

Analyzing the role of subsidies in motor vehicle electrification in the US

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Abstract

In this study, we develop a model to provide a policy framework guiding the transition of transportation systems to alternative-fuel powered ones. The model is capable of obtaining good subsidy strategies by solving an optimization problem that maximizes social welfare. Model results suggest a large net gain to the society from a well-planned transition.

Keywords: electric drive, costs and benefits, subsidy, optimization

1 Introduction

The transition from a motor vehicle transportation system based on internal combustion engines powered by fossil petroleum to near zero-carbon electric-drive vehicles poses an extraordinary problem for public policy. The chief benefits sought are public goods: environmental protection, energy security and sustainability. As a consequence, market forces alone cannot be relied upon to drive the transition. To secure these benefits requires displacing a conventional vehicle technology that has been “locked-in” by a century of innovation and adaptation, together with an enormous infrastructure of physical and human capital [1]. The time constants for transforming the energy basis of vehicular transport are reckoned in decades rather than years. A comprehensive, rigorous, and durable policy framework is needed to guide the transition. As a first step to establish such a framework, this study aims to quantify the private and public costs and benefits of the transition to electric-drive vehicles and, in particular, to investigate the role of government subsidies in the transition.

2 Approach

The biggest challenge of devising a rigorous and efficient transition strategy is the innate uncertainty in the transition process. A desirable methodology is the one that generate robust and adaptive strategies, i.e. strategies should be near optimal for a wide range of future scenarios and be adjusted when new information comes in. At the current stage of study, this analysis still adopts a scenario analysis approach to learn about many unknown areas, particularly transition dynamics and the role of subsidies.

The analysis is based on the Light-duty Alternative Vehicle Energy Transitions (LAVE-Trans) Model. Detailed documentation of the model is available [2]. A brief overview is provided here.

Figure 1 illustrates the relationships between the major components of the model. The exogenous inputs are shown with blue boxes. Major input includes technical attributes of different vehicle technologies, parameters that determine consumers’ willingness to pay for vehicles and their attributes, and government policies. The model translates these into coefficients for the vehicle choice module. The choice module predicts annual new vehicle market shares and sales of each vehicle technology type up to year

2050. New vehicle sales are then passed to the stock module to simulate vehicle aging and retirement and track the number of vehicles of each technology type by model year, for every forecast year. Given the vehicle stock, total energy use, Greenhouse Gas (GHG) emissions and infrastructure costs are calculated. Costs and benefits for each transition scenario are estimated. The benefits are calculated as the net present value of GHG emissions reductions, improved energy security and sustainability, and fuel savings. The costs are quantified as the amount of total subsidies and consumer surplus change. An optimization model is developed to find optimal amount and timing of subsidies in order to maximize social welfare.

2.1 Vehicle Choice Module

Consumer demand is estimated by a Nested Multinomial Logit (NMNL) model with two market segments of innovators and majority. The nesting structure used in the model is shown in figure 2. The first level of choice is to buy or not to buy a new light-duty vehicle. The second is the choice between a passenger car and a light truck. The third level is the choice between an ICE (Internal Combustion Engine) vehicle, a BEV (Battery Electric Vehicle) and a FCV (Fuel Cell Vehicle). Within the ICE nest is the choice between a conventional ICE, an HEV (Hybrid Electric Vehicle) and a PHEV (Plug-in Hybrid Electric Vehicle). The order of nesting does not signify a temporal sequence of choices. Rather it orders choices from least price sensitive (buy v. no-buy) to most price sensitive (ICE, HEV or PHEV) and attempts to group choices within a nest that are closer substitutes than choices within some other nest.

The utility of a vehicle technology type is determined by the following vehicle and consumer attributes:

1. Retail price equivalent (RPE)
2. Energy cost per kilometre
3. Range
4. Annual maintenance cost
5. Fuel availability
6. Public recharging availability
7. Diversity of make and model options available
8. Willingness of consumers to pay to avoid risk or gain novelty.

