.2221 for this value. The -0.1066 value is for the years 1997 to 2001. The -0.2221 value is for the entire study, 1966 to 2001.

reduction in damage caused by gasoline $md_g\Delta x_g^A$ over the life of the hybrid vehicle and a benefit due to a gain in consumer surplus Δcs . This gain in consumer surplus is due to drivers substituting hybrid vehicle for new gas vehicles in the presence of a subsidy. The gain in consumer surplus is calculated using a compensated demand curve for hybrid technology generated by the model and is therefore equal to the compensating variation. The gain in consumer surplus is shown as the dotted area abde in Figure 20. The cost of this alternative is the amount of the subsidy s_h spent on hybrid vehicles and is shown as the area of rectangle acde in Figure 20. As in the gasoline tax alternative discussed above, the imposition of the hybrid subsidy changes the revenue generated by existing taxes (Equation 21). The intuition for the change in existing tax revenue is as follows. Society as a whole spends more on hybrid vehicles and gains the consumption tax revenue on this spending. This is offset by a reduction in spending on the composite good which in turn reduces the consumption tax revenue. Similarly society as a whole spends less on gasoline and loses the consumption tax revenue on this spending. This is offset by an increase in spending on the composite good which in turn increase the consumption tax revenue. The change in social welfare due to the subsidy alternative is:

Equation 23

$$\Delta Social\ welfare = NPV(md_g\Delta x_g^A) + \Delta cs - s_h x_{hv}^A - NPV(\Delta t^E)$$

Figure 20 Hybrid subsidy change in social welfare

The results for the subsidy alternative are shown in Table 8. A self funded program with \$2000 net rebate for hybrid vehicles would result in an annual savings of 1.1 billion liters of gasoline. This is a 4.4% saving. It would result in 1.5 million addition hybrid vehicles on the road. However, the rebate would have to be paid for all hybrid vehicles (3.1 million) so the cost of this program would be \$6.3 billion. If the cost of this program is spread over the non-hybrid vehicles in the fleet the average tax would be \$ 501 per vehicle¹⁴. If the marginal damage of gasoline is \$0.03 per liter then the loss in social welfare is \$2.8 billion. If the marginal damage of gasoline is \$0.2 per liter then the loss in social welfare is \$1.3 billion. There is no change in social welfare if the marginal damage of gasoline is \$0.34 per liter. Based on the change in social welfare this policy alternative is not justified.

¹⁴ . The total price difference between a hybrid and a non-hybrid vehicle would be \$2000. A \$1499 rebate for hybrid vehicles and a \$501 tax on new gas vehicles.

Table 8 Change in social welfare for hybrid subsidy scenarios

Change in social welfare for hybrid subsidy scenarios (000,000)			
Marginal damage of gasoline	\$0.03	\$0.20	\$0.340
Social benefit	\$5,229.2	\$6,775.7	\$8,049.3
NPV change in damage due to gasoline	\$272.9	\$1,819.4	\$3,093.1
Increase in consumer surplus	\$4,956.3	\$4,956.3	\$4,956.3
Social cost	\$8,043.1	\$8,043.1	\$8,043.1
Subsidy	\$6,294.0	\$6,294.0	\$6,294.0
NPV tax revenue lost due to subsidy	\$1,749.1	\$1,749.1	\$1,749.1
Change in social welfare	-\$2,814.0	-\$1,267.4	\$6.2

10.3 Policy – Vehicle emission standards

The use of vehicle emissions standards has been advocated by both Jaccard (2004) and Murphy (2000). The federal government recently announced an initiative aimed at implementing a similar approach by 2010 Transport Canada (2008b)¹⁵. The model used in this thesis does not cover the tradeoffs required to fully assess the costs and benefits of this policy alternative. However it does allow for some commentary on the results published by Jaccard and Murphy.

