

Incorporating Household Transportation Sector into a General Economic Equilibrium Model: Implications for Climate Policy

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Abstract

The transportation sector is responsible for a significant fraction of global anthropogenic emissions. An explicit representation of household transportation technologies, such as internal-combustion engine vehicles, plug-in electric cars, biofuel based vehicles, hydrogen fuel-cell vehicles, is important for quantitative analysis of energy and environmental policy. A methodology for incorporating different household transportation technologies into a computable general equilibrium (CGE) model is presented in this paper. We begin with the basic data that supports CGE models, the Social Accounting Matrix (SAM) that includes the input-output tables of an economy, the use and supply of factors, and the disposition of goods in final consumption. We identify transport-related purchases of the household sector including fuel purchases and disaggregate the data for “own-supplied” transportation service that represents the use of personal automobiles. We then describe our approach to the modeling of improvement in internal-combustion fleet of private automobiles, introduction of plug-in electric vehicles and hydrogen-powered fuel-cell vehicles. We use the MIT Emissions Prediction and Policy Analysis (EPPA) model, a computable general equilibrium model of the world economy, to analyze the expected penetration of different transportation technologies in several scenarios of greenhouse gas emissions control. The effect of introducing of reduced-carbon fuel substitutes, such as biomass fuels, is also explored. In the scenarios for 2010-2100 for the regions of the model we focus on the timing of entry of different household transportation technologies and implications for costs associated with achieving emissions constraints. Availability of low-carbon transportation technology reduces the consumption losses. In the absence of a strong carbon policy, plug-in electric and hydrogen-based cars would not play a significant role unless there is a significant decrease in vehicle cost.

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More information on EPPA model and its applications is available at:
<http://web.mit.edu/globalchange/www/reports.html>

1. Introduction

As the transport sector is responsible for a significant fraction of global anthropogenic emissions, an explicit representation of transportation is important for quantitative analysis of climate policy. IEA (2006) estimates that transportation is the second-largest sector (after power generation) for energy-related CO₂ emissions worldwide, with its share of total emissions stable at around 20 percent both in historic data for 1990-2004 and in the projections to 2030. In most developed countries, emissions from transportation make an even larger contribution to the total carbon dioxide emissions. For example, EIA (2006) reports that the share of CO₂ emissions from transportation in the U.S. was about 31 per cent in 1990, rising to 33 per cent in 2004.

Many climate change assessment models have a detailed electricity sector with several technologies explicitly represented. On the contrary, transportation sector is rarely disaggregated in these models to the details of specific technologies and modes of transportation. In this paper we present a methodology for introducing different household transportation options into a computable general equilibrium (CGE) model. We combine applications of the MIT Emissions Prediction and Policy Analysis (EPPA) model related to private transport: disaggregating the household transportation sector (Paltsev *et al.*, 2004), estimating biofuels production (Reilly and Paltsev, 2007; Gurgel *et al.*, 2008), assessing the potential for hydrogen-based transportation in a carbon-constrained world (Sandoval *et al.*, 2008), and analyzing the plug-in electric vehicles (Karplus, 2008).

For analyzing climate policy many researchers use the Global Trade Analysis Project (GTAP) dataset (Dimaranan, 2006), which incorporates detailed accounts of regional

production and bilateral trade flows. The GTAP dataset has three transportation sectors. However, household transportation expenditures on private automobiles are not represented explicitly in the data. The resulting aggregation of automobile fuel use with other transport fuels makes it impossible to study household transportation explicitly. To facilitate the needed analysis we have developed a method for augmenting the existing GTAP data to disaggregate household transportation.

Improvements in internal combustion engine technology of private cars are not likely to be adequate to achieve the CO₂ emissions reductions needed, for example, under a climate policy goal of stabilization of greenhouse gas emissions. Even significant fleet fuel economy improvements, such as those promised by further penetration of electric-gasoline hybrid vehicles, are probably not enough to offset growth in miles driven and other increases in demand for power and performance in a sector that is growing rapidly worldwide. Among the technology options for further reducing emissions from transportation are replacement of gasoline and diesel with biofuels, all-electric cars or near all-electric plug-in hybrids, and hydrogen fuel cell vehicles. Although large-scale adoption of all of these alternatives has the potential to significantly reduce tailpipe emissions, the total impact on emissions will depend on the carbon intensity of the energy crop and the conversion of any primary energy source to fuel, electricity, or hydrogen.

Our presentation of the data development and analysis is organized in the following way. In the next section we describe the modeling approach, and the sources of the household transportation data used to augment the existing GTAP structure. The modified household transportation sector, disaggregated into purchased and own-supplied transport, is described. Corresponding adjustments to other aspects of the household

demand structure are also presented. Section 3 discusses methodological issues regarding modeling the personal transport sector in EPPA. Section 4 reports the key results of an analysis of the household transport sector under a carbon policy. In section 5 we draw some conclusions about the importance of model and data improvements needed to adequately assess climate policies, taking account of the detailed representation of private transportation options.

2. Disaggregating Household Transport

The GTAP6 dataset represents production and trade flows for 87 regions and 57 sectors of the world economy (Dimaranan, 2006). Among those sectors are three transportation sectors: air transport (ATP), water transport (WTP), and other transport (OTP). The OTP sector includes land transport, transport via pipelines, supporting and auxiliary transport activities, and activities of travel agencies. Commercial transportation services purchased by the household from ATP, WTP, or OTP are already treated in the standard GTAP6 data, and this feature allows us to represent explicitly the substitution possibilities between own-supplied transportation and purchased transport services.

The missing component in GTAP is the transportation service produced by the household itself, i.e., that provided by private automobiles. Our strategy for modeling household transportation is to create a household production activity that combines goods purchased from industry with fuel inputs to produce an “own-supplied” transportation service that represents the use of personal automobiles. Transport-related purchases of the household are, of course, already included in consumer final demands. In some cases we can assume that final consumption from a GTAP sector is used exclusively in own-

supplied transportation, but in other cases only a part of a sector's contribution is used in transportation. The data problem is to identify the appropriate sectors and to estimate the share of final consumption from these sectors that goes to own-supplied transportation. For energy and environmental modeling purposes, for example, a critical data need is to separate purchases of refined oil (gasoline and diesel fuel) used to fuel vehicles from those fuels used for home heating and other household purposes. The methodology for disaggregating the data is described in detailed in Paltsev *et al.* (2004) and here we provide a short outline of the approach.

Households consume both own-supplied (i.e., private cars) and purchased transport. Purchased transport (air travel, water travel, rail service, trucks, etc.) comes from the industry transportation sector. We assume that the own-supplied transportation services are provided using inputs from three sectors of economy: Auto Industries (purchases of vehicles), Services (maintenance, insurance, tires, oil change, etc.), and Refined Oil (fuel).

In order to model the household transportation sector, we make use of the following identity:

$$OWNTRN_r \equiv T_ROIL_r + AC_r + \sum_i OC_{ir}, \quad (1)$$

where $OWNTRN_r$ stands for household expenditures on own-supplied transport in a region r , T_ROIL_r is expenditures on refined oil used in household transportation (i.e., gasoline and diesel fuel), AC_r is vehicles, and OC_{ir} aggregates operating costs such as maintenance and repairs, insurance, financing costs, and parking—the last drawing on several sectors i .

It is useful to define household expenditures on own-supplied transport as a share, ES_r , of total household expenditure,

$$OWNTRN_r = ES_r \times CONS_r, \quad (2)$$

where $CONS_r$, total household expenditure in a region r , is available directly from the GTAP database. Often household expenditure data do not provide T_ROIL_r , but other energy surveys provide data on fuel expenditures, so that household expenditures on refined oil products for own-supplied transportation is usefully stated as a share, OS_r , of total household expenditure on all refined oil products, TOS_r :

$$T_ROIL_r = OS_r \times TOS_r, \quad (3)$$

with TOS_r available directly from the GTAP database.

In order to apply Equations (1) to (3) to the disaggregation of household transportation we need the data for AC_r , OC_{ir} , ES_r , and OS_r . National surveys report that, for developed countries, household expenditures on own-supplied transport as a fraction of total household expenditures is approximately 0.1, and refined oil expenditures within household transportation is around 0.9 as a fraction of household expenditures on oil products—that is, most of the refined oil products used by households are for transportation. The share of own-supplied transportation expenditure (ES_r) can be estimated from household expenditure surveys.

When expenditure data are not available, physical data on oil consumption shares for private transportation and other residential uses combined with fuel tax and price data provide another approach. The International Energy Agency (IEA/OECD) gives detailed energy balances in tons of oil equivalent (or toe) for OECD countries (IEA, 2005a) and non-OECD countries (IEA, 2005b), along with statistics on energy prices and taxes by

fuel and by country in US dollars per toe (IEA, 2005c). A problem with these data is that the ROAD sector defined in IEA energy balances includes trucks and commercial transport. This procedure leads to overestimation of the OS_r coefficients. Canada gives detailed data on fuel consumption in transportation. There, households represent 77% of total expenditure in road fuels (93% of road gasoline and 28% of road diesel). Adjusting the IEA data for the road sector using these coefficients on road fuels for Canada suggests that the error introduced is relatively small. For example, the OS_r coefficient from the country level data for Canada results in an OS_r value of 92% compared with an estimate relying just on the IEA data of 93.7%. In the United States, the share of refined oil products for own-supplied transportation in total household expenditure is estimated from statistics of the U.S. Department of Commerce to be 90%, compared to 94.8% with IEA data. These results indicate that IEA data may be considered as a relatively good proxy for OS_r . In cases where other additional data were not available we used the IEA data without adjustment.

The data for final purchases of vehicles (AC_r) can be taken directly from the GTAP Motor Vehicle (MVH) sector sales to final consumption. From these data and GTAP final consumption we can derive the value of total consumption of own-supplied transportation for each country/region and expenditure on vehicles and fuels.

The other operating costs (OC_{ir}) are derived as a residual of the total value of own-supplied transport less expenditure on vehicles and fuels. To disaggregate this quantity to the GTAP level a further identification of the supplying sectors of these other operating costs would be needed because the operating cost data are divided among the TRD sector (sales, maintenance, repair of motor vehicles, and trade margin on sales of automotive

fuel are part of this sector), the ISR sector (insurance), and an OBS sector (which includes renting of transport equipment)¹.

