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Analyzing the Transition to Electric Drive in California

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Final Report to

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Analyzing the Transition to Electric Drive in California

Final Report

David L. Greene
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I. Introduction: A New Challenge for Public Policy

Achieving sustainability, assuring that the world we leave to future generations allows a quality of life at least as good as our own, may be humanity's greatest task in the 21st century. Transitioning to sustainable energy systems is an essential element of a sustainable global society (IEA, 2012; Fawcett et al., 2009). As the world's vehicle population grows towards 2 billion, motorized transportation is challenged to contribute to protection of the global climate system, energy security and the elimination of the adverse health effects of local air pollution (Sperling and Gordon, 2011). There is no single solution to these problems (NRC, 2013; Yang et al., 2011; Greene and Plotkin, 2011; McCollum & Yang, 2009). However, it is becoming increasingly clear that achieving sustainable transportation implies a transition from petroleum-based, internal combustion engines to zero emission electric drive.[1]

This study investigates how the transition to electric drive vehicles in California and the rest of the U.S. might be accomplished and the role of public policy in managing such a transition efficiently and effectively. Given a new assessment of the potential for future progress in advanced conventional and alternative vehicle technologies (NRC, 2013), this study analyzes the potential costs and timing of a transition to electric drive vehicles in California, and the policies that may be required to achieve it. It investigates the conditions that could lead to a self-sustaining market and when that might be achieved. It analyzes the policies that may be necessary to achieve the transition to e-drive and, in particular, the role of California's ZEV program as a catalyst. Finally, a key goal of the study is to contribute to establishing a new paradigm within which economically efficient energy transition policies can be formulated by developing and applying such a paradigm to the problem of transitioning light-duty vehicles from petroleum internal combustion engines to electric drive.

Bringing about a large scale energy transition to achieve public goods requires a new paradigm for public policy. The concept of externalities enabled a new understanding of the causes of environmental pollution and provided a paradigm for formulating efficient policy responses. Accomplishing major energy transitions for the public good poses a new and different challenge and calls for a new paradigm. It is proposed here that the economic paradigm appropriate for the transition to electric drive vehicles should be built on the concepts of net social value, network external benefits, and adaptation to an

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[1] The International Institute for Applied Systems Analysis' *Global Energy Assessment* (GEA, 2012) concluded that "In all pathways conventional oil is essentially phased out shortly after 2050. Every scenario that achieves the sustainability goals essentially eliminates petroleum use."

uncertain future (e.g., Zachmann et al., 2012). Net social benefits must be the key metric because a broadly based cost/benefit framework is necessary to compare very different future states of the world; marginal analysis is inadequate. Novel technologies must overcome higher initial costs that temporarily prevent them from displacing the incumbent “locked in” technology (Gallagher et al., 2012). Network external benefits are key concepts for understanding technology transition because the process of breaking down the natural economic barriers to transition is comprised of actions that provide future benefits to others with costs incurred in the present (e.g., Köhler et al., 2006). Uncertainty is an inescapable dimension because future technologies and markets will undoubtedly surprise us.

The transition to electric drive vehicles faces six major economic barriers that help lock in petroleum powered internal combustion engine vehicles.

1. Current technological limitations of alternative power-trains and fuels
2. High costs that can be reduced through experience (i.e., learning by doing)
3. High costs that can be reduced by volume production (i.e., scale economies)
4. Consumers’ aversion to the risk of novel products
5. Lack of diversity of choice in the early market for alternatives
6. Lack of an energy supply infrastructure for alternatives

Market researchers recognize consumers’ risk aversion as lack of awareness of, social exposure to, and unwillingness to consider novel products (Struben and Sterman, 2008). Initially, many consumers may not be aware of the existence of novel products. They may not even know anyone who owns or uses the new product and thus lack a source of first-hand knowledge of its pros and cons. These barriers are collectively represented in the LAVE-Trans model by risk aversion to novel products.

Each of these barriers is difficult to quantify and uncertain in the future. The approach taken in this study is to quantify them using the best available information with the understanding that as knowledge improves and conditions change, assessments must be revised and policies adapted. By quantifying the transition barriers, the costs of overcoming them can be measured. Each of the six barriers above can be viewed as a *transition cost*. On the other hand, reductions in these barriers are also *external benefits* created for existing and subsequent customers by early adopters willing to purchase the new vehicles and entrepreneurs willing to produce them and to supply the new fuels they require.

Figure 1 is an attempt to illustrate the problem in two dimensions. In the diagram, lower is better and higher is worse (figure 1). At present, markets perceive that they are in a very good place (the red circle at the bottom of the left-hand valley); costs rise with a move in any new direction. But markets fail to see the costs of air pollution, climate change, energy insecurity and un-sustainability. When these costs are considered, we find ourselves at the bottom of a much higher cost valley, illustrated by the blue star resting on the dashed green line. From the market’s perspective, the alternative valley is not preferable, but when full social costs and benefits are considered it is actually a much better place. Yet even if external costs are internalized and recognized by the market, it is not clear that the benefits of transitioning to the preferable valley would be worth the cost of the transition.

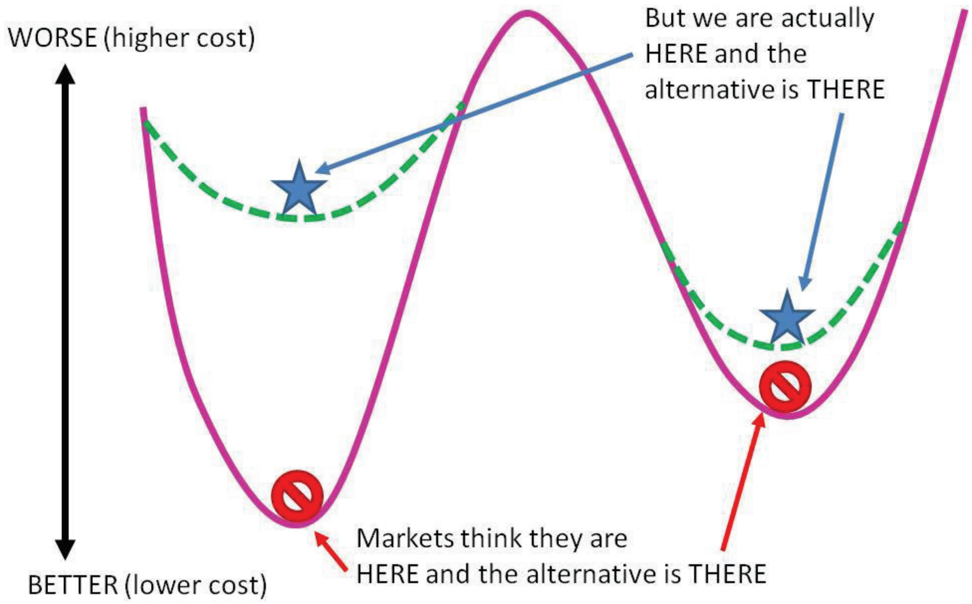

Figure 1. The energy transition in two dimensions.

Unfortunately, making the transition to the better valley requires climbing a rather steep hill, thereby incurring costs that will only be repaid at a later date when the valley on the other side is reached. And because markets don't recognize our true position, the hill seems even larger than it is. Is it worth it to pay the upfront cost of climbing the hill to reach the better valley? How high is the hill? How long will it take to make the climb? How much better is the other valley? In reality, all of these things are uncertain; figure 1 should be much fuzzier than it is, especially on the right hand side. The bottom of the alternative valley could turn out to be higher or lower than it seems to us today, and the value of external benefits could be larger or smaller than we think.

Fortunately, climbing the hill will generate positive feedbacks (reductions in the transition barriers) that will make the transition easier than it first appears. Modern economics calls these positive feedback effects "network externalities", positive external benefits that one user of a commodity can produce for another (Farrell and Klemperer, 2007). Network external benefits have been extensively studied in the development of personal computer operating systems and cell phones. Every consumer who purchases a given computer operating system increases the value of that system to other users by expanding the network of users with whom files can be exchanged seamlessly and by increasing the size of the market for software developers.[2] When software developers produce a new product for the operating system, it increases the value of the system to those who have already purchased it.[3] In the same way, when an innovator purchases one of the first hydrogen fuel cell vehicles, external benefits are produced for other buyers in the form of reduced risk of buying a now slightly less novel technology, as well as via scale

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[2] These are called direct network external benefits.
[3] These are referred to as indirect network external benefits.

economies and learning by doing.[4] When a city installs a public recharging station it increases the value of electric vehicles to current and future owners. Likewise, adding a hydrogen refueling station makes fuel cell vehicles more attractive, while the sale of another fuel cell vehicle improves the economics of the first few hydrogen refueling stations.

Network external benefits will be key drivers of the transition to electric drive vehicles because they create important positive feedbacks that can lead to a self-sustaining transition. The Light-duty Alternative Vehicle and Energy Transitions (LAVE-Trans) model developed for this project was designed to measure these external benefits, albeit imperfectly. Recognizing and measuring the value of early deployment of vehicles and infrastructure at a time when it might appear to be uneconomical is an important part of understanding the new paradigm for energy transitions.

The following section outlines an economic paradigm for producing an efficient transition to electric drive vehicles. The third section briefly describes the LAVE-Trans model; those interested in details can find them in the model documentation report (Greene, Liu and Park, 2013). Section four reviews the key assumptions about vehicle technologies; the corresponding assumptions about fuel technologies and energy prices are covered in section five. The sixth section describes the seven scenarios analyzed using the LAVE-Trans model and presents the resulting estimates of costs and benefits. The implications of uncertainty about the market's response to electric drive vehicles are explored quantitatively in section seven by means of sensitivity analysis. The final section draws some inferences from the LAVE-Trans analysis. Uncertainty about future technologies and markets is great. Many of the key factors that will determine the ultimate outcome are not well understood. Thus, this report is as much about how to think about transition policies and analyze their likely impacts as it is an attempt to understand how the transition to electric drive vehicles could be accomplished.

II. An Economic Paradigm for Sustainable Energy Transitions

This section makes use of a certain amount of mathematics and technical economic jargon and may be safely skipped by readers not interested in such an explanation.

If every path to the future could be assigned a definite value reflecting its overall worth to society, then alternative paths with different policies inducing different combinations of vehicles and fuels could be compared and the path with the highest value chosen. The net social value (NSV) of a path is the sum over all future years ($t=0,\infty$) of its full discounted benefits minus its full discounted costs. To simplify, assume both benefits (B) and costs (C) are in constant, discounted dollars and that they depend only the numbers of vehicles of each technology type, (N_{it}, $i = 1$ to m) sold in each year, $t = 0$ to T, the stock of supporting energy infrastructure (K_{it}), the status of technology (X_{it}) and economic conditions, such as energy prices (E_{it}). Because there are important feedback effects, benefits and costs in year s depend on the present and past vehicle sales and infrastructure deployment. Let $\boldsymbol{N}_t$ and $\boldsymbol{K}_t$ be matrices of vehicle

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[4] The latter two benefits are referred to as pecuniary network external benefits because they are reflected in the prices of the vehicles.

sales and infrastructure inventories with dimensions m by t, and let $\boldsymbol{x}_t$ and $\boldsymbol{e}_t$ be vectors of m elements characterizing the state of technology and energy prices in year t.

$$\boldsymbol{NSV} = \sum_{t=0}^{T} \left(\boldsymbol{B}(\boldsymbol{N}_t, \boldsymbol{K}_t, \boldsymbol{x}_t, \boldsymbol{e}_t) - \boldsymbol{C}(\boldsymbol{N}_t, \boldsymbol{K}_t, \boldsymbol{x}_t, \boldsymbol{e}_t) \right)$$

In any given year, increasing the number of electric drive vehicles or expanding their refueling infrastructure will change the costs and benefits not only in that year but in succeeding years. The costs and benefits of adding electric drive vehicles and infrastructure in any year will also depend on what has happened in previous years. Given vehicle sales and infrastructure deployment in other years, one can construct a societal "demand curve" for deployment of electric drive vehicles in year t. The demand curve is the derivative of NSV with respect to N_{it}, other variables held constant.[5] There will be a change in NSV for the first 100 vehicles e-drive vehicles sold in year t, as well as for the second, third and fourth 100, and so on. A similar set of calculations could be made for infrastructure deployment.