The Jaccard (2004) less aggressive plan calls for 40% of new car sales to be zero, ultralow or low emissions vehicles by 2010. The weighted average minimum fuel economy of these vehicles is 6.76 liters per 100km. Coincidentally this is the same as the value determined in the market survey above¹⁶. At a price of gasoline of \$1 per liter the hybrid substitution case (with elastic demand for vehicle kms) results in hybrid vehicles

¹⁵ This initiative is based on fuel economy instead of emissions but would have a similar impact on emissions.

¹⁶ While zero, ultralow and low emissions vehicles do not necessarily require the use of hybrid technology, the hybrid vehicles available in 2008 in Canada do meet the fuel economy targets of the Jaccard plan.

composing 10% of new car sales. To move this level to 40% either the price of gasoline must be increased to \$2.32 per liter or a subsidy of \$3940 per hybrid vehicle must be given. Assuming, for consistency with Jaccard, that this subsidy is raised by the automobile manufactures charging a premium for high emissions vehicles, the average premium would have to be \$2660 per vehicle and this premium would have to be charged on 60% of new cars. The conclusion is reached that the “less aggressive” plan is in fact aggressive. This program would only make sense if the cost premium of hybrid technology were reduced while the improvement in fuel economy was held constant.

11.0 Conclusions

Hybrid vehicle technology has the potential to provide substantial benefits to Canadian drivers. To achieve this full potential hybrid engine technology must continue to become available in a widening range of vehicles and Canadian drivers must exhibit the same behaviour as European drivers when presented with a choice in engine technology. That is they must choose the most cost effective engine technology for their own driving behaviour. If these conditions are met then hybrid vehicles will represent 10% of the (steady state) fleet, 33% of the vehicle km driven and save 2329 million liters of gasoline annually. This will increase social welfare by present value \$2.4 billion.

Policy alternatives to extend the hybrid penetration beyond that which occur without intervention have been explored. These alternatives, including a tax on gasoline and a subsidy for hybrid vehicles, have been found to reduce, or slightly increase, social welfare. At the same time environmental benefits were found to be small when compared

to the potential benefits available by designing the tax system according to the marginal cost of funds.

These results are likely driven by the low value used for the marginal damage of gasoline and by the large amount of gasoline consumed by Canadians. The low marginal damage of gasoline only justifies a small, \$0.03 per liter of gasoline, market intervention.

However the large amount of gasoline consumed by Canadians results in large tax revenues for even a small tax on gasoline and thus increases the importance of efficiency in the tax system.

The conclusion is reached that, while hybrid vehicles will provide substantial benefits to Canadian consumers, policy initiatives aimed at increasing the penetration of hybrid vehicles in the Canadian personal vehicle fleet are not justified on the basis environmental concerns.

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Appendix A: Tables

Table 9 Pseudo-samples 2004

Km driven quarterly	Number of pseudo-samples
1-999km	91.00
1,000-1,999km	133.00
2,000-2,999km	117.00
3,000-3,999km	101.00
4,000-4,999km	79.00
5,000-5,999km	62.00
6,000-6,999km	47.00
7,000-7,999km	36.00
8,000-8,999km	28.00
9,000-9,999km	20.00
10,000-11,999km	16.00
11,000-11,999km	10.00
12,000-12,999km	10.00
13,000-13,999km	4.00
14,000-14,999km	4.00
15,000-15,999km	3
16,000-16,999km	3
17,000-17,999km	3
18,000-18,999km	2
19,000-19,999km	1
20,000-20,999km	1
21,000-21,999km	1
22,000-22,999km	0
23,000-23,999km	1
24,000-24,999km	1
25,000-25,999km	0
26,000-26,999km	1
27,000-27,999km	1
28,000-28,999km	0
29,000-29,999km	1
30,000-30,999km	1
31,000-31,999km	0
32,000-32,999km	1
33,000-33,999km	1
34,000-34,999km	0