As is evident from the above discussion, for some countries there are multiple sources of data that provide the ability to cross-check results, while for other countries data are more limited and further assumptions are needed. In general, we used household expenditure data directly when available, but often checked these with physical energy data or price-quantity data. We converted expenditure data to shares and applied these shares to the expenditure totals in GTAP to avoid inconsistencies in currency conversion and between the original data source and GTAP.

The approach so far outlined is consistent with National Income and Product Account practices that treat most household purchases of durables, and vehicles in particular, as a flow of current consumption. In reality, of course, vehicles are capital goods that depreciate over time and provide a service flow over their lifetime. To reconstruct the data in this way would require further estimation of annual service flow, depreciation rates, and treatment of vehicle purchase as an investment. In industrial sectors, the residual of the value of sales less intermediate input and labor costs is an estimate of payments to capital, and under the assumption of a normal rate of return and depreciation rate these quantities imply a level of the capital stock. Own-supply from the household sector is not marketed, however, and thus there are no comparable sales data on gross value of the service from which intermediate input costs can be subtracted. An implicit rental value for the vehicle service could be constructed with historical data on vehicle sales, assumed depreciation rates, and an assumed rate of return. Long-term car leasing

¹ As implemented in the EPPA model, however, these GTAP sectors are aggregated, and so we assume that OC_{ir} is supplied by the service (SERV) sector. The EPPA model is discussed in Section 3.

rates could also be used as a basis for comparison, although these data may not be representative of the entire vehicle stock when new vehicles are typically leased for a 3-year period and then sold. Moreover, data on real leasing costs are not completely transparent because they depend on features of the lease—such as limits on mileage, additional payments if mileage limits are exceeded, and the purchase terms at the end of the lease.

3. Household Transportation in the MIT EPPA model

The Emissions Prediction and Policy Analysis Model (EPPA) is a general equilibrium model of the world economy developed by the MIT Joint Program on the Science and Policy of Global Change (Paltsev *et al.*, 2005). For economic data, the EPPA model relies on the GTAP dataset, which accommodates a consistent representation of regional macroeconomic consumption, production and bilateral trade flows. For use in EPPA, the GTAP dataset is aggregated into 16 regions and 24 sectors with several advanced technology sectors that are not explicitly represented in the GTAP data (the EPPA regions and sectors are shown in Table 1).

The energy data in physical units are based on energy balances from International Energy Agency. EPPA also uses additional data for greenhouse gases (carbon dioxide, CO₂; methane, CH₄; nitrous oxide, N₂O; hydrofluorocarbons, HFCs; perfluorocarbons, PFCs; and sulphur hexafluoride, SF₆) and air pollutants (sulphur dioxide, SO₂; nitrogen oxides, NO_x; black carbon, BC; organic carbon, OC; ammonia, NH₃; carbon monoxide, CO; and non-methane volatile organic compounds, VOC) emissions based on United States Environmental Protection Agency inventory data.

Much of the sectoral detail is focused on energy production to better represent different technological alternatives in electric generation and transportation. From 2000 to 2100 the model is solved recursively at 5-year intervals. The EPPA model production and consumption sectors are represented by nested Constant Elasticity of Substitution (CES) production functions (or the Cobb-Douglas and Leontief special cases of the CES). The model is written in the GAMS software system and solved using MPSGE modeling language (Rutherford, 1995). The EPPA has been used in a wide variety of policy applications (e.g., Jacoby *et al.*, 1997; Reilly *et al.*, 1999; Babiker, Metcalf, and Reilly, 2003; Reilly and Paltsev, 2006; US CCSP, 2007; Paltsev *et al.*, 2008).

3.1. Internal Combustion Vehicles

Transport in the EPPA model is represented by two activities: industry transportation sector (aggregating the modal splits in the base GTAP data) and the household transportation sector discussed above. We assume that the current fleet of vehicles is based on internal combustion engines (ICE). The industry transportation (TRAN) supplies transport services (both passenger and freight) to other sectors of the economy and to households. The nesting structure of the industry transportation sector is depicted in Figure 1.

The output of the TRAN sector is produced using energy, capital, labor, and intermediate inputs from different industries. The values for elasticities in the industry transportation sector, labeled as $s_1, s_2, \dots, s_7$, are provided in Table 2. At the top nest, intermediate inputs and the energy-labor-capital bundle are modeled as a Leontief composite. Both domestic and imported intermediates are used in the production

activities, with elasticity of substitution between domestic and imported bundle, s_2 , and between imports from different regions, s_3 . The energy-labor-capital bundle is composed of separate energy and value-added nests. Energy inputs are nested into electricity and non-electric inputs, and the value-added into labor and capital. The data for the modeling of this sector come directly from the OTP (other transport), ATP (air transport), and WTP (water transport) sectors of the GTAP dataset.

Households consume both own-supplied (i.e., private cars) and purchased transport. Purchased transport comes from the industry transportation (air travel, water travel, rail service, trucks, etc.) sector described above. Own-supplied transportation services are provided using inputs from the other industries products (purchases of vehicles), services (maintenance, insurance, tires, oil change, etc.) and refined oil (fuel) sectors.

As noted earlier, the EPPA model uses a nested CES structure to describe preferences as well as production, as this specification is compatible with the MPSGE solver. Figure 2 shows the household sector in the EPPA model. As illustrated, the nesting structure aggregates all Armington goods into a single consumption good, which is then aggregated together with savings to determine the level of consumer utility. Savings enters directly into the utility function, which generates the demand for savings and makes the consumption-investment decision endogenous. The central values for elasticities in the household sector are provided in Table 3. The elasticity between non-energy inputs to consumption is a function of per capita income and thus varies by region and time period. Consumption shares also are function of per capita income.²

² This specification helps to capture the changing structure of consumption as development occurs that otherwise would not be captured by a CES function that is homogenous of degree 1, while allowing solution of the model using the MPSGE algorithm, which was designed for the homogeneous CES family

As described in Section 2, for the own-transportation nest we reallocate a portion of other industries (OTHR), services (SERV), and refined oil (ROIL) consumption to own-supplied transportation. The TRAN sector, which represents purchased transportation is separated from non-energy bundle in consumption. As shown in Figure 2, we rename purchased transportation as PURTRN sector and move it to the nest that represents a trade-off between purchased and own-supplied transportation (OWNTRN). The own-supplied transportation is aggregated from the consumption of other industries (T_OTHR), services (T_SERV), and refined oil (T_ROIL) directly related to private cars.

The EPPA model includes significant continuing advances in gasoline and diesel vehicles with their efficiency improving at 1.0 percent per year, but also increasing fossil fuel prices. Thus our analysis reflects a world where the existing technologies do not “stand still.”

3.2. Biofuel-Based Vehicles

To assess a potential for biofuel-based vehicles we have introduced a liquid fuel production from biomass into the EPPA model (Reilly and Paltsev, 2007; Gurgel, Reilly and Paltsev, 2008). In these studies we focused on advanced (or so-called “second generation”) biomass energy technologies, while currently the largest sources of commercially produced ethanol are from sugar cane in Brazil and from corn in the USA. Biodiesel is produced from rapeseed in Europe. In most cases, current biofuel production is subject to government support and subsidies. In the USA, ethanol is used mostly as an oxygenating fuel additive to reduce carbon monoxide emissions to meet environmental

of production functions. For more details on estimated relationship and its effects on emissions, see Lahiri, *et al.*, 2000.

standards. Thus, it is not competing directly with gasoline on the basis of its energy content.

Energy from biofuels has a mixed record. On one hand, it is often seen as a renewable source of clean energy, a substitute for fossil fuels people fear are growing scarcer, offering energy security for countries without other domestic resources, and a source of income for farmers. On the other hand, current production methods often involve the use of fossil fuels so that the CO₂ benefits are minimal, rely on crops such as maize, rapeseed, or oil palms where the potential to supply significant energy is limited, and through competition for these crops and for land significantly affect food prices and create additional pressure for deforestation. The US and Europe have proposed major initiatives to expand biofuel use in the past couple of years. But even before these programs were fully realized, expansion of the industry has revealed what analysts have long understood - there would be food price and environmental consequences even for an industry that is supplying no more than a few percent of, for example, US gasoline use. The US industry has been seen as responsible for recent rises in world maize prices, with consequences for poorer consumers worldwide. European blending requirements and the demand for biodiesel, in particular, have been linked to expanding oil palm plantations and deforestation in Indonesia. The promise of improving farm income has been realized as commodity prices have risen sharply but that success also spells the limits of the technology in terms of providing a substantial domestic supply of energy.

Advocates for the development of cellulosic conversion methods believe such a second generation technology avoids many of these consequences. It is able to use crops such as switchgrass or waste such as corn stover so the technology does not directly

compete for food. Perennial grasses would have less environmental impacts than row crop agriculture, and per hectare energy yield could be on the order of 5 times that of maize because the entire plant can be converted to fuel.

In terms of the modeling, we have assumed that biofuel is a perfect substitute for refined oil and the structure of private transportation sector is the same as described in Section 3.1. For specific studies we also have added a blending requirement, where refined oil input to private transportation has to be in a fixed proportion with biofuels.

3.3. Plug-in Electric Vehicles

A plug-in hybrid electric vehicle (PHEV) runs on both grid-supplied electricity and refined fuel. Although a plug-in hybrid vehicle could easily look much like any other on the road today, several of its less obvious facets could significantly affect the way individuals use their cars. The plug-in hybrid offers fuel flexibility. The relative cost, availability, and ease of use of electricity and refined fuel is likely to influence consumer decisions to rely on one fuel or the other. Plug-in hybrid vehicles are expected to command a price premium due to technical requirements of battery storage, at least at the outset, over today's ICE-only vehicles. Developers of PHEV technology claim that lifetime fuel savings will more than make up for the additional up-front costs, but the extent of these savings depends on personal discount rates, the evolution of relative electricity and refined oil prices, and any adjustments drivers make to take advantage of the lower-cost fuel.

A PHEV is capable of running on both refined fuels and electricity. It is an electric-drive vehicle (because it runs on electricity via and electric motor) as well as a hybrid

vehicle (because it relies on two fuel sources, refined fuels and electricity). Exactly how this fuel switching is accomplished depends on the vehicle architecture, on-board energy storage capacity, and driver usage patterns.