Plotting the change in NPV against the number of vehicles produces a downward sloping curve describing the value to society of (or the maximum amount society would be willing to pay for) selling different quantities of e-drive vehicles in year t (this is the marginal net present social value curve in figure 2). The subsidy per vehicle required to produce a given level of sales in year t is the marginal cost to society of (or the market's willingness to accept) that level of sales (illustrated by the upward-sloping "required subsidy per vehicle" curve in figure 2). The first 100 vehicles will go to the most eager innovators with ready access to hydrogen fuel. A somewhat larger subsidy would be required to induce the next 100 car buyers to opt for an electric drive vehicle, and each additional increase in sales will require still larger subsidies. Where the two curves intersect, society's willingness to pay to sell one more e-drive vehicles exactly equals the market's willingness to buy the vehicle. If these curves were known for every year in the future, they would define an economically efficient transition pathway.

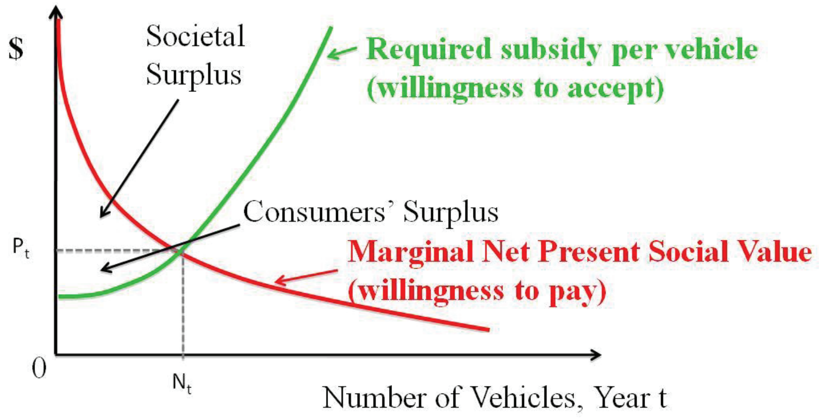

Figure 2. Determination of an efficient quantity of vehicle sales in year t and an efficient subsidy.

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[5] This explanation ignores the existence of tipping points which are, in fact, an important feature of the transition problem. One consequence of tipping points is that the demand curve for electric drive vehicles will not, in general, be smoothly downward sloping.

But energy transitions take decades (Grübler et al., 1999; Nakicenovic et al., 1998) and because of this, deep uncertainty about technology and markets is unavoidable (Gallagher et al., 2012). If, as a consequence, risk-averse decision makers strongly discount expected future benefits, this will lower the marginal net present value curve thereby reducing the efficient number of vehicles to be deployed in year t.

The scenario analyses described in this report do not represent optimal transitions that maximize the net present value to society of the transition. To accomplish optimal transitions societies would have to be either exceptionally lucky or have perfect knowledge of the future. Technology transitions are inherently uncertain and, in addition, self-reinforcing feedbacks create tipping points. Transition policymaking must balance the need to establish long-term goals and supporting policies with the need to adapt policies as society learns about the progress of new technologies and the market's responses (Gallagher et al., 2012). Instead, we have devised plausible policies that, given the numerous assumptions required, appear to be able to produce a sustainable transition to electric drive vehicles.

III. The Light-Duty Alternative Vehicle and Energy Transitions (LAVE-Trans) Model

The analyses of transitions to electric drive vehicles presented in this report were constructed using the Light-duty Alternative Vehicles and Energy Transitions (LAVE-Trans) model. Developed for the project reported on here, the model was also used by the National Research Council's study, *Transitions to Alternative Vehicles and Fuels* (NRC, 2013, Appendix H[6]). The LAVE-Trans model represents consumers' choices among vehicle technologies, the effects of scale, learning and technological change on the costs and performance of vehicles, and the supply of energy for vehicles. Consumers' choices are estimated using a representative consumer, nested multinomial logit model (e.g., Greene, 2001; Greene, Leiby and Bowman, 2007; Struben and Sterman, 2008). There is a great deal of uncertainty about the best values for many of the parameters that determine consumers' choices and firms' decisions, in addition to the uncertainty about future technological progress. The method of deriving key choice model parameters from basic assumptions pioneered by Donndenlinger and Cook (1997) and adapted to vehicle choice modeling by Greene (2001) has been applied here. In the face of great uncertainty this method has the advantage of insuring at least the plausibility of key estimates as well as providing a direct link between assumptions and model behavior. In general, the parameter values of the NRC (2013) study are used in all scenarios in this study.[7]

The LAVE-Trans model includes several feedback loops though which adoption of alternative vehicles and fuels generates network external benefits that drive down costs and increases the acceptability to consumers of the novel technologies and fuels. For example, in the LAVE-Trans model, consumers are

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[6] Model documentation can be found on line at http://www.nap.edu/openbook.php?record_id=18264&page=331 .
[7] One important parameter change was made for this study. The cumulative sales at which innovators' and early adopters' willingness to pay a premium for advanced technology vehicles decreases to one half its initial level was reduced from 2 million units to 1 milion units. This change raises the market barrier for advanced technologies.

divided into innovators/early-adopters and the majority. As vehicles are sold, the risk aversion of the majority is diminished while the preference for novelty of the innovators/early-adopters is likewise eroded. As more fuel cell vehicles are sold, more refueling stations are built. As more stations are built, the attractiveness of hydrogen fuel cell vehicles to consumers increases. As more vehicles are sold, costs approach long-run, high volume levels through the benefits of scale economies and learning-by-doing (e.g., Weiss et al, 2012). At present, quantitative knowledge about many of these relationships is weak. The approach taken in LAVE-Trans is to use best available data, informed by judgment, and to seek to narrow uncertainties over time as knowledge grows.

At the heart of the model are consumers' choices among alternative drive-train technologies. These choices are influenced by the prices and attributes of the drive-train technologies, but also by their familiarity and the availability of fuel for them. These factors together with consumers' preferences determine a quantitative index of utility for each alternative. As the prices and attributes of new vehicles change, vehicle sales may increase or decrease. The nested logit model allows the effects of these changes on consumers' satisfaction (consumers' surplus) to be measured in dollars.

Figure 3 illustrates the relationships between the major components of the model. The areas where exogenous inputs enter the model are shown as blue boxes. A relatively large amount of exogenous information is required to carry out a model run. Baseline projections of vehicle sales and energy prices are required to 2050. Technical attributes of advanced technology vehicles, including fuel consumption per km, on-board energy storage and retail price equivalent at full scale and learning, must be specified for current and certain future years. Parameters that determine consumers' willingness to pay for vehicles and their attributes must also be provided. The model translates these into coefficients for the vehicle choice model. Capital and operating costs of both electric and hydrogen infrastructure must also be provided. The LAVE-Trans model has been implemented as an Excel spreadsheet model comprised of 27 worksheets.

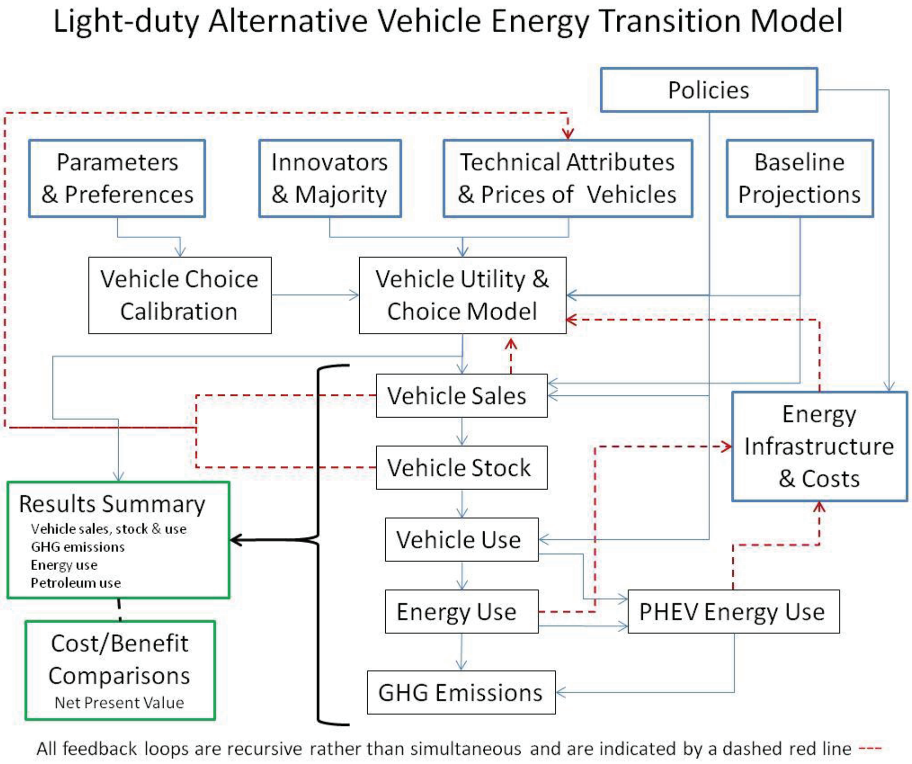

Figure 3. Diagrammatic Representation of the LAVE-Trans Model.

The model was calibrated to the 2011 Annual Energy Outlook Reference (AEO) Case projections of vehicle sales, vehicle use, energy use and energy prices (EIA, 2011). Given a starting sales projection, the Vehicle Choice model first estimates any changes to consumers' vehicle purchase decisions, then estimates the shares of ICE, HEV, PHEV, BEV and FCV technologies for passenger cars and light trucks for both Innovator/Early-adopter and Majority market segments. Sales are passed to the Vehicle Stock worksheet which retires vehicles as they age and keeps track of the number of vehicles of each technology type by model year, for every forecast year using the U.S. Department of Transportation's scrappage function (NHTSA, 2006). Vehicle kilometers by age and vehicle type depend on fuel prices and energy efficiency, are calculated in the Vehicle Use worksheet and are also based on NHTSA (2006). In the Energy Use worksheet energy use is calculated for all but PHEVs by multiplying vehicle kilometers by number of vehicles and by energy consumption per kilometer. PHEV use of electricity and gasoline depends on specified utility factors and is calculated in a separate worksheet. Well-to-wheel greenhouse gas, NO_x, HC, and PM10 emissions factors are applied in other worksheets to calculate total emissions.

The structure of the nested multinomial logit choice model is shown in figure 4. Consumers evaluate the three kinds of drive-trains that include internal combustion engines (ICE, HEV, PHEV) and compare the internal combustion alternatives with the battery electric and fuel cell options. At the lowest level in the diagram, choices are most price sensitive, reflecting the greater similarity (or degree of substitutability) of the choices. The choice between a passenger car and a light truck is less sensitive to price; the choice between buying and not buying a new car is assumed to have a price elasticity of -1, that is, a 10% increase in price will cause a 10% reduction in sales volume.