The NMNL model attempts to capture transition dynamics. For example, cumulative vehicle sales generate learning-by-doing effects that lower vehicle prices over time. Vehicle sales also affect future vehicle prices via economy of scale

effects. The model represents these effects using feedback loops. Feedbacks are recursive (with a one year lag) rather than simultaneous. For example, current year vehicle sales affect next year's vehicle prices. This simplifies the solution of the model greatly but is also generally more representative of how changes can be made in the motor vehicle industry

2.2 Optimization Model

In this analysis, decision variables are amount of subsidies to vehicles at each year. Future study may include other form of subsidies to fuels and infrastructure. The objective of the optimization model is the net present value of discounted social welfare over the period of 2010 to 2050, which is calculated as a function of subsidies and attributes of vehicles and consumers. Market penetration rate of a vehicle technology is capped, i.e., market share increase for a vehicle technology at any single year should be less than a threshold value. The optimization model is solved by the genetic algorithm using Evolver of @risk software [3].

3 Results

3.1 Scenarios

Three scenarios are used in this analysis with different assumptions on vehicle technology progress. Scenario 1, the reference scenario, assumes that the proposed 2016-2025 fuel economy and CO₂ emissions standards will be met. Scenario 2, the high technology scenario, assumes fuel economy/emissions standards beyond 2025 and consequently a more aggressive and optimistic vehicle technology progress, using data provided by the International Council on Clean Transportation (ICCT). Scenario 3, the high technology & high subsidy scenario, assumes the same technology progress as scenario 2 but also a large amount of subsidies to PHEVs and BEVs. The amount and timing of vehicle subsidies are from the solution of an optimization model that maximizes social welfare (the net present value of social welfare over the period of 2010 to 2050). The energy efficiency and vehicle prices data are illustrated by figure 3 to 6 below. PHEVs are assumed to have the same energy efficiency as HEVs when operated on gasoline and the same energy efficiency as BEVs when operated on electricity. The prices in figure 4 and 6 are fully learned and scaled (FLS) prices. At the initial period of the transition, actual retail prices are