One design choice the developer faces is whether to arrange the major components of a hybrid vehicle drive train in series, in parallel, or in a combination of the two configurations. In the parallel design, the engine and electric motor both connect to the transmission, allowing each to drive the wheels directly. The electrical and mechanical sources of energy remain physically separate, and advanced electronics components allow the vehicle to alternate between the two sources. However, many features of the car remain powered by the electric motor exclusively, such as the power steering, radio, and air conditioning.

In the series design, by contrast, all energy is converted into electricity via an electric motor before it is used to drive the wheels. The ICE is used to charge a generator, which in turn drives the wheels or, when needed, recharges the battery. This configuration is typical of a battery-electric vehicle (BEV). A series hybrid may not require a transmission, since the electric system is efficient over a wide range of speeds. One advantage of the series configuration is that the ICE engine can be run constantly, which is more efficient than the on-off pattern required during fuel switching in a parallel hybrid. Series hybrids operate more efficiently during stop-and-go driving conditions, but less efficiently during long-distance travel at constant speeds.

Combined series and parallel hybrid designs incorporate features from both series and parallel hybrid configurations. A so-called “power-split” is used to create redundant mechanical and electrical paths for power to travel from the engine to the wheels. For

instance, the Toyota Hybrid System (Hybrid Synergy Drive) uses a single power split to allow use of the optimal power path over variable driving speeds.

Efforts to quantify the fuel requirements and efficiency of the PHEV have relied on a convention called the utility factor (UF). The UF is defined as the fraction of vehicle miles traveled on electricity, while the fraction powered by refined fuels can be expressed as $1 - \text{UF}$. The value of the UF is a function of several parameters. First, the all-electric range (or AER) of the battery dictates how far a vehicle can be driven on a single charge. A PHEV with a certain all electric range is typically denoted as PHEVX, where X is equal to the vehicles' all-electric range. Depending on how many miles an individual drives before recharging a battery the all-electric range will be able to supply energy for the first X miles of travel, before the internal combustion engine is required. If individual driving patterns are assumed to be fixed, then the UF is determined solely by the all-electric range (AER) of the vehicle.

It may be inaccurate, however, to assume that driving patterns are fixed, especially in the long run as individuals have more opportunities to relocate home or work to reduce travel distance (and thus refined fuel consumption in ways that allow greater reliance on electricity). As a result, the UF will also change if driving habits are altered significantly. This change in behavior may even be affected by the availability of electric-drive vehicles, if the proposition that proactive consumers will relocate to take advantage of fuel savings holds in practice. The UF forms an important input to the EPPA model, since it establishes the relative electricity and refined oil requirements for the sector.

We have assumed that the PHEV operates either as an all-electric vehicle in charge-depleting mode, and then as a conventional hybrid once the battery has been sufficiently

depleted. However, an alternative “blended” mode, in which the battery operates in charge-depleting mode to assist the ICE over a fixed range, has been suggested, and may prove superior to the all-electric configuration over the long term. The advantages of this system stem from the reduced need for either a full all-electric system or a full-size ICE. Running the vehicle in all-electric mode requires a sizable battery pack, and once charge is depleted, the ICE must be able to handle the remaining load, limiting the extent to which it can be downsized (Kromer and Heywood, 2007). A blended mode, on the other hand, allows the engine to be further downsized, which is attractive from cost and performance standpoints. All-electric operation also reduces the need for engine cold-starts, as well as up-front petroleum consumption compared to blended mode.³

The battery has been widely cited as the greatest barrier to development of a commercially-viable PHEV. So far, batteries with energy density and specific power adequate to propel vehicles more than a few tens of miles are prohibitively costly, adding a 50 to 100 percent premium to the up-front vehicle cost. The challenge of designing batteries for electric vehicles is to increase the energy density (the energy that can be supplied in a fixed period) without compromising specific power (directly related to vehicle acceleration), cycle life, or safety of use. A number of different battery chemistries have been tried in an ongoing search for the right balance of these attributes. A brief overview of ongoing research is presented here.

The first off-the-shelf PHEV models on the market are expected to use lithium-based battery chemistries. Other available chemistries include the nickel metal hydride (used in

³ In all-electric mode, the engine needs to be turned on only once per drive during the switch from charge-depleting to charge-sustaining mode. A parameter called the degree of hybridization (DOH) is used to capture this trade-off, with a 55 percent DOH corresponding to the minimum required for all-electric operation in the US06 drive cycle.

the first Toyota Prius models) or lead acid-based technology (used in the General Motors EV-1). Among the possible lithium-based chemistries are lithium-ion and lithium-metal chemistries, while lithium-polymer (including so-called thin-film batteries) may be prove more promising in the future.

Lithium ion batteries offer important advantages over other alternatives. Lithium has the greatest propensity to give up its electrons, making it well suited for battery applications. As a result, lithium batteries offer the highest energy density, but are very light in weight compared to other candidate chemistries, a property that has contributed to their rapid adoption in the electronics industry. For vehicle applications, lithium chemistries have the greatest potential for reducing the battery's contribution to weight and volume of the vehicle. Remaining concerns about the viability of lithium-ion chemistry for use in the PHEV include concerns about safety, durability, and cost. The recent recall of lithium ion laptop batteries that overheated has prompted research into the substitution of other, more stable materials in the electrodes that could rectify this problem. The safety problem is being addressed through ongoing research to reduce dendrite formation, the cause of thermal instability, by using lithium alloys, or improving the performance of the safer lithium polymer chemistries. Durability is also a top concern, given that in a vehicle context the battery will have to endure many deep discharge cycles over its lifetime, while still maintaining the ability to assist the motor in a near charge-depleted state. At present, the NiMH batteries are less expensive and a more "proven" technology (Duvall, 2004). However, many scientists are optimistic that technological and cost barriers to the development of lithium ion batteries can be

overcome, making the Li-ion battery the most promising candidate at present for PHEV applications (Kromer and Heywood, 2007; Simpson, 2006).

The internal combustion engine design used in a PHEV is also an important consideration. Due to the electric-assist function of the battery, the engine can be downsized compared with a ICE-only vehicle, and its coupling to an electric motor allows the vehicle function as a conventional hybrid once the all-electric range has been exhausted. When driven as a conventional hybrid, a PHEV is limited only by the size of the fuel tank and efficiency of fuel conversion, making it essentially equivalent to ICE or conventional hybrid vehicles on the road today. The modeling work in later chapters assumes that the PHEV has achieved this level of performance. In today's conventional hybrids, engine power ranges from a maximum of 50 kW (Toyota Prius) up to 160kW in a Lexus LLS 600h, and electric traction motors provide about half the maximum power of the propulsion system.

Advanced electronics components are also required to coordinate power management between the ICE and the battery, and more research is required to identify an option that maintains cost-effectiveness without compromising performance. Current designs under consideration include using electronics controls similar to those in the Toyota Prius, but with the ability to mediate between charge-depleting and charge-sustaining mode. Improvements in capacitors, heat management strategies, and component configurations, as well as development of new materials for the electronics components, are also listed as targets of ongoing PHEV research. Additional strides will also need to be made in developing a standardized interface with wall sockets in homes. Advances in battery technology, along with electronics, that allow recharging from the electric grid may

further promote cost and energy savings, as well as shorten recharging times, improving convenience of using a PHEV.

Past studies have taken a variety of approaches to estimating the vehicle and fuel costs of the PHEV. In all cases, the battery is the primary driver of the incremental PHEV manufacturing cost. Some studies used a simple inventory and summation of up-front and recurring costs to estimate PHEV life cycle costs, while other studies have assumed advances in battery technology and production at scale to estimate how costs will have evolved by some specified future point (Kromer and Heywood; Simpson, 2006). A detailed discussion of estimates of PHEV and fuels costs can be found in Karplus (2008). Table 4 presents a summary where the PHEV vehicle cost is divided into two categories. The first category includes near-term projections for PHEV vehicle cost, and is based on the existing state of the technology and small production volumes. The second category assumes improvements in the cost-effectiveness of the technology, a scale up of production volumes, or both, and is referred to as long-term projections. These two categories of estimates are summarized here for a PHEV20 and PHEV60.

Translating these battery mark-ups into vehicle mark-ups involves adding the cost of safety systems and other required components. As presented in Table 5, two studies offer detailed estimates of the cost of a PHEV, based on engineering cost information. One study, but Simpson (2006) for the National Renewable Energy Laboratory, takes outputs from a series of engineering models that size vehicle components accordingly and uses them as inputs to an overall vehicle cost model to estimate the retail price of the vehicle based on the underlying component costs. Graham (2001) similarly uses a combination of vehicle and cost models to estimate the retail price of different HEV and PHEV

configurations. The main differences between the two studies include lower estimates (by around half) of the power to energy ratio in the Simpson study compared with the Graham study. The main difference between near and long term projections in the Simpson study are that lithium ion replaces the nickel metal hydride battery in the long term scenario.

Overall, these estimates suggest that plug-in hybrid vehicles will be more expensive than conventional vehicles by 22 to 66 percent for a plug-in hybrid vehicle with a 20-mile AER, whereas the mark-up could be as high as 41 to 114 percent for a PHEV60. The Graham (2001) estimates are systematically lower than the Simpson (2006) estimates for both the near and long term, driven by different assumptions about the pace and extent of battery technology development.

Fuel costs for the PHEV can be calculated directly using the prevailing prices of refined oil, electricity, and the utility factor (described above), which reflects the fraction of total miles traveled on each fuel in a fixed period of time. Included in Table 6 is a sample comparison of ICE, conventional hybrid, and PHEV30 based on long term estimates from the Simpson (2006) study. Despite the higher up-front cost, improved fuel economy translates into savings within the lifetime of the vehicle due to the high avoided costs of refined fuels. The reader should be aware of the fact that recurring savings are not discounted, and the cost advantage due to higher fuel economy is likely to be less visible to consumers in practice.

The above comparison also illustrates how the PHEV derives its cost advantage from the ability to use electricity, combined with the fuel economy benefits of the conventional hybrid technology. The evolution of the relative prices of electricity and gasoline, as well

as the emergence of other alternative vehicle designs, will influence the magnitude of the trade-off the consumer faces between up-front vehicle costs and recurring savings.