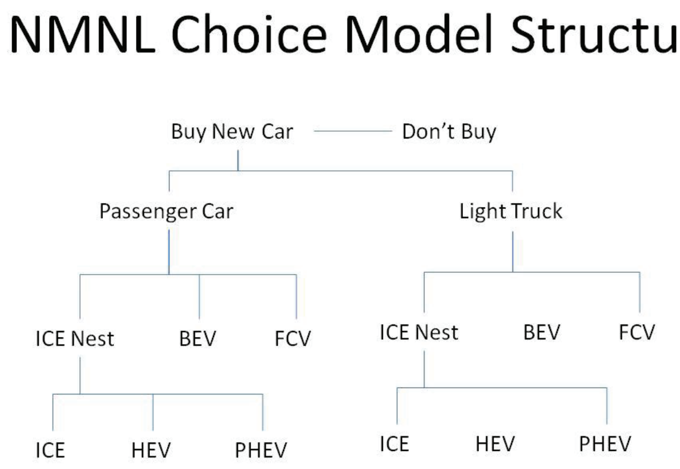

Figure 4. Choice Structure of the Nested Multinomial Logit Model

There are several important feedback loops in the model. Feedbacks are recursive (with a one year lag) rather than simultaneous. 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. Cumulative vehicle sales generate learning-by-doing effects that lower vehicle prices over time. Annual sales volumes create economies of scale which also lower prices. Sales are calculated in the Vehicle Sales worksheet and learning effects are calculated there, as well. Current sales affect not only scale economies but also the numbers of different makes and models, i.e., the diversity of choices available to consumers for both advanced and conventional ICE technologies. At low production volumes and low levels of cumulative production, the prices of alternative vehicles will be much higher than the long-run potential costs presented below in section IV.

The LAVE-Trans model also estimates the costs and benefits of a transition to electric drive vehicles. The effects of policies to induce transitions to alternative vehicles and fuels are estimated by comparing a Policy Case to a Base Case. The two cases are based on identical assumptions about technological progress and market conditions so that the difference between the two reflects only the impacts of the transition policies. The LAVE-Trans model produces 6 cost and benefit measures:

1. Net subsidies to vehicles and fuels
2. Value of changes in GHG emissions
3. Energy security value of changes in oil consumption
4. Value of changes in NO_x, HC, and PM10
5. Net change in consumers' surplus due to increased or decreased satisfaction with new vehicles
6. Value of fuel savings consumers may not have considered at the time of vehicle purchase

Category 6 is necessary because the vehicle choice model assumes that consumers consider only the first three years of (undiscounted) fuel savings when making vehicle purchases (Greene, 2011). Because the remaining fuel costs have economic value, they are calculated separately and added to the cost/benefit calculations.

The value per ton of GHG emissions avoided is based on the Interagency Working Group on the Social Cost of Carbon's (2010) High case which discounts future costs at a 2.5% rate, and rises from $35/ton CO_2 equivalent in 2010 to $65/ton in 2050 (figure 5). The value of reducing petroleum consumption is based on the EPA/NHTSA (2011) estimate of approximately $19/barrel for economic costs, to which is added $5/barrel for national defense costs, rounded to $25/barrel. Beginning in 2025, the cost per barrel gradually declines to $20 per barrel by 2050, reflecting a declining per barrel benefit as U.S. petroleum consumption decreases. Future costs are discounted to present value at 2.3% per year consistent with OMB (2012) guidance for cost-effectiveness analyses.

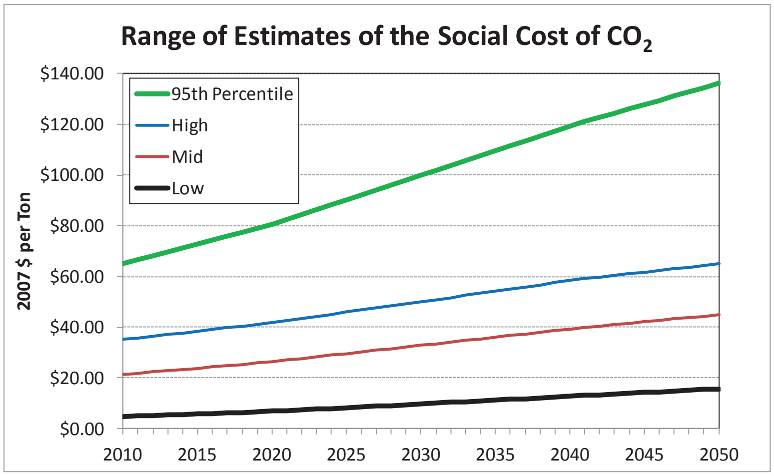

Figure 5. Range of Estimates of the Social cost of CO_2 Emissions (Interagency Working Group, 2010).

Two versions of the LAVE-Trans model, one representing California and the "Section 177" states[8] and another representing the rest of the U.S., were linked together for this study. Each was calibrated to the 2011 AEO based on the Census Regions to which each state belonged. Because individual states are not represented in the AEO model, this gives only an approximate calibration. The linkage between the two regions is recursive. Sales of vehicles and other outputs for California and the Section 177 states in year t are passed to the rest of U.S. model where they affect year t+1. Outputs of year t+1 in the U.S. model affect year t+1 in the California model. The total sales in the two regions affect vehicle prices via scale economies and learning, and reduce the risk aversion of the majority consumers. However, sales in one region do not affect hydrogen fuel availability or public recharging availability in the other region.

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[8] The Section 177 states are those that have adopted the California vehicle standards (CT, ME, MA, RI, VT, NJ, NY, PA, DE, MD, AZ, NM, OR and WA.)

IV. Advanced Vehicle Technology Scenarios

The future costs and energy efficiencies of advanced vehicle power-trains are of central importance to the transition to electric drive. The future attributes of electric drive vehicles are critical but so are those of the internal combustion engine vehicles with which they will compete in the market. The technology projections used in this study anticipate major advances in energy efficiency by all five technologies driven by continued tightening of fuel economy and greenhouse gas emissions standards beyond 2025.

The projections are taken from the National Research Council (2103) report *Transitions to Alternative Vehicles and Fuels* (Chapter 2 and Appendix F). The NRC Committee used a three-step method to estimate the potential for efficiency improvements in light-duty vehicles from 2010 to 2050. For the efficiency impacts and synergistic effects of ICE and HEV technologies, the Committee based its estimates on estimates derived from full vehicle simulation modeling. This allowed them to determine the efficiencies of component technologies, as well as losses in the drive-train and other parts of the vehicle system. The estimates were extrapolated to 2050, assuming that rates of improvement would slow down in the future and insuring that physical limits were not violated. The third step combined the estimates of future drive-train efficiencies and losses in a model that accounted for reductions in the factors that determine the energy required to propel a vehicle: mass, rolling resistance, aerodynamic drag and accessory loads.

The analysis was carried out for six drive-train technologies: ICE, HEV, PHEV, compressed natural gas vehicle (CNGV), BEV and FCV, five of which are included in this study (all but CNGV). Two sets of estimates, mid-range and optimistic, were created. The resulting energy efficiency estimates (in gallons per 100 miles) are compared with historical data for new light-duty vehicles in figure 6 (NRC, 2013). The data displayed in figure 6 are based on unadjusted test values for new vehicles sold in the indicated year and have not been discounted to reflect real-world driving conditions. The gallons per mile estimates are discounted by dividing by 0.85 in the LAVE-Trans model runs. Efficiency improvements to 2025 are consistent with the CAFE/GHG emissions standards now in effect through that date. After 2030 energy efficiency is expected to improve at half the 2005 to 2030 rate. In either case, vehicles in 2050 are highly efficient, about 70 miles per gallon for a typical ICE passenger car and 90 MPG for an HEV.

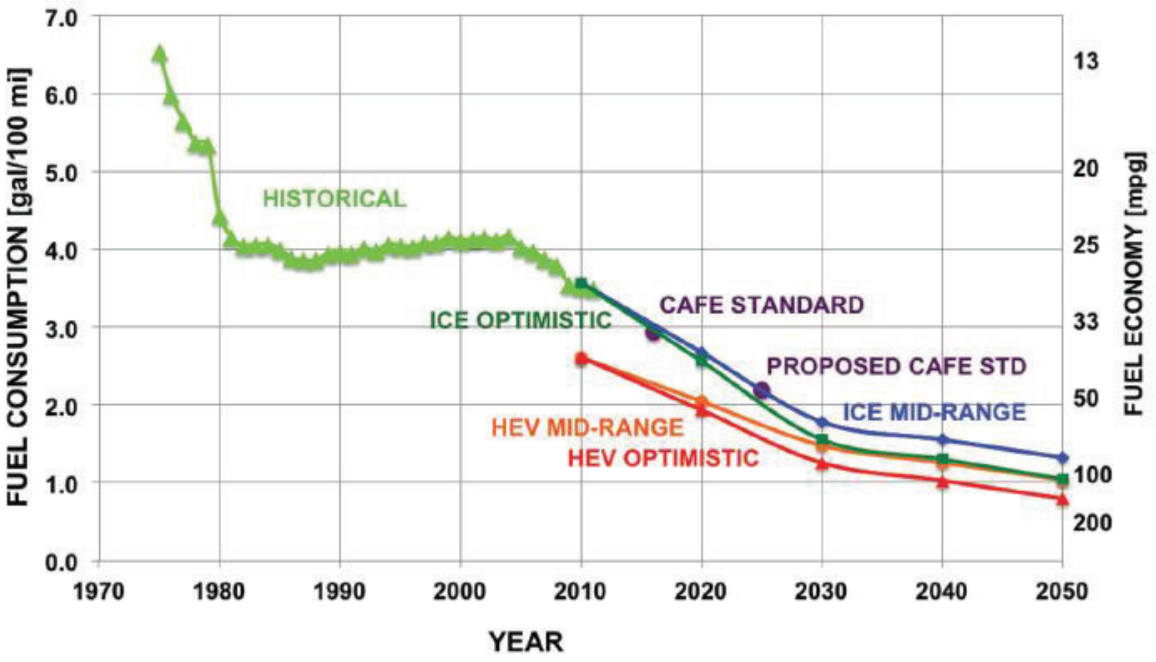

Figure 6. Energy efficiency projections of the NRC's (2013) *Transitions to Alternative Vehicles and Fuels* (Figure 2.1), used with permission of the National Academies Press.

The NRC (2013) assessment is one of the few that projects technological progress to 2050 and appears to be the only one that incorporates major reductions in vehicle loads (mass, aerodynamic drag, rolling resistance and accessories) and their synergistic benefits (e.g., engine downsizing, reduced battery size and weight, etc.) as well as energy conversion efficiencies. For example, in the mid-range case the weight of a typical passenger car in 2030 is 20% less than a 2010 vehicle; by 2050 a typical passenger car weighs 30% less than a comparable 2010 vehicle. Weight reductions for light-trucks designed for towing and hauling are smaller: 15% by 2030 and 22% by 2050. Aerodynamic drag and tire rolling resistances are also greatly improved.

Driven by increasingly rigorous fuel economy and emissions standards, the fuel economy of ICEs and HEVs increases nearly fourfold and that of BEVs and FCVs nearly doubles (figures 7a & 7b). PHEVs[9] are assumed to get the same fuel economy as BEVs when operating in charge-depleting mode and the same as HEVs when operating in charge-sustaining mode.

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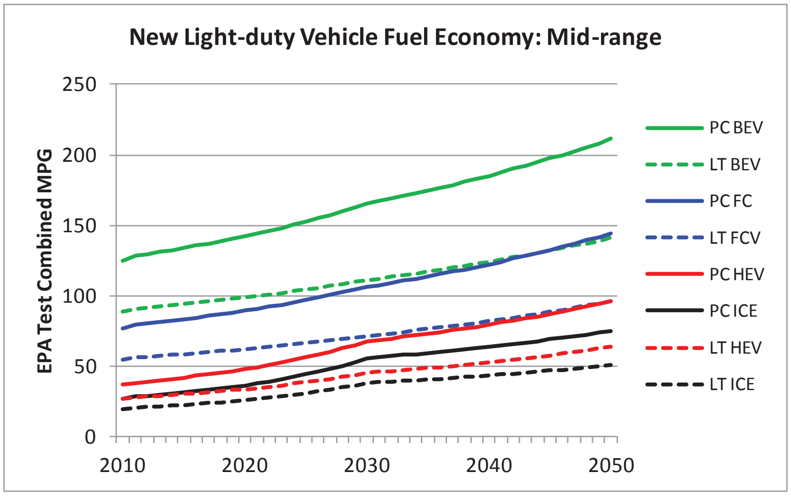
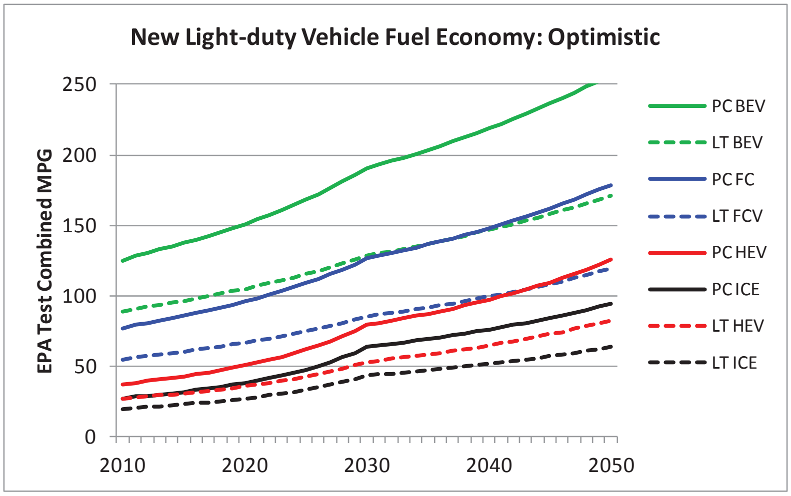
[9] PHEVs are assumed to be PHEV30s with a 25 mile all-electric real world range.