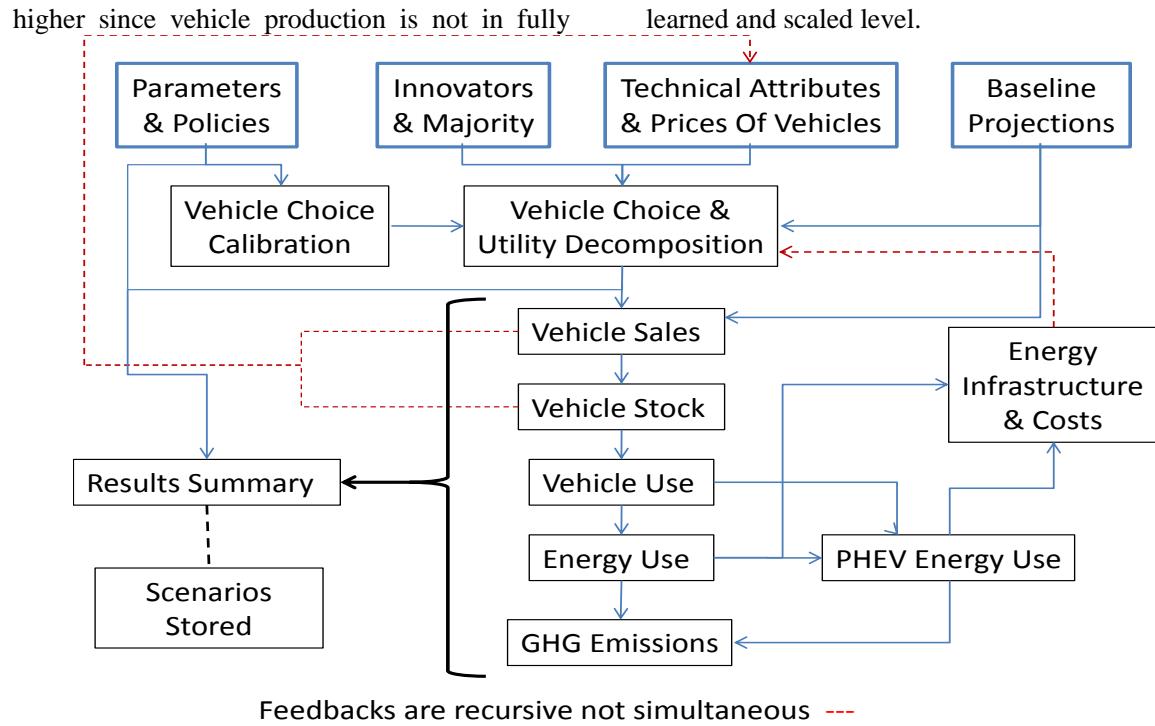


Figure1: Structure of the LAVE-Trans Model

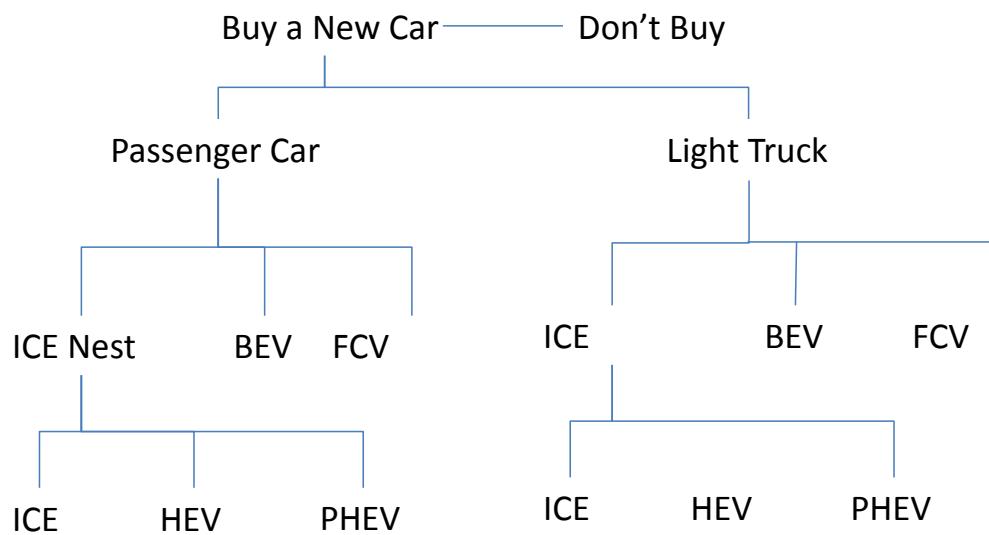


Figure2: NMNL Choice Structure

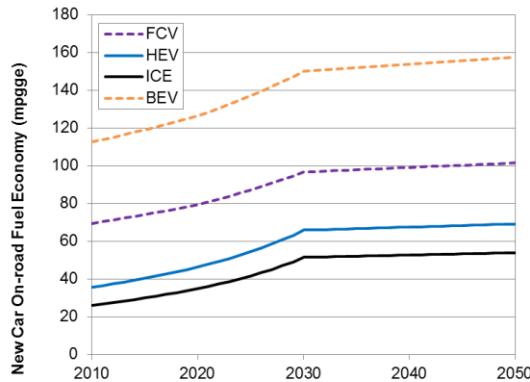


Figure3: New Passenger Car Fuel Economy for Reference Scenario

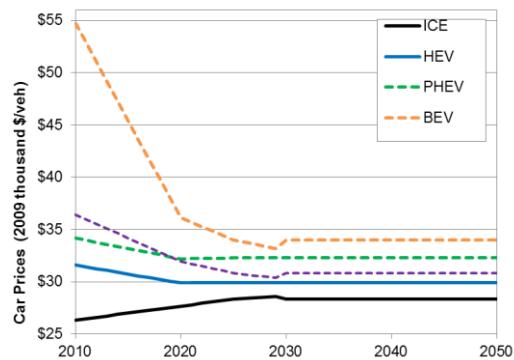


Figure4: New Passenger Car Fully Learned and Scaled (FLS) Prices for Reference Scenario