Energy use and emissions from a PHEV come from its use of energy stored in two different forms, refined fuel and electricity. In the case of refined fuels, emissions occur both in the upstream process of extracting, refining, and transporting the fuel (well-to-tank) and combustion emissions released from the tailpipe (tank-to-wheels). It is important to consider each of these sources explicitly when estimating energy use and emissions due to the miles driven using the internal combustion engine. If the per-barrel emissions associated with extraction and production of refined oil continue to increase, even limited usage of the internal combustion engine in a PHEV could have a sizable emissions footprint.

In the case of electricity, emissions associated with energy use by the plug-in hybrid vehicle can be traced back to the fuel sources used to generate grid-supplied electricity. When the vehicle is running in all-electric mode, there are no tailpipe emissions. However, it is important to examine how the output of the electricity sector changes with the addition of a plug-in hybrid electric vehicle fleet and determine which primary fuels are used to meet the increase in production at the margin. Depending on when the PHEV is charged, the average grid mix will not reflect the marginal output, which would most likely be used to recharge the PHEV. These sources may be cleaner or dirtier than the average mix, with ramifications for the amount of carbon dioxide emissions associated with electric-only vehicle travel.

The goal of the modeling work was to implement a vehicle technology in the own-supplied transport sector that would use both refined oil and grid-supplied electricity, and

compete directly with gasoline-only (or diesel-only) transportation. The structure of the new PHEV sector is shown in Figure 3, and is based on the original ICE-only vehicle sector presented in Section 3.1. The inputs to the PHEV sector include electricity and refined oil as fuels, as well as services, the vehicle itself, and a fixed factor. On the fuels side, it is assumed that there is no substitution between electricity and refined oil. This relationship derives from the fact that here the PHEV is assumed to operate only in all-electric mode before switching to rely on the internal combustion engine. Since drivers are likely to purchase a PHEV for the benefits of its all-electric range, the vehicle is assumed to be operated first in all-electric mode, beyond which the only option available is the ICE. The input shares of electricity and refined oil are determined by the vehicle's utility factor, according to the amount of each required to drive a vehicle of the all-electric range indicated by the utility factor. As explained before, the utility factor is a function of both battery all-electric range and prevailing driving habits. Expenditure shares for PHEV transportation in the United States are shown under each of the inputs in Figure 3.

Since the PHEV is expected to be more expensive compared with ICE-only vehicles when it becomes available, a representative parameter, the vehicle mark-up, was specified in the model. The vehicle mark-up is simply the cost of the PHEV divided by the cost of its ICE-only counterpart. Based on the estimates given above, 30 to 60 percent is expected to be a reasonable estimate of the PHEV mark-up. This range is consistent with quotes from prospective PHEV manufacturers. For example, the GM Volt, an all-electric sports car (an all-electric, not hybrid, plug-in vehicle), is expected to be sold for around \$20,000 to \$30,000 once manufacturing has reached sufficient scale. The range of

cost mark-ups used in the model covers the expected range of mark-ups for the PHEV. This mark-up is only applied to the expenditure share in PHEV transport that corresponds to the purchase of a vehicle. Services costs for the PHEV are assumed to be similar to an ICE-only vehicle.

As part of our modeling strategy, we have to consider how to represent the rate of plug-in hybrid vehicle entry once the technology becomes cost competitive. Without a constraint on the rate of PHEV sector growth, the technology would immediately take over the vehicle fleet in the first period in which the PHEV is available and total cost of PHEV transportation drops below the total cost of ICE-only vehicle use. At this point, if unconstrained, the PHEV would immediately take over the entire vehicle fleet. In order to restrain PHEV sector growth, we specify a fixed factor, or additional resource requirement for sector growth. The fixed factor in this case is calibrated to grow as the fraction of plug-in hybrid vehicles in the total fleet increases. While this representation is a crude approximation of the combined influences of fleet turnover and technological change, it does capture the intuition that a new technology would be expected to grow as a function of its success in the market. More important than the actual value of the fixed factor is the fact that all scenarios use the same fixed factor, and as a result the effects are consistent across scenarios compared. Furthermore, the fixed factor we have chosen does not allow the technology to enter faster than the rate of fleet turnover. The vehicle has a half life of approximately 15 years, and thus we assume that in the most optimistic case, complete fleet turnover could occur in less than 30 years (Bullis, 2006). We thus take 30 years as an upper bound estimate of the smallest time frame over which the PHEV could fully penetrate the fleet.

3.4. Hydrogen Vehicles

Existing engineering studies of the potential for hydrogen vehicles show that the technology must advance significantly to be commercially competitive (Ogden *et al.*, 2004; NRC, 2004; Rogner, 1998; Kosugi *et al.*, 2004). If a hydrogen fuel cell vehicle fleet is to become a reality, it requires advances in vehicle technology and reliable, cost-effective means of hydrogen production and distribution. Hydrogen does not exist in pure form on earth but can be obtained from two main sources, hydrocarbons and water. Natural gas is a promising candidate for hydrogen production because of its high hydrogen to carbon ratio, which results in lower CO₂ emissions per unit of hydrogen produced compared with other cost-effective sources, such as coal. Coal is, however, less expensive and is more abundant. For either to offer significant reductions in CO₂ emissions, carbon capture and storage (CCS) would need to be a part of the hydrogen production process. Other forms of hydrogen production, such as electrolysis or thermochemical water splitting, are more expensive. In our model, we consider hydrogen production only from natural gas and coal because they are the least costly sources at present and are likely to remain so.

Extensive fuel storage and distribution infrastructure would also be necessary components of a hydrogen transportation system. Developing this infrastructure would be a challenge, since industry is unlikely to invest without evidence of consumer demand for hydrogen. At the same time, consumers are unlikely to purchase vehicles that lack a convenient fueling infrastructure.

Turning to the literature on production and distribution costs, surveys have often revealed highly disparate estimates of hydrogen production costs, which are hard to compare given that assumptions behind the estimates are often not explicitly stated. Sandoval et al. (2008) provide cost estimates for the production of hydrogen with and without distribution made over the last thirty years, with no obvious trend over time.

Regarding the vehicle fleet, two possible hydrogen vehicle technologies exist: one would retain an internal combustion engine fueled by hydrogen in a manner similar to using compressed natural gas to power a vehicle. The other approach is to replace the internal combustion engine with fuel cells where hydrogen is reacted with oxygen to generate electricity that drives an electric motor. Both designs require on-board hydrogen storage. Hydrogen can be stored as compressed gas, in liquid form, or by absorption on metal hydrides or carbon-based materials (Padró and Putsche, 1999). Aside from design modifications to allow for safe and efficient storage and conversion of hydrogen, hydrogen-powered vehicles are otherwise expected to be functionally similar to conventional designs.

Hydrogen fuel cells offer several advantages over conventional vehicle technology. The major byproduct of hydrogen conversion is water, resulting in near-zero tailpipe emissions. Fuel cell conversion also offers very high theoretical conversion efficiency compared with hydrocarbon combustion in an internal combustion engine (Kromer and Heywood, 2007). Although present fuel cell technology does not reach this upper bound, fuel cell electric vehicles powered by hydrogen still have a favorable estimated fuel economy of around 66 miles per gallon of gasoline-energy-equivalent (Padró and Putsche, 1999). Large-scale substitution of hydrogen for gasoline or diesel as a

transportation fuel would also have the advantages of centralizing emissions at the point of hydrogen production for easier control, allowing greater flexibility in the choice of a primary energy source used to produce the hydrogen, and reduce dependence on oil and refined products.

So far, however, a number of practical constraints exist to market penetration of fuel cell vehicles. Fuel cell performance, durability, and cost limit competitiveness with conventional technology (Kromer and Heywood, 2007). In the review of the FreedomCAR and Fuel Partnership, the NRC (2005) estimated that fuel cell durability measured in load hours was only one-fifth of commercialization targets. Apart from these technological challenges, at present the cost of a fuel cell vehicle is essentially prohibitive at ten to twenty times that of a conventional vehicle (NRC, 2004). The cost and performance of on-board hydrogen storage will also need to be improved to meet commercialization targets.

Our modeling strategy is to parameterize a hydrogen fuel cell vehicle fleet and hydrogen production/distribution sectors based on key conversion efficiencies and the non-fuel cost shares based on existing literature assuming near-competitive costs, i.e., assuming that the necessary breakthroughs occur. We then use a mark-up factor to scale the cost for both the vehicle and the hydrogen production/distribution sectors to evaluate different combinations of costs for fuels and the vehicle fleet. We choose many pairs (vehicle, fuel production) of cost mark-ups and map out fleet penetration frontiers to indicate those cost mark-up pairs that result in penetration in different years. The cost mark-up pairs can be viewed as R&D targets for hydrogen vehicle and fuel cost. If, for example, the goal of an R&D program was to have vehicle fleet penetration by 2030, our

frontiers would indicate combinations of hydrogen and vehicle costs that would be necessary to achieve that goal under different assumptions regarding greenhouse gas policy. Our research does not say anything directly about whether these cost goals are realistic, or the size of the R&D program that would be needed to achieve them, but indicates under what conditions their achievement would lead to market penetration.

Turning to the modeling details, we introduce into the EPPA model two hydrogen production sectors, one that uses natural gas and one that uses coal, with both including an option of carbon capture and storage. The sector mark-ups are intended to cover the full retail cost of delivering hydrogen. We introduce an alternative private automobile technology to represent a fuel cell vehicle fleet that runs on hydrogen.

The production of hydrogen fuel is discussed in detail in Sandoval et al. (2008), here we summarize the modeling of the hydrogen-based household transport. We introduce a new transportation sector that as shown in Figure 4. This hydrogen fleet is in direct competition with the pre-existing own-supplied household transportation. The characteristics of vehicles in terms of, for example, power, performance, safety, reliability, interior space, refueling, and range, are important considerations in vehicle choice. We make the simplifying assumption that the conventional and hydrogen fuel cell vehicles are perfect substitutes. This means that the different power source is essentially invisible to the consumer—any problematic aspects of the hydrogen technology have been successfully addressed—and all that matters is the relative cost of the vehicle and fuel cost per mile, accounting for the greater efficiency of hydrogen use in a fuel cell compared with gasoline or diesel use in a conventional internal combustion engine. The production structure of the conventional and hydrogen fleet are identical except for the

replacement of conventional fuel with hydrogen. Differences among the technologies are reflected by values of parameters that control input cost shares.