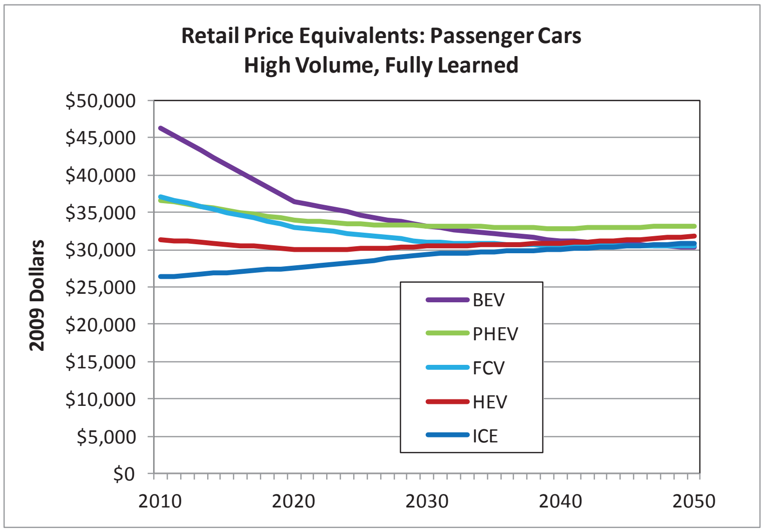
7(a)



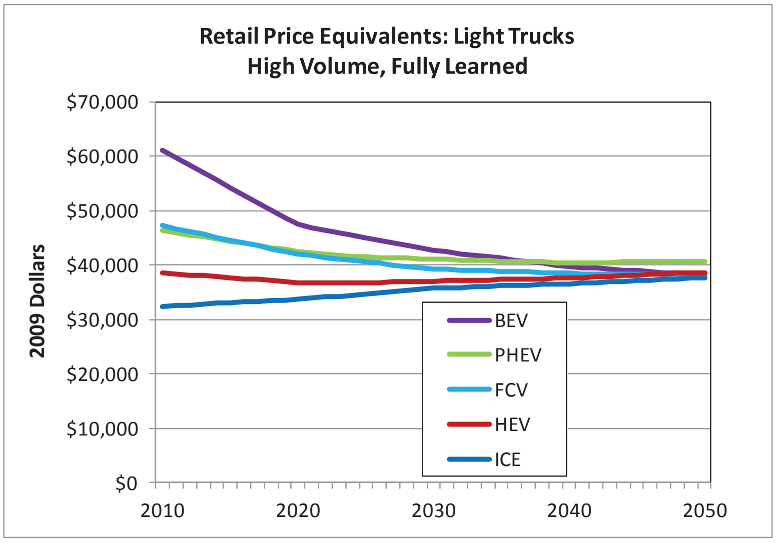
7(b)

Figure 7a and 7b. EPA Test Combined Fuel Economies by Technology Type: Mid-Range and Optimistic Estimates (NRC, 2013)

The NRC's longer time frame and focus on load reduction produced to two novel conclusions. First, because the cost of battery-electric and fuel cell power-trains scale more directly with power than ICE power-trains, load reduction is of greater value to these technologies. Second, unlike previous assessments extending to 2035 (e.g., Bandivedkar et al., 2008), after 2040 BEVs and FCVs become less costly than comparable ICEs or HEVs. PHEVs, on the other hand, remain a few thousand dollars more expensive through 2050 (figures 8a & 8b) because they require a powerful electric motor, an internal combustion engine and a substantial battery pack. Other studies have projected the narrowing of cost differences over time (e.g., element energy, 2011; McKinsey, 2011; Kromer and Heywood, 2007) but the crossover predicted by the NRC study is a new development. These new projections will increase the likelihood of accomplishing a self-sustaining transition to electric drive vehicles. The cost estimates shown in figures 8a and 8b assume fully-learned, high-volume production (at least 200,000 units per year). In the LAVE-Trans model, these costs must be achieved over time through cumulative production and the growth of market demand. Costs in the early years of a transition will be far higher.



8(a)



8(b)

Figures 8a and 8b. Retail Price Equivalents (Long-run Average Costs)[10] of Advanced Technologies at High Volume and Fully Learned, Mid-Range and Optimistic Estimates: Passenger Cars (NRC, 2013).

Battery and fuel cell system costs are key to the projections. The estimated costs of batteries are consistent with NHTSA and EPA (Joint TAR, 2011) estimates for 2025, and the fuel cell system costs for 2010 are consistent with high-volume, fully-learned cost estimates by James (2011). The reductions in high volume production costs are generally consistent with other projections of high-volume costs over the next 15-20 years. Based on historical learning rates Weiss et al. (2012) estimate that HEVs will reach a break-even price relative to conventional ICE vehicles in 2026, and that EVs will do the same in 2032. Battery electric vehicles were designed to have a 100 mile range. The range of battery electric vehicles is held constant over time, so that battery cost reductions translate directly into vehicle cost reductions. Plug-in hybrids were designed for a 25 mile real-world all-electric driving range.

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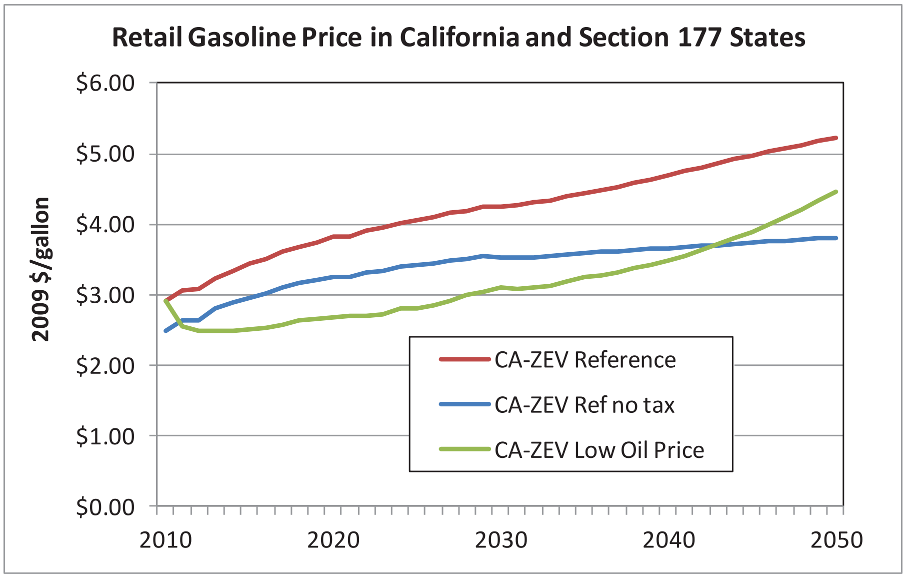
[10] Retail price equivalents include mark-ups over manufacturing costs and normal returns on investment.

Table 1. Estimated Future Costs of Automotive Battery and Fuel Cell Systems.

Technology	Units	2010	2030 (Mid/Opt)	2050 (Mid/Opt)
BEV battery	$/kWh	$450	$250/$200	$160/$150
PHEV battery	$/kWh	$550	$320/$260	$200/$190
HEV battery	$/kWh	$2,000	$750/$650	$650/$650
FC system	$/kW	$50	$33/$27	$27/$22

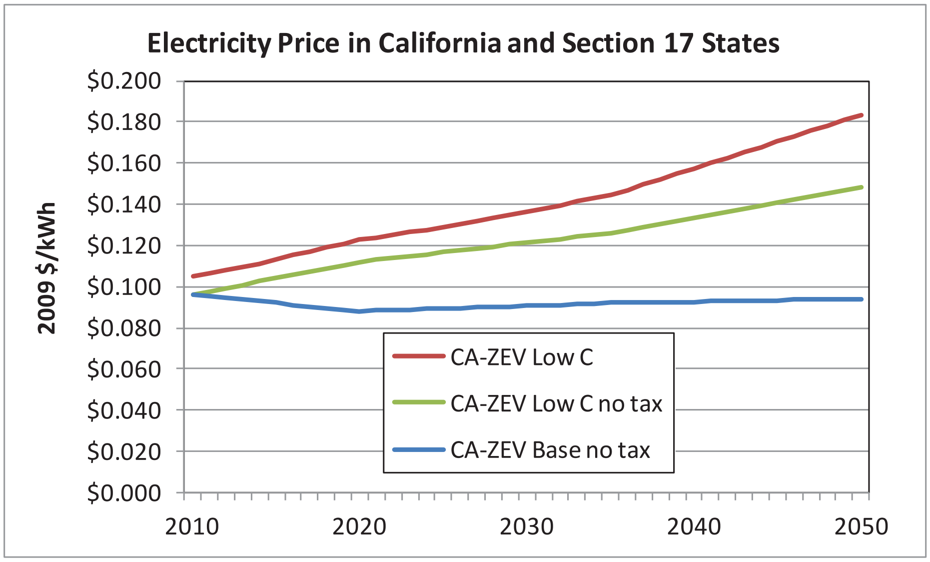
Reference energy prices are based on the Energy Information Administration's 2011 Annual Energy Outlook (EIA, 2011). Low carbon energy prices are from the NRC (2013) *Transitions* study. All forms of energy are assumed to bear road user tax. Prices of gasoline, electricity and hydrogen for highway use are shown in figures 9a-9c. Regional prices were calculated by weighted averaging of prices for relevant Census Regions, provided in the EIA projections. In all scenarios, low-carbon hydrogen and a low-carbon electricity grid were assumed, and an indexed highway user fee (IHUF) was added to the price of all fuels. The indexed highway user fee assigns the motor fuel tax to all forms of energy used by light-duty vehicles and indexes the fee to the average miles per gallon of the entire vehicle stock. This prevents Highway Trust Fund revenues from being eroded by fuel economy improvements and insures a constant average level of revenue per vehicle mile traveled (Greene, 2011).

Assuming the AEO Reference Oil Price projection and including the IHUF, gasoline prices rise from $3/gallon in 2010 to over $5/gallon by 2050 (figure 9a). Approximately $1 of that increase is due to the IHUF. The AEO Low Oil Price projection foresees prices dropping quickly and remaining at least a dollar below the Reference prices until after 2040.