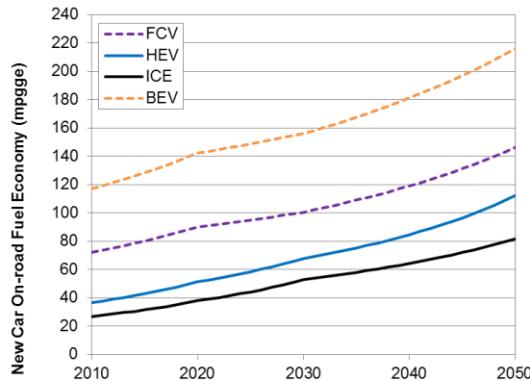


Figure5: New Passenger Car Fuel Economy for High Technology Scenario and High Technology & High Subsidy Scenario

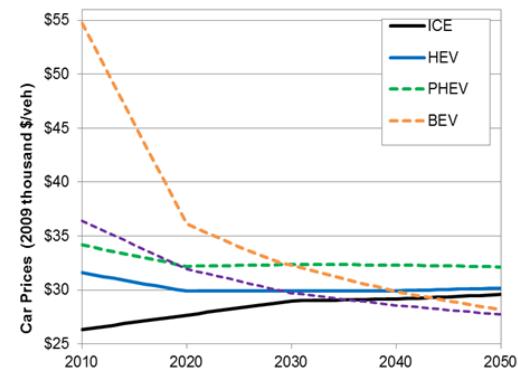


Figure6: New Passenger Car Fully Learned and Scaled (FLS) Prices for High Technology Scenario and High Technology & High Subsidy Scenario

3.2 Results

3.2.1 Electric Drive Vehicle Market Penetration

The LAVE-Trans model was first run for reference and high technology scenarios. Figure 7 and 8 (new Light duty vehicle annual market share) shows that advanced vehicle technologies have very low market penetration for these two scenarios. Although at the high technology scenario FCV and BEV FLS prices are very competitive after 2040, consumers face much higher retail prices when vehicle production volume is low (Figure 9). The LAVE-Trans model calculates retail prices as functions of manufacturers' learning by doing and scale economies level, which again depend on cumulative production or sales and annual sales. The transition to electric drive vehicles faces other market barriers, including

1. Consumers' aversion to the risk of novel products

2. Lack of diversity of choice

3. Lack of an energy supply infrastructure

The transition cannot naturally happen due to the existence of these barriers. It suggests the need of strong policies to help to break down barriers and facilitate the transition.