As shown in Figure 4, own-supplied household transportation relies on the outputs of three sectors: fuels (refined oil or hydrogen), Services, and Other Industries products, with elasticities of substitution shown between inputs and the factor shares shown beneath the inputs. The vehicle input is an output of the Other Industries sector, capturing the cost of automobiles, since the automotive industry is part of that sector in the database. The fuel input represents the cost of fuel for private automobiles which, based on initial parameterization, implies a specific physical quantity of hydrogen fuel and, along with other parameters of the production function, also implies an efficiency of power conversion that depends on the fuel mark-up as discussed below. The Services share represents all non-fuel operation costs. Among these are the costs of insurance, financing, and maintenance and these are assumed to be the same as for the conventional vehicle fleet.

The mark-up approach described briefly at the beginning of the section is a standard approach used within the EPPA model for representing new technologies. A mark-up is a multiplicative factor that reflects the cost in the model base year of the advanced technology relative to the one against which it competes. If the mark-up is larger than 1.0 it indicates that the new technology is more expensive relative to its conventional counterpart given the input costs in the base year. A technology with a mark-up greater than 1.0 can eventually enter if the price of inputs it requires in large amounts fall (or rise less) relative to the price of inputs required by its conventional counterpart. Thus, a technology that uses less fuel, or a fuel whose price does not rise as fast, can eventually

compete successfully, and if carbon dioxide emissions differ between the technologies a carbon price will also differentially affect them.

The overall efficiency of the hydrogen fuel cycle (from coal to production of hydrogen to miles driven) can be compared to the conventional fleet in terms of miles per energy content of the fuel, which can then be converted to miles per gallon equivalent based on the energy content of gasoline. In the model, it is determined by the fuel shares in production of hydrogen and in the hydrogen share in the specification of the vehicle fleet, and since we apply the production sector mark-up to all inputs, including the coal or gas feedstock it also depends on the mark-up. To determine these parameters (and thus the implied efficiency) we use the supplemental physical flows of energy and implied energy prices in the EPPA data set. For a fuel mark-up of 1.0 the implied hydrogen vehicle fleet efficiency is 3.36 times more efficient than the conventional fleet in the USA and 3.70 times more efficient in Europe. For example, if the average fleet efficiency of cars (and light trucks) on the road in the USA is 20 mpg, the efficiency of fuel cell vehicle of about 66 mpg in energy equivalents. This implied efficiency varies inversely with the mark-up—if the fuel production mark-up is 1.3, the relative efficiency of hydrogen vehicles in the US is 2.58—a 52 mpg equivalent.

4. Scenario Analysis

We used the modified EPPA model to examine the timing of plug-in electric vehicles and hydrogen-based vehicles penetration. We focus on the initial date and conditions at which plug-in electric and hydrogen transport becomes cost-competitive with conventional technology and starts penetrating the market. For this paper, we have used two separate

modified version of the EPPA model: one with additional plug-in electric household transportation sector, and another – with additional hydrogen household transportation sector. In both versions, biofuels is an option for transport as well.

To explore the impact of climate change mitigation policies, the cases in which carbon concentrations in the atmosphere would be stabilized at 450 ppm and 550 ppm are considered. We use regional constraints for the stabilization scenario developed for the U.S. Climate Change Science Program (US CCSP, 2007). The policy is implemented in the model by constraining GHG emissions and allowing for trading in GHG emission permits across sectors to determine a carbon-equivalent price.

Figure 5 shows the impact of vehicle mark-up in both the *No policy* (represented by the solid lines) and *450 ppm* policy (represented by the dashed lines) scenarios. Under certain conditions, rising oil prices make PHEV economic even without a climate policy. An increase in the vehicle mark-up causes a pronounced delay in the entry of the PHEV in both the *No policy* and *450 ppm* policy cases. Even with a mark-up of 1.3 (i.e., PHEV is 30% more expensive than ICE vehicle), the initial date of entry and percentage of the PHEV in the vehicle fleet in 2100 drop dramatically compared with the no mark-up case. With a mark-up of 1.8, PHEV does not entry without a climate policy in a model horizon. The implementation of a 450 ppm policy dramatically hastens the entry of the PHEV, with full fleet penetration occurring sometime between 2050 and 2070. Advanced biofuels discussed in Section 3.2 are not available in these scenarios.

Figure 6 changes that assumption and makes biofuels available. The effect on PHEV entry turns out to be relatively minor in the absence of a climate policy, but pronounced in the presence of a 450ppm climate stabilization policy. In the *No policy* case, a PHEV

with a 1.3 mark-up is economically viable approximately one to two decades later than it otherwise would have been in the absence of biofuels. However, under a climate policy, PHEV entry slows dramatically for all mark-ups compared with the no biofuels case discussed above — and a PHEV with 1.8 mark-up does not enter at all before the end of the century. This result is due to the fact that bio-fuels is a low carbon substitute for refined oil, making the ICE engine more competitive with the PHEV that it might otherwise have been.

Turning to hydrogen-based household transportation, the timing of hydrogen sector entry is expected to vary depending on the relative prices of hydrogen and gasoline fuel and relative price of hydrogen vehicles. First, we explore the potential for hydrogen sector entry in the *No climate policy* scenario. Figure 7 shows in which decade the technology will become viable at various initial markup combinations in USA. The frontiers indicate, for example, that combinations of fuel mark-up of 0.9 and vehicle mark-ups of less than 1.2 or a vehicle mark-up of 1.0 and a fuel mark-up of less than 1.3, or other combinations inside the frontier between these points would lead to hydrogen vehicle entry by 2020. If the mark-up is above 1.5 and the fuel mark-up is not lower than 0.9, we find that no entry through the year 2100 time horizon of the model. To generate these frontiers, hundreds of simulations of the model were run to exhaustively map out combinations of markups that lead to entry of hydrogen vehicles through the century.

An introduction of climate policy would create a strong advantage for hydrogen. Not surprisingly, the effect of the 550 ppm scenario is to shift the frontiers forward in time for a given markup, as shown in Figures 8 and 9. The maximum allowable mark-up for entry by 2100 was 1.5 in the Baseline scenario, while in the 550 ppmv scenario it rises to 3 if

no biofuels available. As discussed before, biofuels offer a significant vehicle fuel alternative, particularly under a carbon dioxide emissions constraint, but is ultimately limited by rising land prices. If this alternative is available, then the hydrogen vehicle fleet would penetrate later and at lower mark-ups. As presented in Figure 9, with the hydrogen mark-up of 0.9, the vehicle mark-up that would be necessary to achieve in this scenario is 1.8 (in comparison to 3.0 with no biofuels available).

An important measure of the potential of the alternative transportation technologies is its ability to reduce the adjustment costs associated with climate policy adoption by providing an economical low carbon alternative to prevailing transportation technology. We explore that potential by evaluating the macroeconomic consumption loss with and without the PHEV available in the presence and absence of biofuels. The model results show that the PHEV only makes a significant difference in offsetting the cost of climate policy when bio-fuels are not available (Figure 10b). If low cost biofuels are available (Figure 10a), even a PHEV with no mark-up makes little difference. However, if land use issues, trade policies, or other constraints limit the availability of bio-fuels or drive up their costs, the plug-in hybrid could provide an important stopgap measure to reduce the cost of adjustment under a climate policy.

We also measure the macroeconomic cost of emissions mitigation measures in the presence of hydrogen vehicles. For stabilization policies, these costs can be quite large in part due to the absence of good low carbon technology options in the transportation sector (US CCSP, 2007). A complicating factor in the analysis for individual regions is the particular allocation of reduction among countries, resulting in possible benefits related to selling of excess allowances in an international permit market, and other terms

of trade effects. To eliminate these complicating factors, we consider a climate policy in the USA only and in Europe only without emissions trading with other regions and with GHG reductions in these countries as in a 550 ppmv scenario. This allows us to get a more accurate picture of the implications for cost of just the breakthrough in hydrogen technology (US CCSP, 2007).

The results of this scenario analysis indicate that a carbon-free alternative in the transportation sector could mitigate consumption losses associated with the introduction of a carbon stabilization policy in both the U.S. and Europe. When the cost of hydrogen transportation is prohibitive, the introduction of a carbon policy results in consumption losses of 0.4 per cent and 3.2 per cent in the U.S. and Europe, respectively, compared to the expected 2100 consumption levels in the no climate policy case. However, if hydrogen transportation is available at the time the policy takes effect, these losses are reduced to only 0.3 per cent and 0.9 per cent in the U.S. and Europe, respectively. We also found out that even in the absence of a policy to limit emissions, the availability of a reasonably priced low carbon alternative enables modest increases in consumption relative to the baseline, as prices of gasoline rise more in the no hydrogen scenarios, suggesting that the availability of hydrogen or another alternative could have welfare benefits even without considering the potential benefits in reducing CO₂ emissions.

The impact of hydrogen on expected policy-related welfare loss is further illustrated by comparing the CO₂ price that emerges in the policy cases in the presence and absence of hydrogen. Without the hydrogen transportation alternative, the CO₂ price rises to \$600 per ton in Europe and \$170 per ton in the United States by 2100. However, with a hydrogen alternative, the price in both regions remains well below \$100 per ton. Of

course, these estimates depend on hydrogen achieving the breakthroughs assumed in these scenarios--if the breakthroughs achieve a more modest reduction in hydrogen costs, the reduction in CO₂ price and consumption loss would not be as big.

5. Conclusion

In this paper we present a methodology for incorporating household transportation technologies into a CGE model. We focus on internal combustion engine vehicles, plug-in electric vehicles and hydrogen-based vehicles. We also discuss implications of biofuel use in transportation.

The availability of a low cost PHEV could help to reduce economic welfare loss (measured in terms of consumption loss) due to the implementation of a strict (450 ppm) climate policy by up to threefold in the year 2100, but this conclusion only holds if advanced cellulosic biofuel technologies are not available. If biofuels are available, they provide a low carbon substitute in transportation instead, and severe consumption loss is averted. Given that biofuels can be used immediately without the need for deployment of a new vehicle design, their impact is felt long before new vehicle technologies can enter the fleet due to the slow rate of turnover. However, if the use of biofuels is limited by land or other constraints, the PHEV could provide a viable low carbon alternative that could serve the same function in reducing consumption losses.