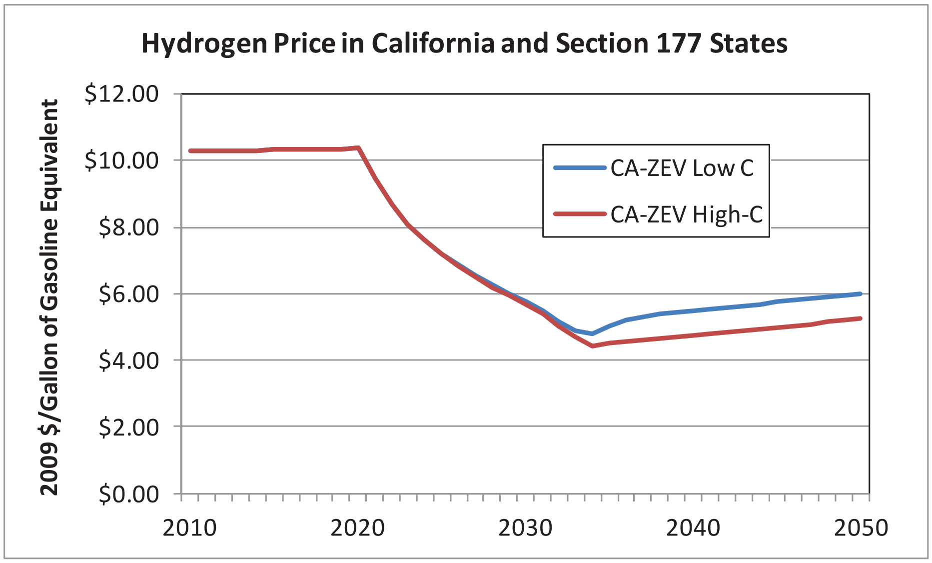
(9a)

Imposing road user taxes on electricity initially adds about 1 cent per kWh to the average retail price. In the long run the IHUF grows to almost 4 cents per kWh. The cost of low carbon electricity increases gradually to about 5 cents per kWh in 2050. The costs are based on the NRC (2013) *Transitions* study which also starts with the AEO 2011 energy price projections.



(9b)

The retail price of hydrogen is initially above $10/kg due to the high cost of supplying hydrogen in small volumes and the high cost of operating refueling outlets below design capacity. The cost of hydrogen in a scenario thus depends on the quantities sold. Low GHG hydrogen, which becomes available after 2030, costs approximately $0.75/gge more than hydrogen produced from natural gas without carbon capture. Hydrogen prices are also taken from the NRC (2013) *Transitions* study.



(9c)

Figures 9a, 9b and 9c. Energy Prices Used in the LAVE-Trans Model Runs.

All the scenarios considered in this report assume that the energy sources for advanced vehicles will be de-carbonized. The well-to-wheels greenhouse gas emission estimates and costs of de-carbonization are taken from the NRC (2013) report. Details can be found in chapter 3 and appendix G of that report. The fossil carbon content of gasoline is gradually reduced by the replacement of up to 38% of gasoline with synthetic gasoline derived from biomass via pyrolysis and refining. U.S. average emissions are shown in figure 10; emissions from electricity and other fuels in California will be lower due to the different primary energy sources used to generate electricity and the Low Carbon Fuels Standard. At low volumes, hydrogen is assumed to be produced from fossil fuels without carbon capture and storage. Once hydrogen use begins to increase rapidly, the additional hydrogen is assumed to be produced primarily from renewable energy or natural gas with carbon capture and sequestration. Although the carbon intensity of electricity is initially very high, the much greater energy efficiency of electric vehicles more than offsets the difference. In the long-run the carbon intensity of electricity is decreased to less than one-fourth of its 2010 level.

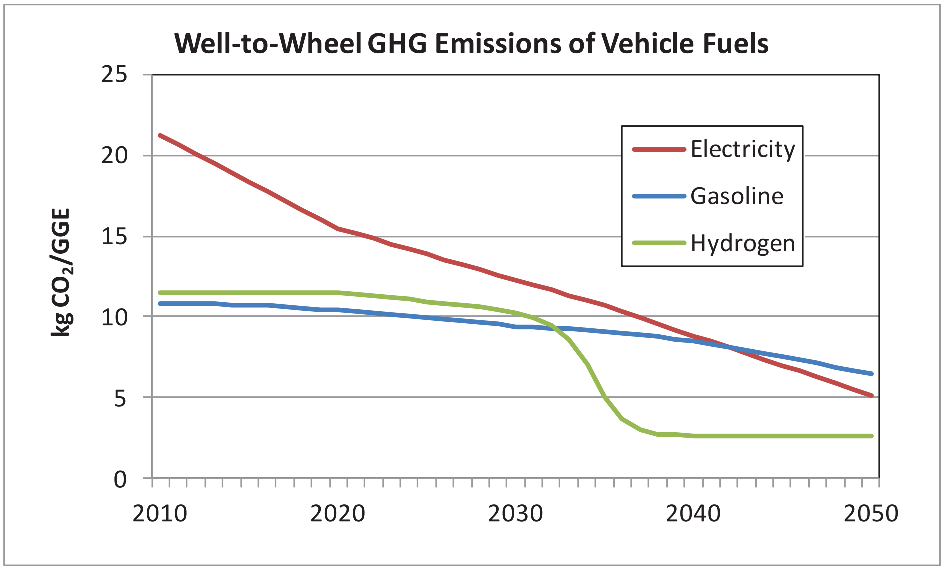


Figure 10. Well-to-Wheel Greenhouse Gas Emissions from Vehicle Fuels, U.S. Averages.

The above assumptions about vehicle efficiencies and well-to-wheel GHG emissions are consistent with the premise that society is making a strong and sustained effort to reduce GHG emissions and petroleum dependence. This seems to be the most appropriate context in which to assess the transition to electric drive vehicles.

V. The Transition to Electric Drive in California and the Section 177 States

Transitioning to electric drive vehicles is a complex process that requires policy initiatives of many types, from adjusting codes and standards to mandates or subsidies for vehicles and fuels (e.g., Gallager et al., 2012). In the scenario analyses that follow we focus on just two: 1) early provision of refueling and recharging infrastructure through mandates and/or subsidies and, 2) incentivizing early vehicle sales through subsidies and/or mandates. This is done to simplify the modeling and is not a policy recommendation. In fact, who pays the additional costs of the early infrastructure and electric drive vehicle sales is not specified. Current policies are continued until they expire. In the future, governments may elect to subsidize all or part of the additional transition costs or may transfer the burden to vehicle manufacturers and energy suppliers by means of regulatory requirements.

Two key policies are assumed to remain in effect and be strengthened over time: 1) fuel economy and emissions standards and 2) renewable and low carbon fuels standards. The effect of fuel economy standards was described in the previous section. Consistent with the assumptions of the NRC's *Transitions to Alternative Vehicles and Fuels* report, ethanol continues to be blended with gasoline up to 10 billion gallons per year gasoline equivalent. Additionally, "drop-in" biofuel, chemically equivalent to gasoline, is produced from cellulosic biomass via pyrolysis and refining. It is expected to cost $3 to $4 per gallon, before tax. Total U.S. production grows to 13.5 billion gallons in 2030 and remains at that level through 2050 (NRC, 2013, p. 92).

The California Zero Emission Vehicle Standard is the key policy promoting the early marketing of electric drive vehicles in California and the Section 177 states. The standard is a technology-neutral performance requirement that mandates that a portion of each major manufacturer's sales must have zero tailpipe emissions (Shulock et al., 2011). The latest Air Resources Board staff estimates suggest that in the initial phase in years 2015-2017, manufacturers are likely to sell 6,500 to 7,000 hydrogen fuel cell vehicles (FCVs), approximately 20,000 battery electric vehicles (BEVs) and 80,000 transitional zero emission vehicles (most likely plug-in hybrid electric vehicle: PHEVs) in California and Section 177 states. The heavy weighting in favor of plug-in vehicles partly reflects the "travel" provision of the ZEV mandate, which allows fuel cell vehicles sold in California to count in the other Section 177 states. The provision reflects the earlier presence of plug-in vehicles in the market, as well as the initial challenge of establishing a hydrogen refueling infrastructure. Through 2025, the ARB estimates sales of nearly 1 million TZEVs, about 385,000 BEVs and approximately 170,000 FCVs. An alternative ZEV scenario was constructed that eliminates the travel provision after 2017. Detailed assumptions about vehicles sales under the ZEV scenarios can be found in appendix tables A.1 and A.2.

California's plan for deploying hydrogen refueling stations begins with the strategic placement of 68 stations in five linked clusters (CAFCP, 2012) during a pre-commercial period from 2012 to 2014 (Table 2). Clustering the stations allows a density of hydrogen stations equivalent to about 5-7% of the gasoline stations in the local areas where they will be clustered. This will be far less than 5-7% of the gasoline stations in California; more like 0.5-0.7%. Once these stations are in place, the plan is to increase the number of stations as vehicles sales grow. The California Fuel Cell Partnership's (CAFCP) 68 station deployment plan is the basis for our assumptions about early hydrogen station availability. In the scenarios testing lifting of the travel provision, the 68 stations are factored up to 204 to reflect the larger California + Section 177 states market. When the rest of the U.S. adopts similar transition policies, 324 mandated or subsidized stations are assumed to be deployed before 2020. Once the early infrastructure has been deployed, the number of stations is assumed to increase with hydrogen demand. The CAFCP's plan calls for 53,000 FCVs on the road in California by the end of 2017, far more than anticipated by the ARB's projection of ZEV sales requirements.

Table 2. Station Deployment and Expected FCV Sales in California: ARB and CAFCP Estimates

Station Deployment and Expected Vehicles Sales in California					
Year	Start of Year Station Total	Added Stations	CAFCP Number of Vehicles on the Road	CAFC Sales	Estimated Minimum ZEV Sales Requirement
2012	4	4	312	100	0
2013	8	9	430	118	0
2014	17	20	1389	959	0
2015	37	31	10000	8611	2134
2016	68	Market needs	20000	10000	2269
2017	*84*	Market needs	53000	33000	2297
2018	*100*	Market needs	*95000*	*42000*	2943
Sources: CAFCP, 2012, table 5; ICCT estimates.					
Numbers in italics have been approximated based on lower bounds given in CAFCP table 5.					

Not only are PEVs (PHEVs + BEVs) less dependent than FCVs on the deployment of infrastructure, but the current and planned deployment of recharging infrastructure is much farther advanced. The California Plug-in Electric Vehicle Collaborative (CAPEVC, 2010) reported that installation of more than 7,500 residential and public recharging stations in California was receiving public support, including 50 public DC fast-charging stations. In addition, the scenarios presented below assume that half of the BEVs sold and 20% of the PHEVs sold will be purchased with level 2 home rechargers, that 1 public level 2 charger will be installed for every 20 PHEVs or BEVs and 1 public DC fast charger will be installed for every 1,000 BEVs sold.

Given this basic policy framework, scenarios were constructed along four principal dimensions (Table 3):

1. Subsidy and infrastructure policies of CA and Section 177 states
2. Subsidy and infrastructure policies of the rest of the US
3. Sales of PEVs and FCVs outside of the US
4. Rate of technological progress
5. The 2011 AEO High, Reference and Low Oil Price Projections

Each scenario has its own "Base Case" for the purpose of calculating costs and benefits. A scenario's base case includes identical assumptions about technologies' energy efficiencies and costs, and about fuel prices. On the policy side, the base cases assume that fuel economy/emissions standards are in effect and that highway trust fund revenues are maintained by means of a user fee on energy indexed to the average energy efficiency of all vehicles on the road.[11] This maintains a level of revenue per vehicle mile that does not change as the energy efficiency of the vehicle stock improves. Beginning in 2018 the strict fuel economy and emissions standards necessary to drive the dramatic improvements in fuel economy shown above in figure 6 are assumed to induce pricing of the alternative technologies that

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[11] In this case, the highway user fee is indexed to the average efficiency of the stock of light-duty vehicles since other vehicle classes are not included in the model.

reflects their greenhouse gas emissions and petroleum use.[12] However, the current tax credits for advanced technology vehicles are assumed to expire after 2014, to be replaced or not by transition policies.