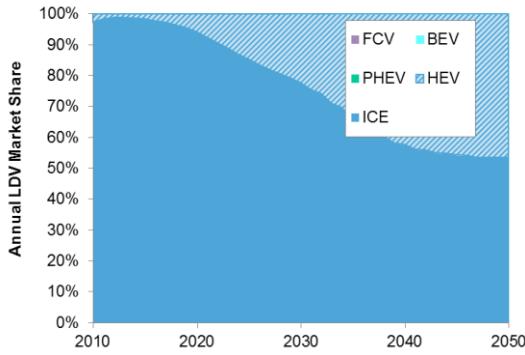


Figure7: Annual LDV Sales for Reference Scenario

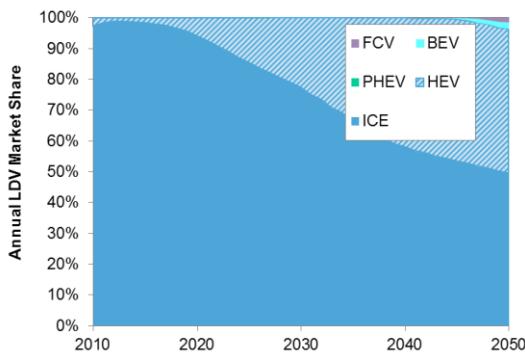


Figure8: Annual LDV Sales for High Technology Scenario

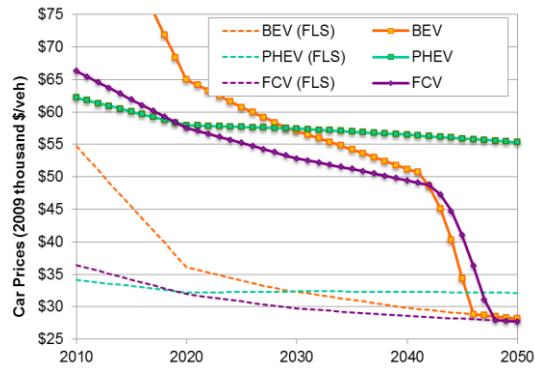


Figure9: Actual Prices vs. FLS prices for High Technology Scenario

3.2.2 Explore Optimal Subsidies

The timing and amount of subsidies are vital to facilitate a successful transition. This study has conducted a preliminary analysis on exploring optimal subsidies. The LAVE-Trans model was run with high technology assumption. Evolver of @risk software searches the space of subsidies using the genetic algorithm, trying to maximizing net present value of social welfare. At this experiment, only subsidies to the purchase or

sales of PHEVs and BEVs are tested. Light truck PHEVs and BEVs are assumed to get the same subsidies as passenger car PHEVs and BEVs.

The “optimal”¹ subsidies are illustrated by figure 10. PHEV subsidies start from 2016 at the amount of \$25000 per vehicle and gradually decrease to 0 at 2050. BEV subsidies start from 2020 at the amount of \$25000 per vehicle and also decrease over time to 0 at 2050. These subsidies should be viewed in a broad context. They are not limited to government subsidies. Sometimes manufacturers subsidize these vehicles in order to get a competition advantage. Dollar value per vehicle subsidies can include subsidies to fuel and refuelling/recharging infrastructure. With these subsidies, PHEVs and BEVs are able to achieve a high market penetration (figure 11). Figure 12 shows PHEV and BEV retail prices quickly converge to FLS prices.

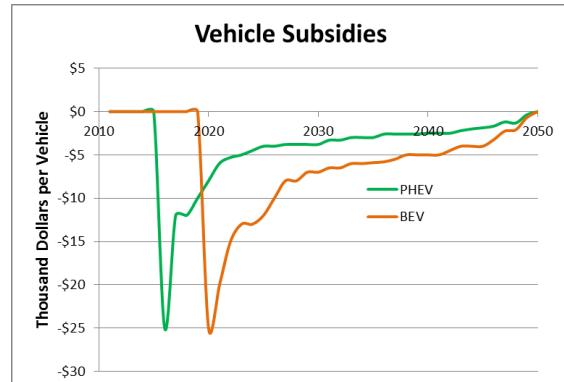


Figure10: Optimal Vehicle Subsidies

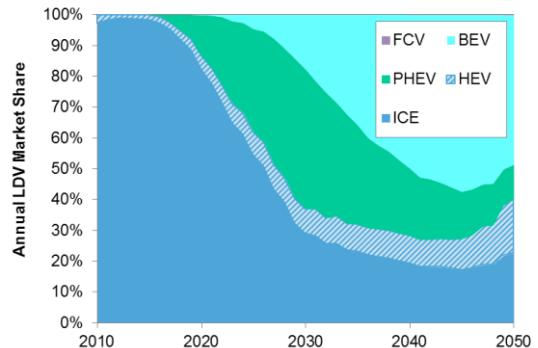


Figure11: New LDV Market Share Given High Subsidies

¹ We don't really claim it as optimal subsidy strategy due to limitations of the model and our insufficient understanding to transition dynamics and uncertainty.