Our analysis of the behavior of a hydrogen transport sector within a general equilibrium model of the economy provides several important insights. Under reference conditions, hydrogen fuel cell vehicles would have to reach a mark-up of less than 1.5 over conventional vehicles to penetrate the U.S. market before 2100. However, even if

hydrogen vehicles do penetrate the market, carbon emissions for the US increase slightly because coal is used to produce the hydrogen and there is no incentive to sequester the carbon when the hydrogen is produced in the absence of climate policy.

A carbon constraining policy favors the entry of hydrogen transportation to some extent. A 550 ppmv stabilization policy increases the maximum vehicle mark-up that allows entry in USA from 1.5 to 1.8. If advanced biofuel technology is not available so that it does not compete with hydrogen transportation technology, the favorable effect is much larger. If the 550 ppmv stabilization policy is imposed in the absence of advanced biofuels, hydrogen transportation can penetrate the U.S. market with a vehicle mark-up of up to 3.0. This scenario is the most favorable for hydrogen transportation in the USA.

Without a low carbon alternative technology in the transportation sector, the consumption losses in both the U.S. and Europe could be far larger than if such an alternative were available. Our analysis shows that the availability of a low carbon alternative could reduce the consumption loss, an expected result of limited emissions reduction potential of the current transportation fleet.

This paper focused on the supply side of transport sector by looking at the different household transportation technologies. By disaggregating household transportation sector we have been able to more accurately characterize the range of economic costs of a sample policy for GHG reduction. Other aspects of our current research agenda on transportation also merit additional attention. To analyze the development of the automobile sector it is also important to consider changes in transport demand for public and private transportation, in particular, regional changes in the number of vehicles per capita, miles driven, saturation levels for private cars, and development of reliable public

transport alternatives. While this issue is beyond the scope of this paper, our preliminary results show that these shifts in transportation demand are especially important for developing countries experiencing fast income growth.

For additional information on different aspects of the EPPA modeling activities related to the transportation sector we refer a reader to the detailed descriptions of our studies: Paltsev et al., (2004), Reilly and Paltsev (2007), Sandoval et al., (2008) and Karplus (2008).

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Table 1. Sectors and regions in the EPPA model

Sectors:	Regions:
<i>Non-Energy</i>	<i>Developed</i>
Agriculture	USA
Services	Canada
Energy-Intensive Products	Japan
Other Industries Products	European Union+
Industrial Transportation	Australia & New Zealand
Household Transportation: Internal Combustion Vehicles	Former Soviet Union
Household Transportation: Hydrogen Vehicles	Eastern Europe
Household Transportation: Plug-in Electric Vehicles	<i>Developing</i>
<i>Energy</i>	India
Coal	China
Crude Oil	Indonesia
Refined Oil	East Asia
Natural Gas	Mexico
Electric: Fossil	Central & South America
Electric: Hydro	Middle East
Electric: Nuclear	Africa
Electric: Solar and Wind	Rest of World
Electric: Biomass	
Electric: Natural Gas Combined Cycle	
Electric: Natural Gas Combined Cycle with CO ₂ Capture and Storage	
Electric: Integrated Coal Gasification with CO ₂ Capture and Storage	
Synthetic Gas from Coal	
Hydrogen from Coal	
Hydrogen from Gas	
Oil from Shale	
Liquid Fuel from Biomass	

Note: Agriculture, services, energy-intensive products, other-industries products, coal, crude oil, refined oil, and natural gas sectors are aggregated from GTAP data; hydropower, nuclear power and fossil-fuel electricity are disaggregated from the electricity sector (ELY) of the GTAP dataset; hydrogen vehicles, solar and wind power, biomass electricity, natural gas combined cycle, natural gas combined cycle with CO₂ capture and storage, integrated coal gasification with CO₂ capture and storage, synthetic gas from coal, hydrogen from gas, hydrogen from coal, oil from shale, and liquid fuel from biomass sectors are advanced technology sectors that were not operating in the base year or do not exist explicitly in the GTAP dataset; details on advanced technology sectors and regional grouping is provided in Paltsev *et al.* (2005).

Table 2. Elasticity Values for the Industry Transportation Sector

Notation	Elasticity	Value
s1	between Energy-Capital-Labor and Intermediate Goods	0
s2	between Domestic and Imported Intermediates	3
s3	between Imports from different regions	5
s4	between Energy and Value-Added	0.5
s5	between Electricity and Other Energy	0.5
s6	between Capital and Labor	1
s7	between Non-electric Energy inputs	1

Table 3. Elasticity Values for the Household Sector

Notation	Elasticity	Value
s8	between Aggregate Consumption and Savings	1
s9	between Aggregate Consumption and Transport	0.5
s10	between Energy and Non-Energy Consumption	0.25
s11	between Energy Inputs to Consumption	0.4
s12	between Non-Energy Inputs to Consumption	0.25-0.65
s13	between Domestic Goods and Imports	3
s14	between Imports from different regions	5
s15	between Own-Transport and Purchased-Transport	0.2
s16	between Gas and Other Inputs to Own-Transport	0.3-0.7
s17	between Services and Other Inputs to Own-Transport	1

Table 4. Overview of battery cost estimates from two detailed studies for the PHEV20 and PHEV60.

	Near Term (\$/kWh)	Long Term (\$/kWh)
Simpson, 2006		
PHEV20	\$531	\$265
PHEV60	\$482	\$241
BTAP, 2000		
PHEV20	\$320	
PHEV60	\$350	\$250
Cost Parity Target (Duvall, 2004)		
PHEV20	\$316	
USABC Target		
		\$150

Note: PHEV60 vehicle might have a smaller cost per kWh than PHEV20 vehicle, but it requires a bigger battery.

Table 5. Estimates of plug-in hybrid vehicle retail costs.

Study and Vehicle Type	Near Term	Long Term
Simpson (2006)		
ICE only	\$23,392	\$23,392
HEV0	\$28,773	\$26,658
PHEV20	\$38,935	\$31,828
PHEV60	\$50,184	\$36,681
Graham (2001)		
ICE only	\$18,000	
HEV0	+\$2,500-\$4,000	
PHEV20	+\$4,000-\$6,000	
PHEV60	+\$7,400-\$10,000	

Note:

ICE-only – internal combustion engine vehicle;

HEV0 – conventional hybrid vehicle (e.g., Toyota Prius);

PHEVX – plug-in hybrid electric vehicle with all-electric range equal to X.

Table 6. Example of costs for ICE-only, conventional hybrid, and plug-in hybrid electric vehicles.

Cost estimates by type of mid-size sedan	ICE	Hybrid	PHEV, 30-mile range
Vehicle cost (MSRP)*	\$20,000	+\$3,000	+\$10,000
All-electric range	N/A	N/A	30 miles
Miles per gallon (ICE engine)	20mpg*	43mpg*	43mpg*
Annual amount of fuel (gal, kWh, kg per year)	543 gal	340 gal	136 gal 1,200 kWh
Annual cost of fuel**	\$1,618	\$1,013	\$405.28 \$96.00
Payback period (undiscounted)	N/A	~5 years	~9 years

Notes:

*Estimated from CV, HEV, and PHEV long term scenarios in Simpson (2006). For the PHEV, 60% of miles driven are assumed to be supplied by electricity, while the remaining 40% are supplied by gasoline. Total annual miles traveled are assumed to be 13,000.

**Assumes January 2008 price of gasoline of \$2.98 per gallon and wholesale price of electricity of \$0.08/kWh.

MSRP is the manufacturer's suggested retail price.