It is further assumed that the combination of the federal Renewable Fuels Standard and California's Low Carbon Fuel Standard lead to 13.5 billion gallons of low-carbon gasoline produced from biomass via thermo-chemical conversion processes in addition to 10 billion gallons of ethanol produced from corn. These are strong policy assumptions and go a long way to reducing light-duty vehicle GHG emissions on their own. In all cases, decarbonization of the electricity grid is assumed, as is low-carbon production of hydrogen. By 2050 each kWh is responsible for 150 g of CO_2, and each kg of hydrogen consumed is associated with 2.7 kg of CO_2. This compares with 11.2 kg per gallon of gasoline today.

Scenario 1 ("California Leads") is a pessimistic policy scenario that assumes the rest of the U.S. does not follow the lead of California and the Section 177 states and does not implement policies to promote a transition to electric drive vehicles. It further assumes that the rest of the world is not transitioning to electric drive. **Scenario 2** ("California Leads/US Follows") assumes that the rest of the U.S. follows the California + Section 177 states lead starting in 2020, five years after the start of mandated ZEV sales in California in 2015. Two variations on Scenario 2 were created. The first tests the effects of oil prices on the transition by re-running Scenario 2 with the LAVE-Trans model calibrated to the 2011 High and Low Oil Price Cases. The second estimates the effect of eliminating the ZEV mandate's "Travel Provision", a rule that allows FCVs sold in California to count in the Section 177 states and vice versa. **Scenario 3** ("Global Transition") adds an independent world sales scenario to Scenario 1 (figure 11). In the Global Transition scenario, overall penetrations of PEVs and FCVs are similar to the assumptions of the International Energy Agency's 2° C scenario but with greater emphasis on BEVs and FCVs and less on PHEVs (IEA, 2012, pp. 445-446). **Scenario 4** ("No early infrastructure") tests in the context of Scenario 2 how the failure to insure that refueling infrastructure is present before market commercialization might affect the market acceptance of fuel cell vehicles. **Scenario 5** ("Better Technology", Scenario 1) explores the impact of the ZEV program using the optimistic technology assumptions but in the context of Scenario 1 with no comparable U.S. or world program. **Scenario 6** ("Better Technology", Scenario 2) examines the effect of better technology when the rest of the U.S. does follow California in implementing transition policies, as in Scenario 2.

None of the scenarios reflects uncertainty about the market's response to alternative vehicles and fuels. Instead, a sensitivity analysis was carried out for Scenario 2 using Monte Carlo simulation to illustrate the importance of consumers' preferences and the need to better understand likely market behavior. The simulation results were analyzed to identify the key parameters likely to affect the transition to electric drive vehicles.

The scenarios are not predictions of the future. Not only are they conditional on assumptions about technological progress and market behavior, but the modeling of energy transitions is still in an early

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[12] The strict fuel economy and emissions standards are assumed to induce a "shadow price" on vehicle's expected GHG emissions and petroleum use, reflecting the vehicle's value to a manufacturer constrained to meet strict fuel economy and emissions standards. The value is set equal to the social value of reducing GHGs and petroleum.

stage of development. Nevertheless, they can provide insights about the nature of the transition, the factors on which its success are likely to depend, and a sense of the sizes of the costs and benefits of the transition to electric drive. All of these are conditional on the premises and assumptions just described.

Table 3. The Seven Electric Drive Vehicle Scenarios

Scenarios	CA + S177 States' Policies	Rest of US Policies (with 3-year lag)	Rest of World Sales (Exogenous)	Vehicle Technology	Energy Prices
1	Infrastructure + Vehicle Subsidy	NO	NO	Expected	2011 AEO Reference
2	Infrastructure + Subsidy	Infrastructure + Subsidy	NO	Expected	2011 AEO Reference, High and Low
3	Infrastructure + Subsidy	NO	Introducing Rest of World Sales	Expected	2011 AEO Reference
4	Subsidy Only	Subsidy Only	NO	Expected	2011 AEO Reference
5	Infrastructure + Subsidy	NO	NO	Optimistic	2011 AEO Reference
6	Infrastructure + Subsidy	Infrastructure + Subsidy	NO	Optimistic	2011 AEO Reference

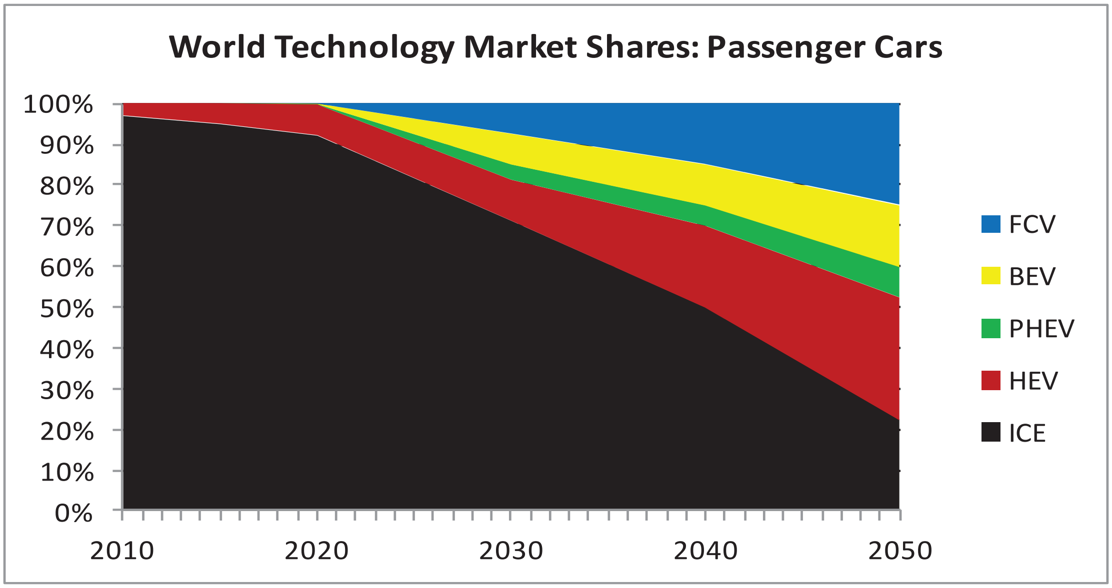

Figure 11. World Scenario Technology Market Shares: Passenger Cars

a. Base Case: No ZEV Program

The No-ZEV case serves as a point of comparison for all the scenarios. It is the Base Case against which all are compared. The No-ZEV case includes very significant policy actions. California and federal fuel economy and emissions standards are continuously tightened to produce the fuel economy improvements shown above in section III, figures 7a and 7b, as well as the manufacturer pricing strategies the standards induce. It also includes the Indexed Highway User Fee on all vehicle energy use and 13.5 billion gallons gasoline equivalent of drop-in biofuels. These actions reduce 2050 petroleum use by and estimated 66% relative to 2005, and greenhouse gas emissions by 55%.

However, plug-in hybrids and fuel cell vehicles never achieve significant market shares because the existing tax incentives, assumed to expire in 2015, are insufficient to overcome the barriers to market acceptance. Battery electric vehicles eventually succeed, but their annual sales do not exceed 20,000 units per year until after 2035 (figure 12). After that point, sales take off, eventually capturing an estimated 38% of the market in 2050.

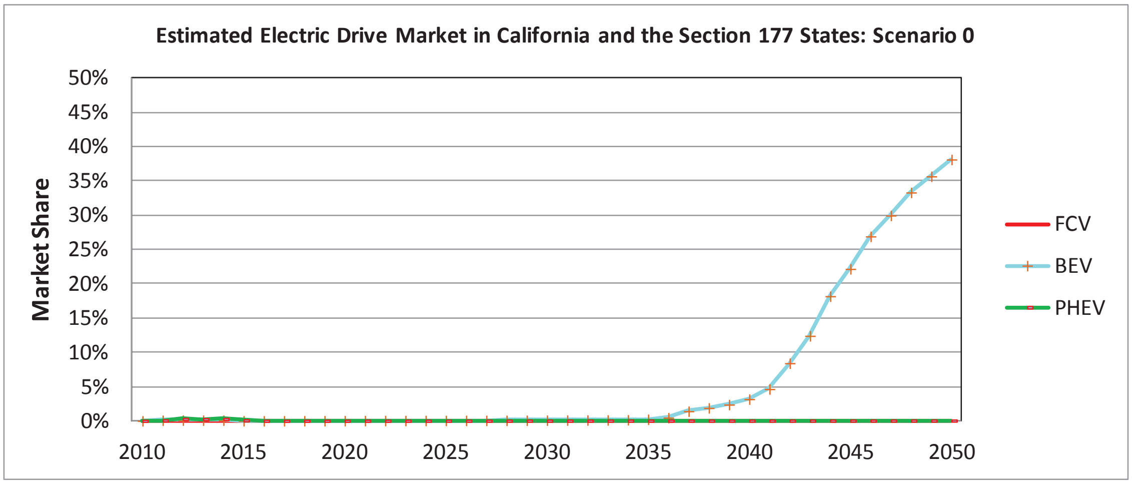

Figure 12. Estimated Electric Drive Market in California and the Section 177 States: Scenario 0.

The estimated eventual market success of BEVs is attributable to their low operating costs and low initial price which from 2040 to 2050 is below that of advanced ICEs. The remaining scenarios explore what additional benefits might be obtained by pursuing the ZEV mandates combined with early infrastructure provision in California and the Section 177 states and similar policies in the rest of the U.S.

b. Scenario 1: California Leads

The first scenario estimates what could happen if California and the other states that have adopted the ZEV standards follow through with the ZEV requirements and provide early infrastructure for plug-in and hydrogen fuel cell vehicles, but the rest of the US does not adopt any specific transition policies. This does not mean there are no relevant policies in effect outside of California and the Section 177 states. As in all scenarios the indexed highway user fee concept is assumed to be implemented throughout the nation, causing energy costs to rise with the improvement in the average fuel economy of the vehicle stock. Likewise, manufacturers use pricing of alternative technologies to help them meet fuel economy/emissions standards and the CAFE-induced pricing favors ZEVs.

If the rest of the U.S. allows existing policies to expire and makes no additional effort whatever to promote electric drive vehicles, the model runs indicate that a far greater number of electric drive vehicles will be sold throughout the U.S. as a consequence of the ZEV mandates. In Scenario 1, the ZEV standards drive the sales of plug-in hybrid, battery electric and hydrogen fuel cell vehicles in California and the Section 177 states through 2025. After 2025 the ZEV requirements are held constant (at the same number of vehicles of each type) through 2030. However, in all cases the mandates are no longer binding on manufacturers after 2030 and are frequently non-binding earlier.

Keeping in mind the very large uncertainties about the market's response to electric drive vehicles, it appears that substantial explicit (governmental) and/or implicit (manufacturer) subsidies may be required to meet the mandated ZEV sales through 2025. The LAVE-Trans model does not distinguish among types or sources of subsidies but rather calculates the total monetized subsidy required to achieve the level of sales required by the ZEV standards. In reality, subsidies could come as tax incentives, rebates, manufacturer price reductions, free parking, HOV lane access or any other policy that makes the new vehicle technologies more attractive to consumers. However, the estimated subsidies are in addition to manufacturers' pricing of vehicles to help meet national fuel economy and emissions standards.

Subsidies in the historical years from 2010 to 2012 were estimated to match the model's estimates to actual sales of PHEVs and HEVs (figure 13). These subsidies are substantially higher than the combined $7,500 federal tax credit and California's $2,500 credit, suggesting that manufacturers were also subsidizing the earliest sales. The implied subsidies start at roughly $10,000 per FCV and $15,000 per BEV or PHEV in 2015 (figure 13). They increase to $12,000 and $22,000 per vehicle, respectively, in 2018 because the federal subsidies for fuel cell and plug-in vehicles are assumed to end in 2016 while the ZEV requirements are increasing. The estimated subsidies decline steadily after 2018. After 2025, it is assumed that the ZEV program flatlines, i.e., continues at the same level as 2025. By 2030 no further subsidies are required, implying that the ZEV mandates are no longer binding and the market for ZEVs in California and the Section 177 states is sustainable.