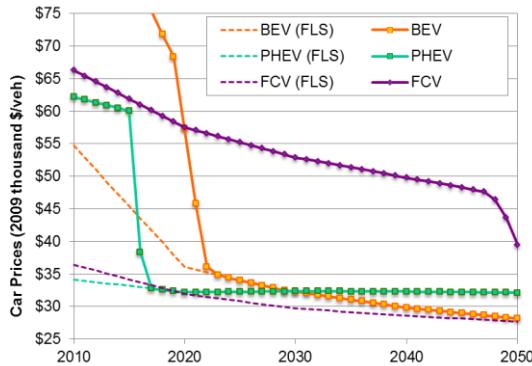


Figure 12: Actual Prices vs. FLS prices for High Technology & High Subsidies Scenario

High cost of subsidies is compensated by social value of GHG emissions reduction, petroleum consumption reduction, positive consumer surplus change, and energy savings that are not accounted by consumers² but should be included for social welfare analysis (see figure 13). The net present value is quite large, at the order of \$700 billion. Figure 14 shows emissions and petroleum consumption reduction (comparing 2050 to 2005) from this transition is close to or more than 80%.

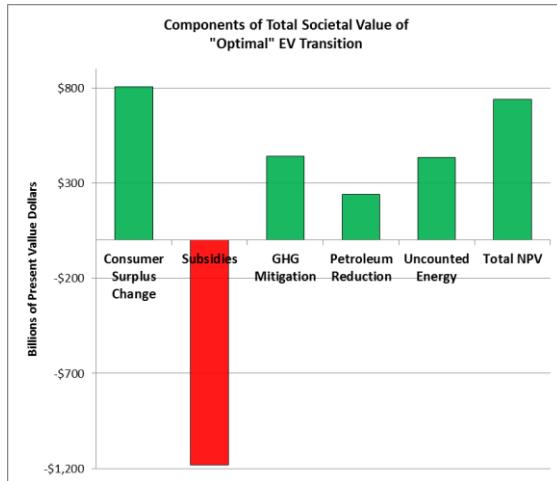


Figure 13: Components of Total Social Value of the “Optimal” EV Transition

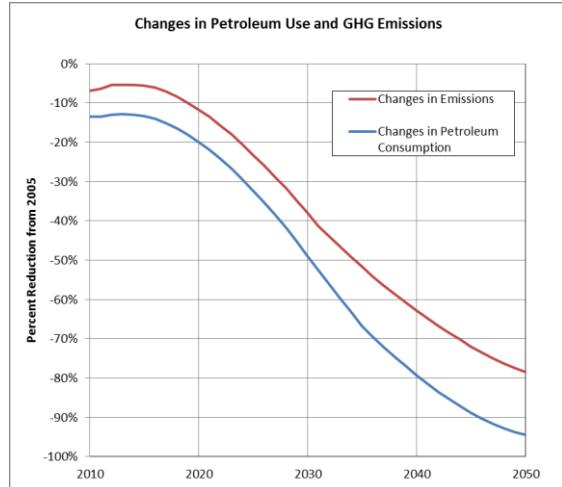


Figure 14: Emissions and Petroleum Consumption Reductions Compared with 2005 Quantities

4 Discussions

This study is our initial effort to reach the ultimate goal of building a rigorous policy framework that guides an efficient transition to electric drive vehicles. At such a stage, our analysis has several important limitations. Although there is a large body of literature on modelling light duty vehicle consumer demand, the understanding to transition dynamics (e.g. quantifying the cost due to the lack of refuelling infrastructure) is still insufficient. Also, the values of GHG emissions and petroleum reductions varied widely among literature studies. Different assumptions on these values can significantly change the results reported in this paper. Careful sensitivity analysis is needed to test different assumptions. Finally model results strongly depend on technology progress assumption.

With the limitations of the analysis, the results shall be viewed as suggestive. The following conclusions are likely to be robust to alternative assumptions:

- Without a strong policy, the transition to electric drive vehicles is unlikely to happen
- The payoff from subsidies may greatly exceed the cost of the subsidy program. The social net benefit from a well-planned transition could be in the scale of hundreds of billions of dollars.

Acknowledgments

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² Consumers are assumed to undervalue fuel savings, only account for the first 3 years pay back since the purchase of a new vehicle

(DOE). Opinions and views expressed are those of the authors and do not necessarily reflect those of the U.S. DOE.

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