Table 10 Market survey results

Model	proxy for	city (l/100km)	highway (l/100km)	msrp	combined (l/100km)
Chevy Malibu	Intermediate				
hybrid		8.5	6.2	\$26,995.00	7.465
2.4 1LT		9.5	6.1	\$24,895.00	7.97
delta		1	-0.1	-\$2,100.00	0.505
Chevy Tahoe 4x4	Large utility, Large pickup, Large van				
Hybrid		10.5	9.8	\$69,125.00	10.185
FFV		15.4	10.4	\$50,995.00	13.15
delta		4.9	0.6	\$18,130.00	2.965
Chevy Tahoe	Large SUV, Large Pickup, Large Van				
Hybrid		9.8	9.2	\$66,125.00	9.53
FFV		14.9	10	\$47,155.00	12.695
delta		5.1	0.8	\$18,970.00	3.165
Ford Escape	Compact utility				
hybrid		5.7	6.7	\$31,499.00	6.15
XLT 2.3L		10.3	7.7	\$25,399.00	9.13
delta		4.6	1	-\$6,100.00	2.98
Ford Escape 4x4	Compact utility				
hybrid		6.8	7.3	\$33,899.00	7.025
XLT 2.3L 4x4		10.9	8.5	\$27,799.00	9.82
delta		4.1	1.2	-\$6,100.00	2.795
Honda civic	Compact				
hybrid		4.7	4.3	\$26,350.00	4.52
1.8 lx		8.2	5.7	\$22,180.00	7.075
delta		3.5	1.4	-\$4,170.00	2.555
Lexus GS	Luxury				
GS450h		8.7	7.8	\$71,100.00	8.295
GS460		12.4	8.1	\$73,000.00	10.465
delta		3.7	0.3	\$1,900.00	2.17
Lexus GS	Luxury				
GS 450h		8.7	7.8	\$71,100.00	8.295
GS 350		10.9	7.4	\$52,900.00	9.325
delta		2.2	-0.4	\$18,200.00	1.03
Lexus LS	Luxury high				

Model	proxy for	city (l/100km)	highway (l/100km)	msrp	combined (l/100km)
600hL		10.6	9.1	\$125,400.00	9.925
460L		12.9	8.2	\$92,700.00	10.785
delta		2.3	-0.9	\$32,700.00	0.86
Lexus RX	Intermediate utility, Luxury utility				
RX 400h		7.8	8.4	\$55,050.00	8.07
RX 350		12.4	9	\$51,550.00	10.87
delta		4.6	0.6	-\$3,500.00	2.8
Nissan Altima	Intermediate				
Hybrid		5.6	5.9	\$33,998.00	5.735
2.5s CVT		8.9	6.3	\$25,698.00	7.73
delta		3.3	0.4	-\$8,300.00	1.995
Saturn Aura	Intermediate				
hybrid		8.5	6.2	\$27,575.00	7.465
xe 4dr		9.6	6.5	\$24,240.00	8.205
delta		1.1	0.3	-\$3,335.00	0.74
Saturn Vue	Intermediate utility, Luxury utility				
hybrid		8.2	6.1	\$30,790.00	7.255
xe FWD		11	7.5	\$26,990.00	9.425
delta		2.8	1.4	-\$3,800.00	2.17
Toyota Camry	Intermediate				
Hybrid		5.7	5.7	\$32,000.00	5.7
SE a5		9.5	6.2	\$28,050.00	8.015
delta		3.8	0.5	-\$3,950.00	2.315
Toyota Highlander	Intermediate utility, Luxury utility				
Hybrid		7.4	8	\$41,075.00	7.67
V6 AWD		12.3	8.8	\$36,900.00	10.725
delta		4.9	0.8	-\$4,175.00	3.055
Toyota Highlander	None				
Hybrid ltd		7.4	8	\$54,220.00	7.67
ltd		12.3	8.8	\$47,150.00	10.725
delta		4.9	0.8	-\$7,070.00	3.055