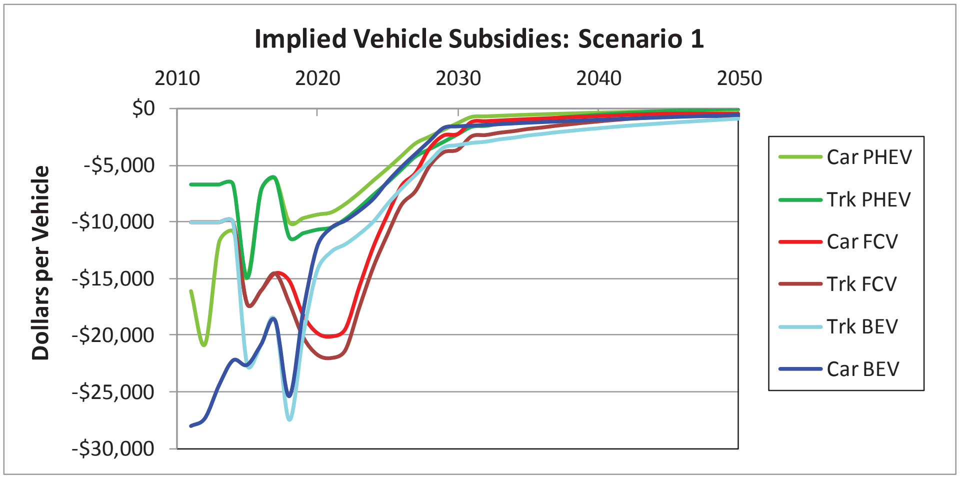

Figure 13. Implied Subsidies to Achieve the ZEV Mandate Sales in California and the Section 177 States

Sales of electric drive vehicles track the ZEV requirements through 2025. Just before 2030, sales of BEV's begin to accelerate and in the absence of any subsidies increase steadily, reaching a sustainable share of about 30% of the market in 2045 (figure 14a). Sales of PHEVs are slower to take off; they begin to exceed the ZEV mandate levels just after 2030, eventually climbing to an 18% market share. FCV sales on the other hand remain at very low levels until about 2045 and reach 15% of the market in 2050.

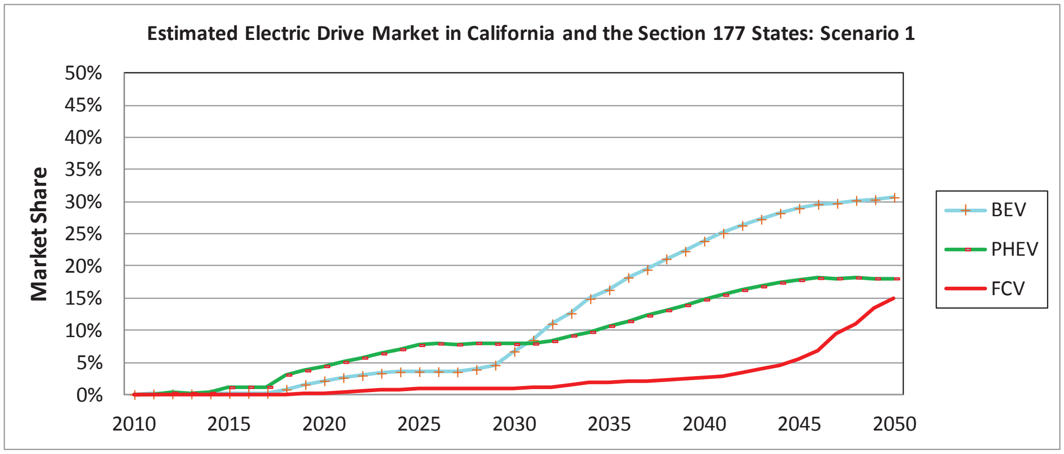

Figure 14a. Estimated Electric Drive Market Shares in California and the Section 177 States: Scenario 1

Scenario 1 includes early installation of hydrogen refueling infrastructure in California: 68 stations are assumed to be in operation before 2015, consistent with the roll-out strategy of the California Fuel Cell Partnership (2012). Implied subsidies for FCVs can be reduced and the ultimate market share substantially increased by providing additional early infrastructure. The rest of the U.S. is assumed to do nothing to promote sales of hydrogen fuel cell vehicles. No hydrogen stations are deployed in advance of FCV sales. No incentives for FCVs are offered after the existing incentives expire in 2016. As a consequence, no significant numbers of FCVs are sold outside of California and the Section 177 states (figure 14b). This hinders the evolution of the FCV market in the ZEV region, by slowing down achievement of scale economies and the reduction of the majority's risk aversion and restricting the diversity of choice. Scenario 1 does not consider the potential impact of FCV sales in the EU or Asia, which is the subject of Scenario 3. As will be seen, scenario 3 indicates that deployment of FCVs in the rest of the world could greatly accelerate FCV sales in the ZEV region, even if the rest of the US does not follow their lead.

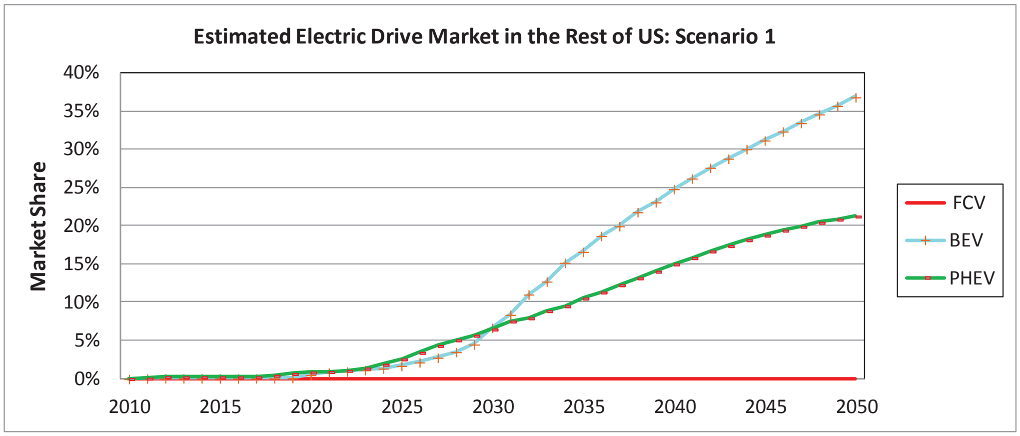

Figure 14b. Estimated Electric Drive Market in the Rest of the US: Scenario 1

Despite the absence of national transition policies, the ZEV program is estimated to be sufficient to break the transition barriers for EVs and PHEVs, such that they become self-sustaining without implicit subsidies after 2030 (figure 14). Without a national program to promote a transition to hydrogen FCVs, however, sales remain well below 5% of the market through 2040 but do not disappear despite the absence of FCV-specific subsidies. FCV sales eventually begin to take off around 2045, reaching a 15% market share by 2050.

FCV sales could grow rapidly if even a small number of hydrogen stations were deployed in the rest of the U.S. Figure 15a and 15b illustrate the potential impact of deploying 68 stations in the rest of the U.S. starting with 8 in 2020, followed by 20 in 2021 and 40 in 2022. Station deployment in advance tips the scales in favor of FCVs leading to rapid market penetration after 2035 and a 45% market share in 2050.

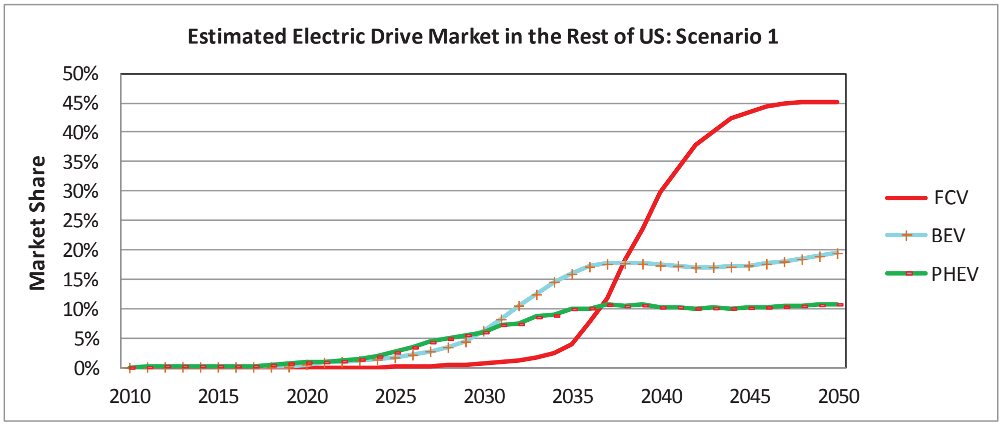

Figure 15a. Estimated Electric Drive Market in the Rest of the U.S.: Scenario 1 with Hydrogen Station Deployment Outside of the ZEV Region.

The LAVE-Trans Model estimates that just this small change would lead to a 75% market share for electric drive vehicles by 2050. However, there are so many uncertainties that the estimates should not be taken literally. The key inferences are: 1) that U.S. policy to promote fuel cell vehicles is likely to be very important to the evolution of the market in California, 2) that in the absence of any supporting transition policies and especially advanced deployment of hydrogen refueling infrastructure a transition to hydrogen FCVs is highly unlikely, 3) that the transition process almost certainly has tipping points at which small additional efforts can have very large impacts.

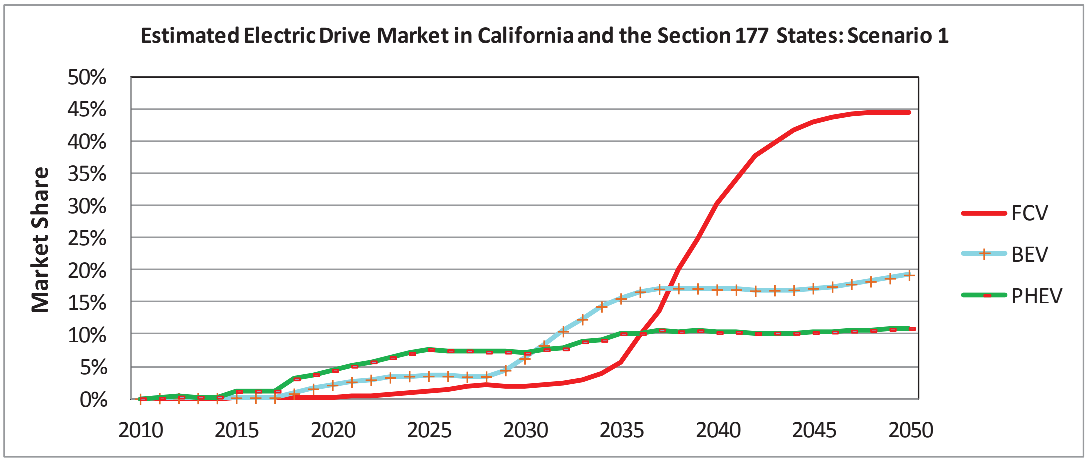

Figure 15b. Estimated Electric Drive Market in California and the Section 177 States: Scenario 1 with Hydrogen Station Deployment in the Rest of the U.S.

By 2030, GHG emissions in California and the Section 177 states are estimated to be 30% below 2005 levels and petroleum use is 38% lower. By 2050, GHG emissions are estimated to be 68% lower than 2005 while petroleum use is reduced by 81% in comparison to 2005.

The scenario's costs and benefits are calculated based on changes from the Base Case (figure 16). The estimated net benefits of the transition, although they come late in the period due to the absence of national transition policies, are substantially greater than the estimated costs. This is despite the fact that the rest of the US is assumed to implement no policies to promote a transition advanced, clean vehicle technologies after 2015. Still, an estimated $43 billion in implied subsidies in California and the Section 177 states gains an estimated $192 billion in total benefits from GHG mitigation, reduced petroleum dependence, consumers' increased satisfaction with the range of technology choices, air quality improvement and energy savings not accounted for by new car buyers in their purchase decisions. The value of additional energy savings alone exceeds the implied subsidies by $54 billion, largely due to the much lower energy costs of plug-in vehicles. The costs are paid up front, however, and the benefits come later. Net present value is negative until after 2025.