Figure 1. Structure of Production Sector for the Industry Transportation Sector

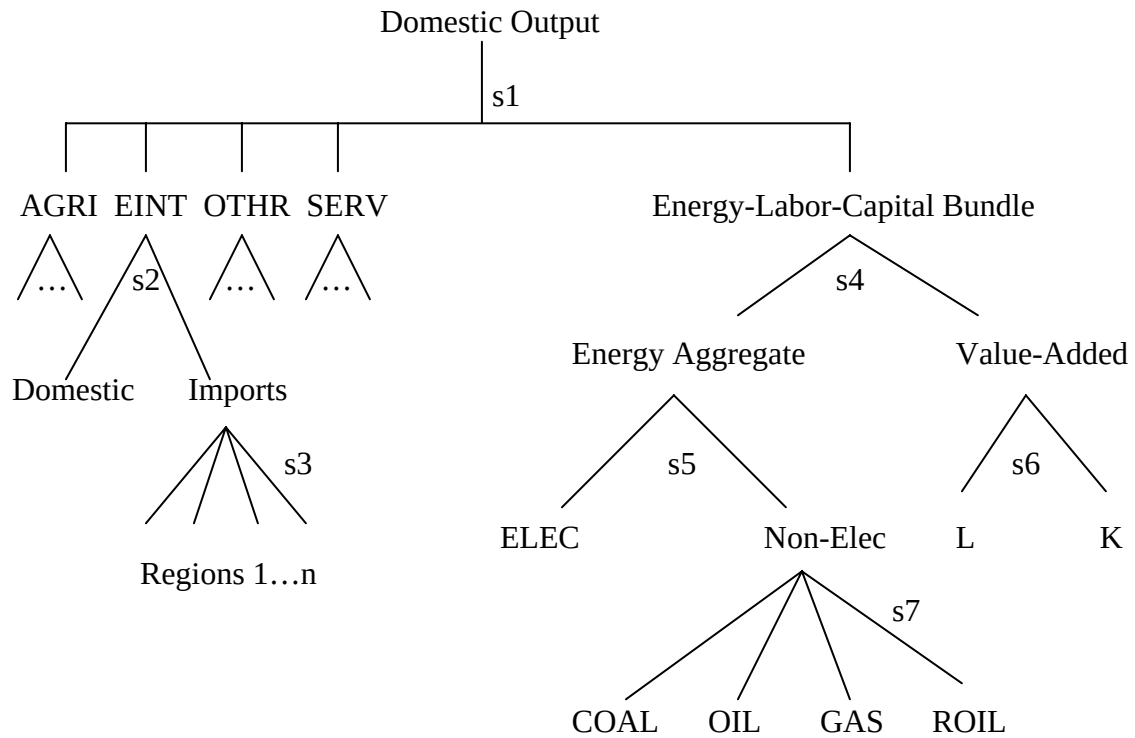


Figure 2. Structure of the Household Sector

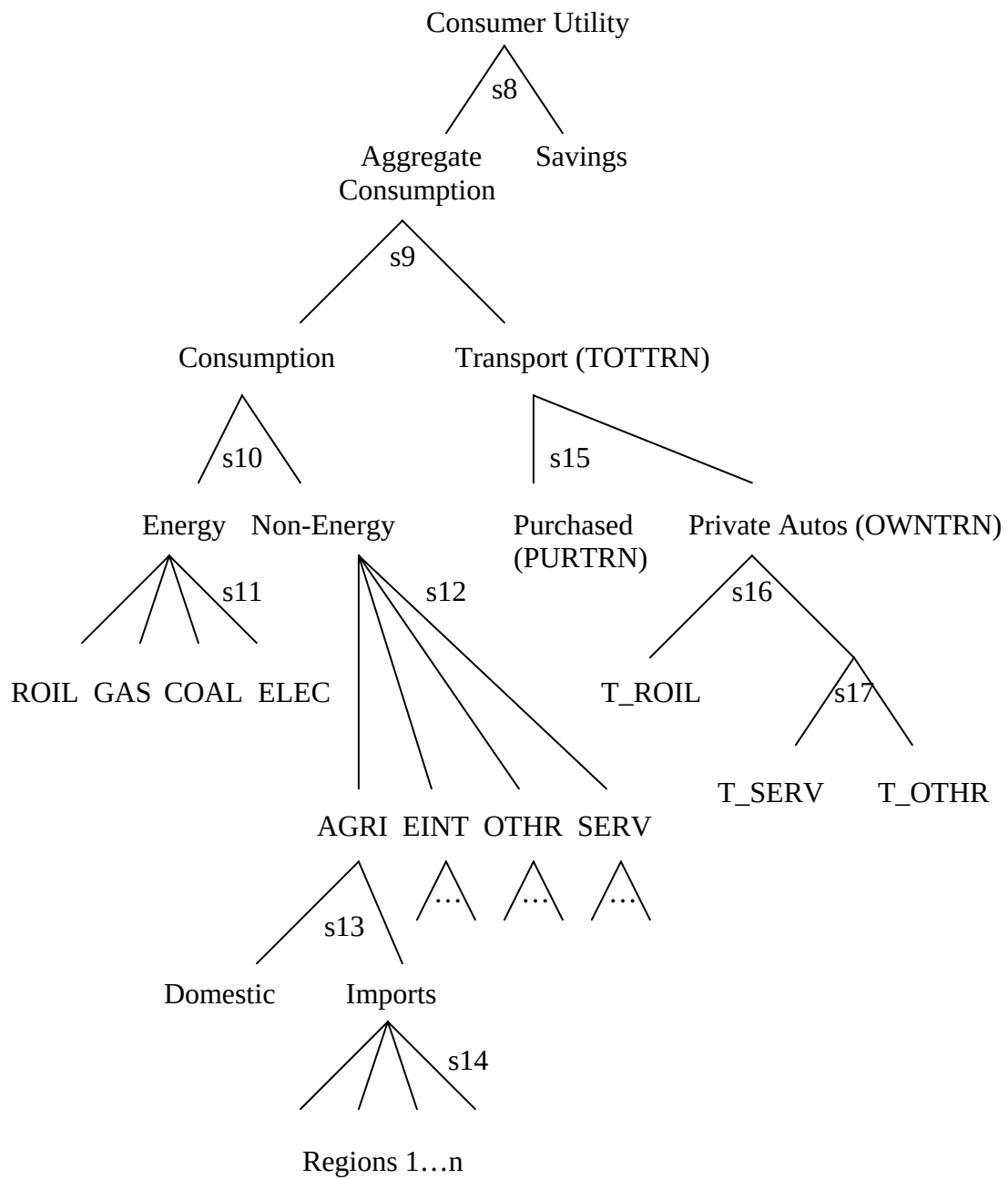
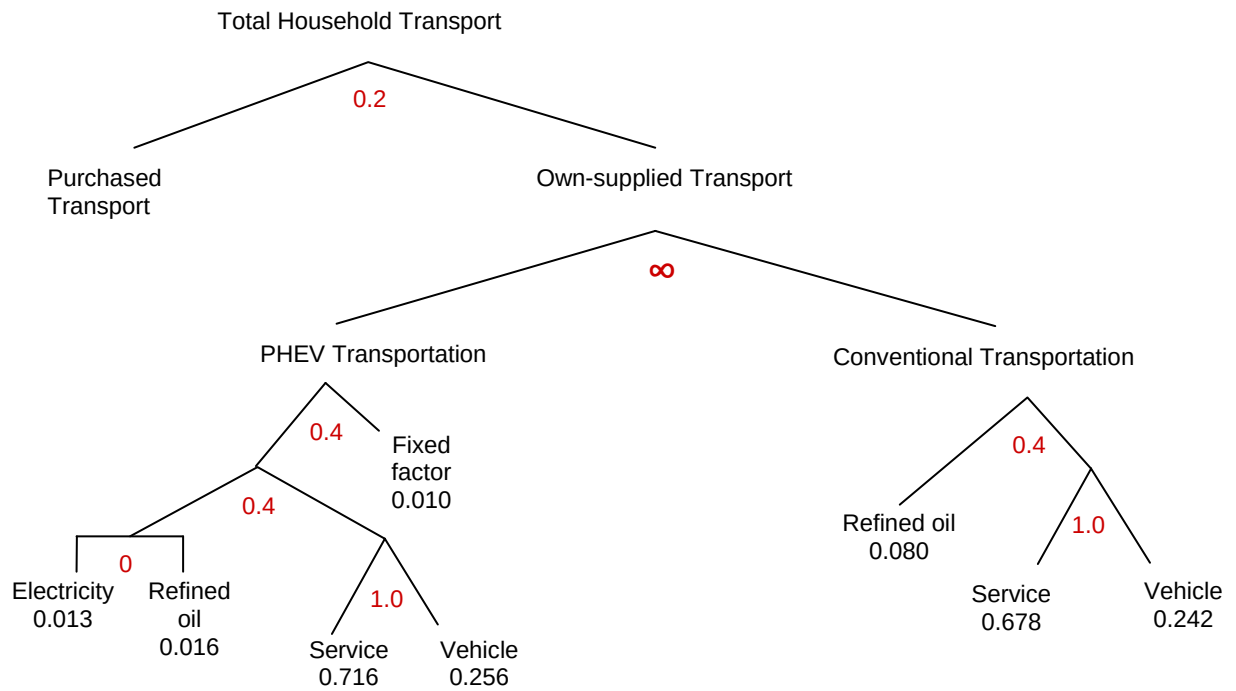
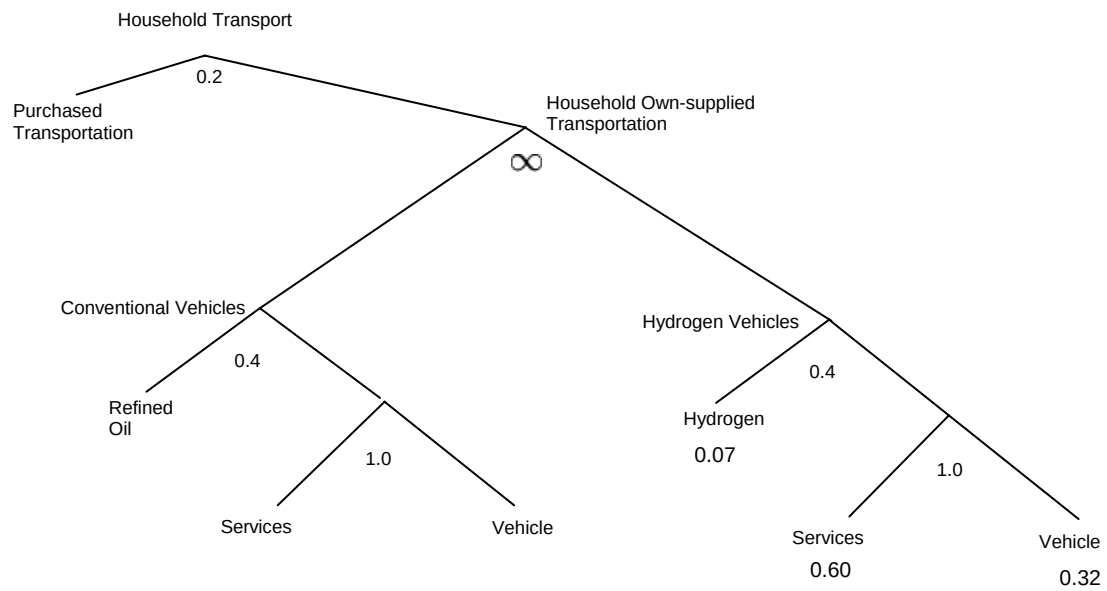


Figure 3. Structure of household transport with an addition of a plug-in hybrid electric transportation technology.



Note: numbers below the nest represent the corresponding elasticities; numbers below the inputs represent cost shares.

Figure 4. Structure of household transport with an addition of hydrogen transportation technology.



Note: numbers below the nest represent the corresponding elasticities; numbers below the inputs represent cost shares.

Figure 5. Impact of vehicle markup on PHEV sector entry in the absence of advanced biofuels and carbon capture and storage. Policy indicates a stabilization path aimed at 450ppm.