Source GM Canada

Table 11 Fuel economy per vehicle class

Class	Monthly sale Canada ,000	% of lights	Price delta \$	delta fuel economy l/100km
Compact utility	15.7	13.396	-6100	2.8875
Intermediate utility	7.9	6.741	-4636.25	2.77
Large pickup	16.5	14.078	-18550	3.065
Large utility	1.4	1.195	-18550	3.065
Large van	1.7	1.451	-18550	3.065
Luxury utility	4.2	3.584	-4636.25	2.77
Small pickup	3.8	3.242	-6100	2.8875
Small van	7.9	6.741	-6100	2.8875
Total light truck	59.1	50.427		
Compact	24.6	20.990	-4170	2.555
Intermediate	17.6	15.017	-4421.25	1.38875
Luxury high	1.9	1.621	-32700	0.86
Luxury	4.7	4.010	-8150	1.6
Luxury sport	0.2	0.171	-8150	1.6
Subcompact	7.4	6.314	-4170	2.555
Sport	1.7	1.451	0	0
Total passenger car	58.2	49.659		
total light vehicles	117.2			

Source DesRosiers Automobile Consultants Inc.

Table 12 Factors used

Table of factors used	
Elasticity of vehicle kms with respect to fuel cost per km	-0.1066
Vehicle price elasticity of vehicle kms	-0.0876
Interest rate	5%
Marginal damage of gasoline (\$ / liter)	\$0.03
Household income	\$57,217.00
Number of Households in Canada	12755572
Reference price of gasoline (\$ / liter)	\$1.00
Price new gas vehicle	\$25,000.00
Price hybrid vehicle	\$32,500.00
Fuel economy new gas vehicle (liters / 100 km)	9.20
Fuel economy hybrid vehicle (liters / 100 km)	6.80
Fuel economy old gas vehicle (liters / 100 km)	10.80
Excepted life of a vehicle (years)	11

Appendix B: Sensitivity

Table 13 Sensitivity to elasticity of vehicle kms – set for maximum rebound

Change in social benefit for three gasoline tax scenarios, maximum rebound effect (,000,000.)			
Elasticity of vehicle kms with respect to fuel cost per km	-0.2221	-0.2221	-0.2221
Vehicle price elasticity of vehicle kms	0	0	0
Interest rate	5%	5%	5%
Marginal damage of gasoline	\$0.03	\$0.03	\$0.03
Tax on gasoline	\$0.03	\$0.20	\$1.00
Social benefit	\$1,517	\$9,657	\$41,270
NPV change in damage due to gasoline	\$57	\$353	\$1,269
Lump sum benefit of tax shift	\$1,460	\$9,303	\$40,001
Social cost	\$906	\$6,258	\$31,843
NPV tax revenue lost due to incremental tax	\$882	\$5,489	\$21,069
NPV excess burden	\$24	\$769	\$10,774
Change in social benefit	\$611	\$3,398	\$9,427

Table 14 Sensitivity to interest ratesensitivity to interest rate

Change in social benefit for three gasoline tax scenarios, reduced discount rate (,000,000.)			
Elasticity of vehicle kms with respect to fuel cost per km	-0.1066	-0.1066	-0.1066
Vehicle price elasticity of vehicle kms	-0.0876	-0.0876	-0.0876
Interest rate	2%	2%	2%
Marginal damage of gasoline	\$0.03	\$0.03	\$0.03
Tax on gasoline	\$0.03	\$0.20	\$1.00
Social benefit	\$1,752	\$11,259	\$49,994
NPV change in damage due to gasoline	\$51	\$322	\$1,142
Lump sum benefit of tax shift	\$1,701	\$10,938	\$48,852
Social cost	\$880	\$5,853	\$26,706
NPV tax revenue lost due to incremental tax	\$861	\$5,429	\$21,419
NPV excess burden	\$19	\$424	\$5,287
Change in social benefit	\$872	\$5,406	\$23,288