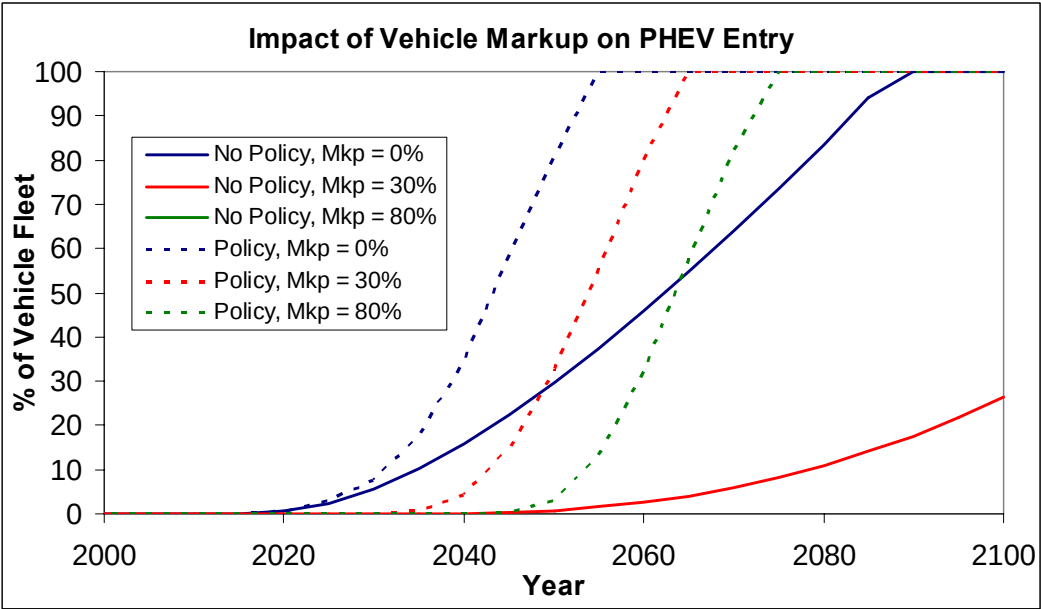


Figure 6. Impact of vehicle markup on PHEV sector entry when cellulosic biofuel technologies are available. Policy indicates a stabilization path aimed at 450ppm.

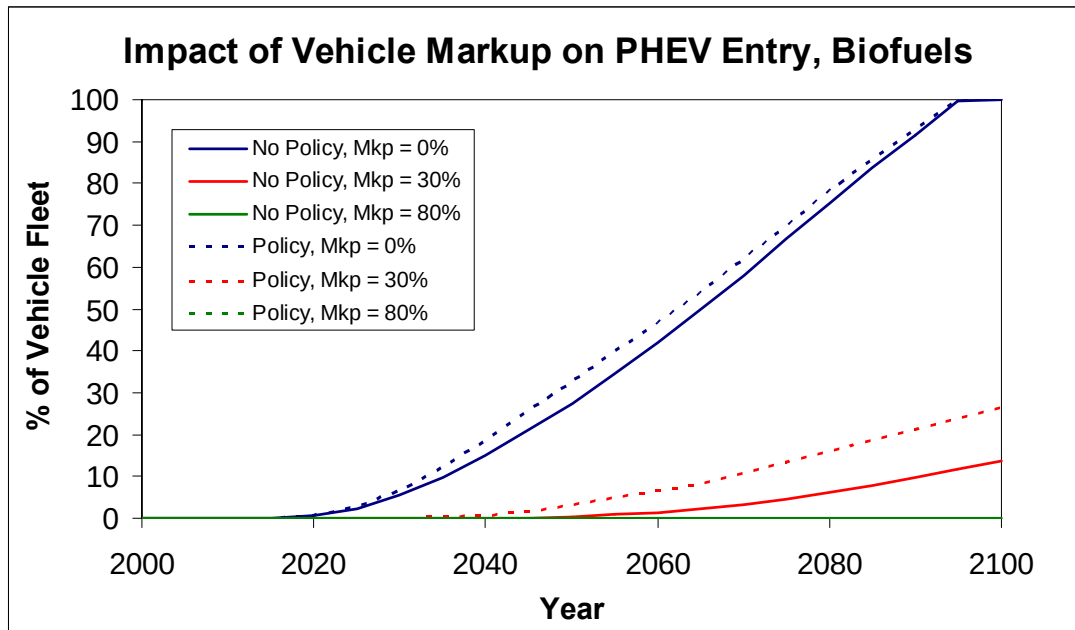


Figure 7. Entry decade for hydrogen transportation in USA in the *No Policy* scenario

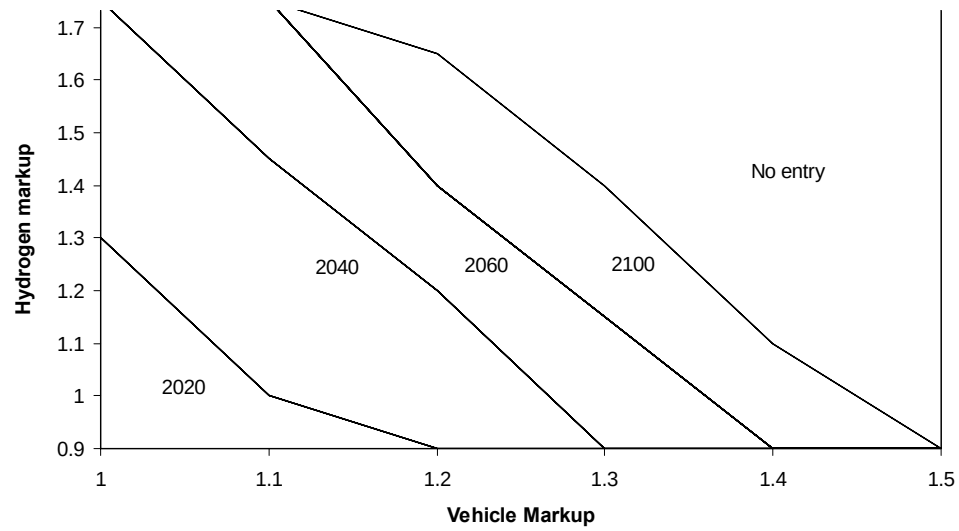


Figure 8. Entry decade for hydrogen transportation in USA in the 550 ppm with No Biofuels scenario

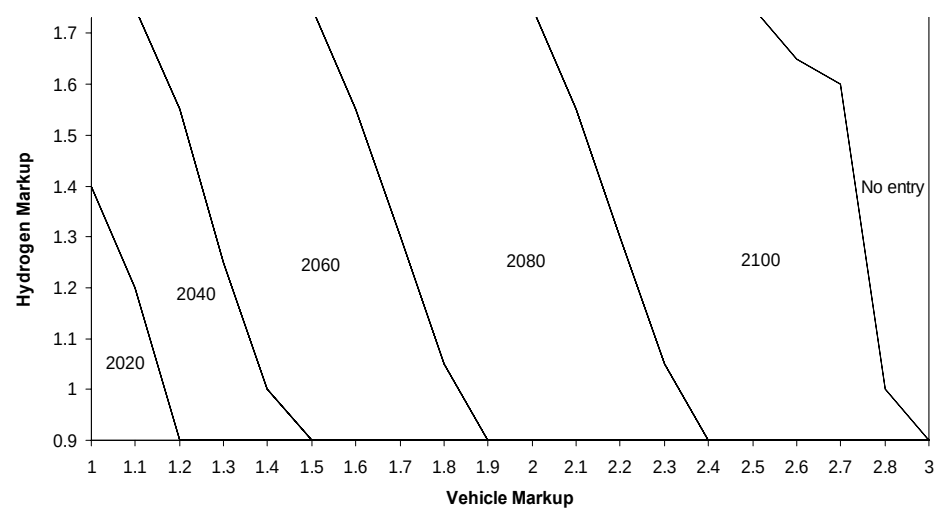


Figure 9. Entry decade for hydrogen transportation in USA in the 550 ppm with Biofuels scenario

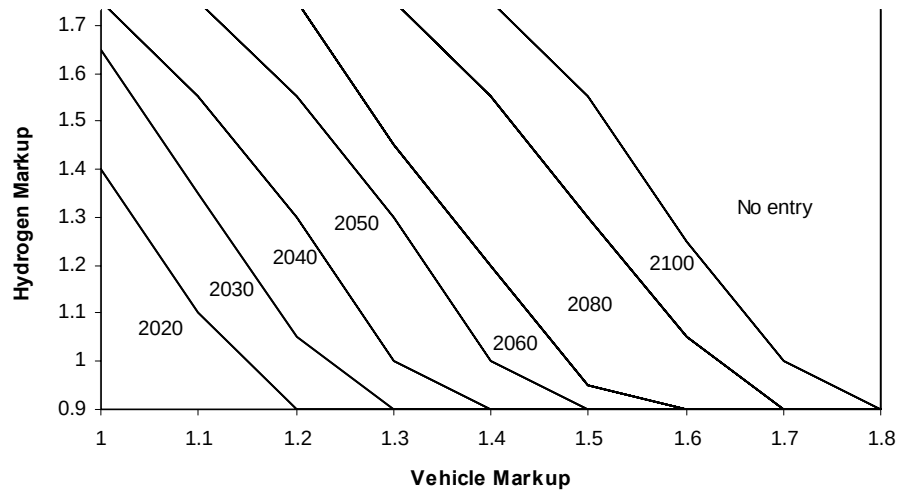
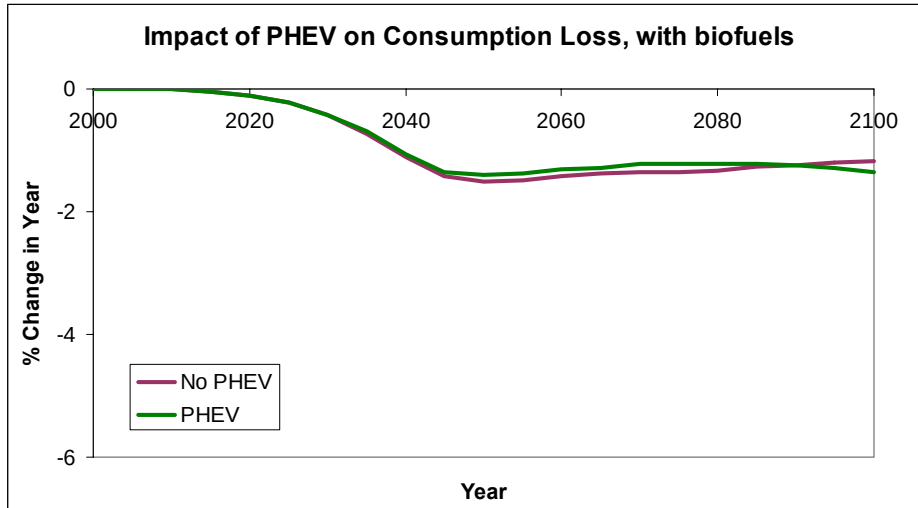


Figure 10. Impact of the availability of a low cost plug-in hybrid on economic consumption losses due to implementation of a climate policy a) with advanced bio-fuels and b) without bio-fuels.

a)



b)