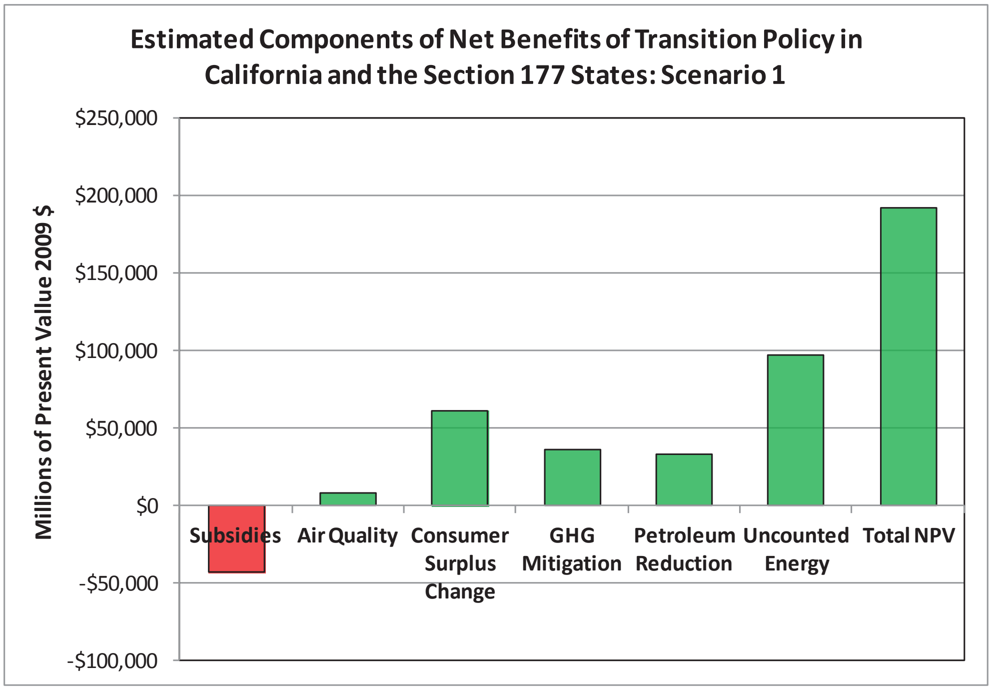

Figure 16. Estimated Components of Net Benefits of Transition Policy in California and the Section 177 States: Scenario 1. (discounted to present value at 2.3% per year).

c. Scenario 2: California and the Section 177 States Lead, Rest of U.S. Joins

Success of the ZEV program in California and the Section 177 states is likely to induce other states and the federal government to join in the effort. In Scenario 2 the rest of the U.S. adopts similar transition policies with a five year lag. U.S. transition policies include both early infrastructure deployment and mandates or subsidies for ZEVs, however, the per-vehicle subsidies are lower than required to meet ZEV requirements because of the external benefits created by the ZEV mandate. The result is an earlier and more successful transition to ZEVs than seen in Scenario 1, not only in California and the Section 177 states but throughout the U.S. By 2050, 75% of new vehicle sales are FCVs, PHEVs or BEVs and most of the remainder are HEVs (figure 17). Because the transition begins almost a decade earlier than in Scenario 1, 60% of the light-duty vehicles on the road are estimated to be electric drive by 2050 and another 15% are hybrid vehicles.

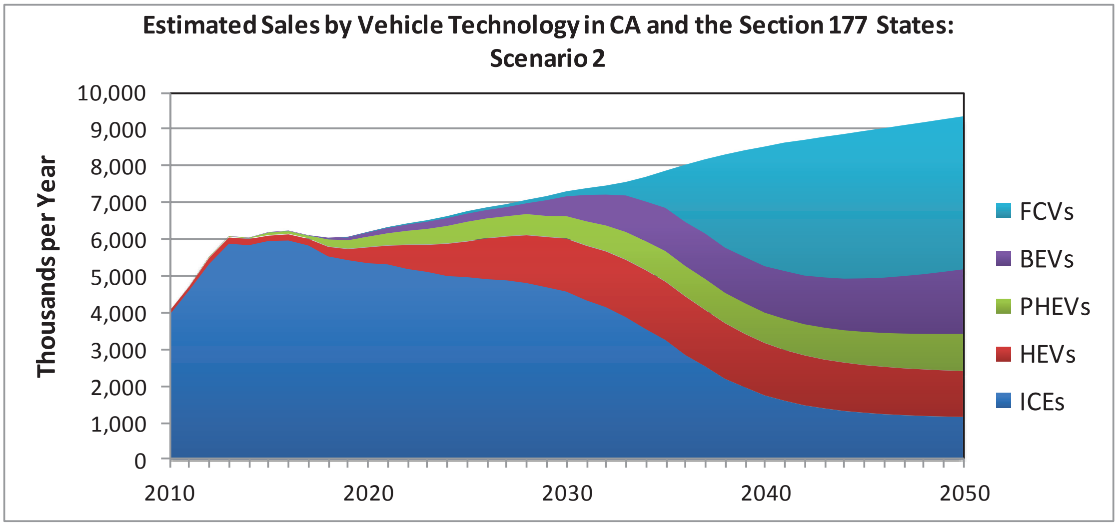

Figure 17. Estimated Sales by Technology in California and the Section 177 States: Scenario 2.

The transition to electric drive vehicles, combined with low-carbon electricity, hydrogen and gasoline (4.6 billion gallons or 35% of which is produced thermo-chemically from biomass), achieves a 79% reduction in GHG emissions[13] and virtually eliminates petroleum use by light-duty vehicles by 2050 (figure 18).

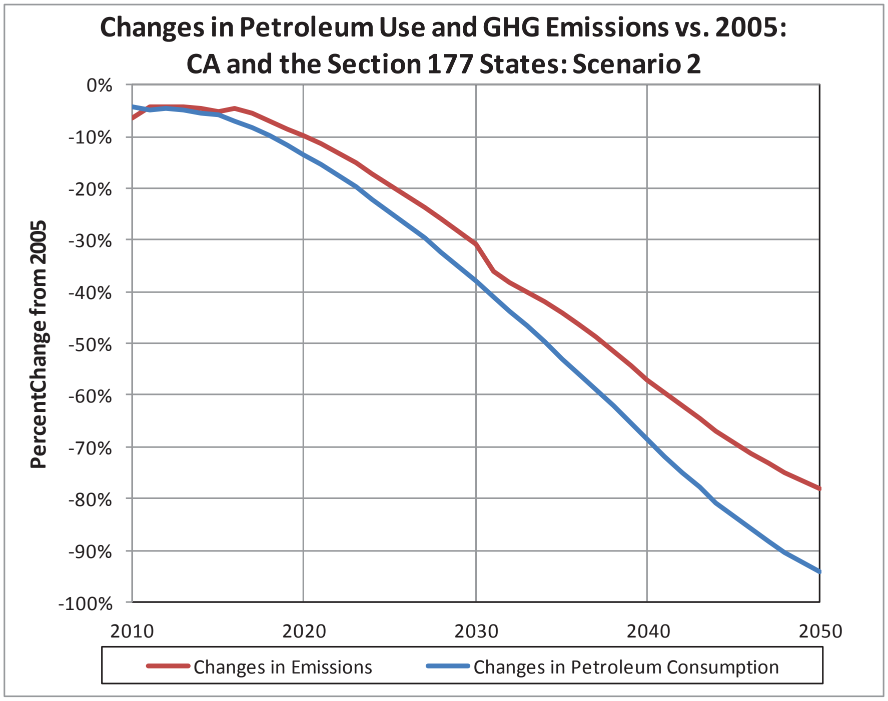

Figure 18. Changes in Petroleum Use and GHG Emissions vs. 2005 in California and the Section 177 States: Scenario 2

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[13] The "hump" on the GHG emissions curve is caused by accounting for the indirect land use effects of biomass production at the time the production is initiated rather than amortizing it over the life of the activity.

Although substantial costs must be borne up front, the net present value of the transition to e-drive vehicles appears to be very large (figure 19a). The present value of explicit and implicit subsidies for vehicles and infrastructure is estimated at $3.4 billion annually (present value) in the peak years and adds up to an estimated $36 billion total present value. The fact that the costs must be paid up front causes the total net present value to be negative for almost a decade. The overall net present value of the transition amounts to more than a quarter of a trillion dollars ($294 billion), comprised of consumers' surplus benefits derived from a greater range of choice among vehicle technologies, roughly equal values for GHG mitigation, reduced petroleum dependence and energy savings not counted by new car buyers at the time of purchase, followed by significant air quality improvements.

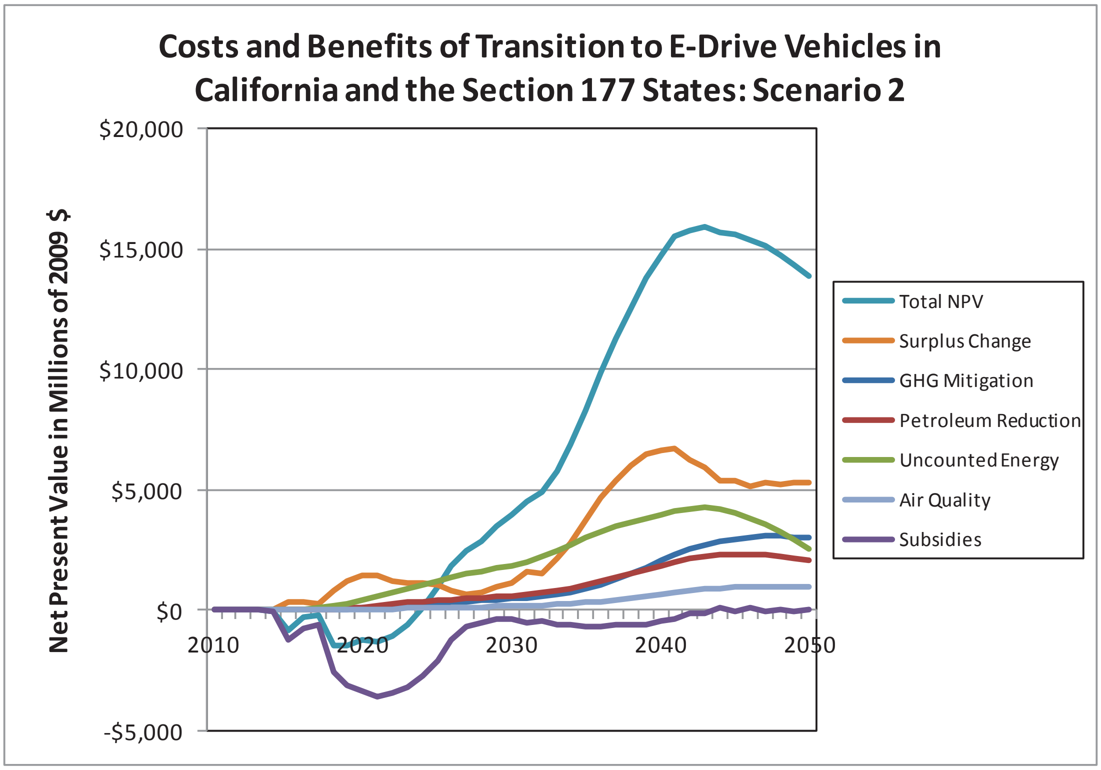

Figure 19a. Costs and Benefits of Transition to E-Drive Vehicles in California and the Section 177 States: Scenario 2

The benefit/cost ratio for the rest of the U.S. is even more favorable: $18 billion in subsidies buys an estimated half of a trillion dollars ($538 billion) in benefits, thanks to the spillover benefits created by the pioneering efforts of California and the Section 177 states (figure 19b). The costs and benefits have been calculated relative to a base case containing exactly the same assumptions about energy efficiency improvements, low-carbon biofuels, and technological progress but omitting the policies necessary to drive a transition to electric drive vehicles, such as the ZEV standards.

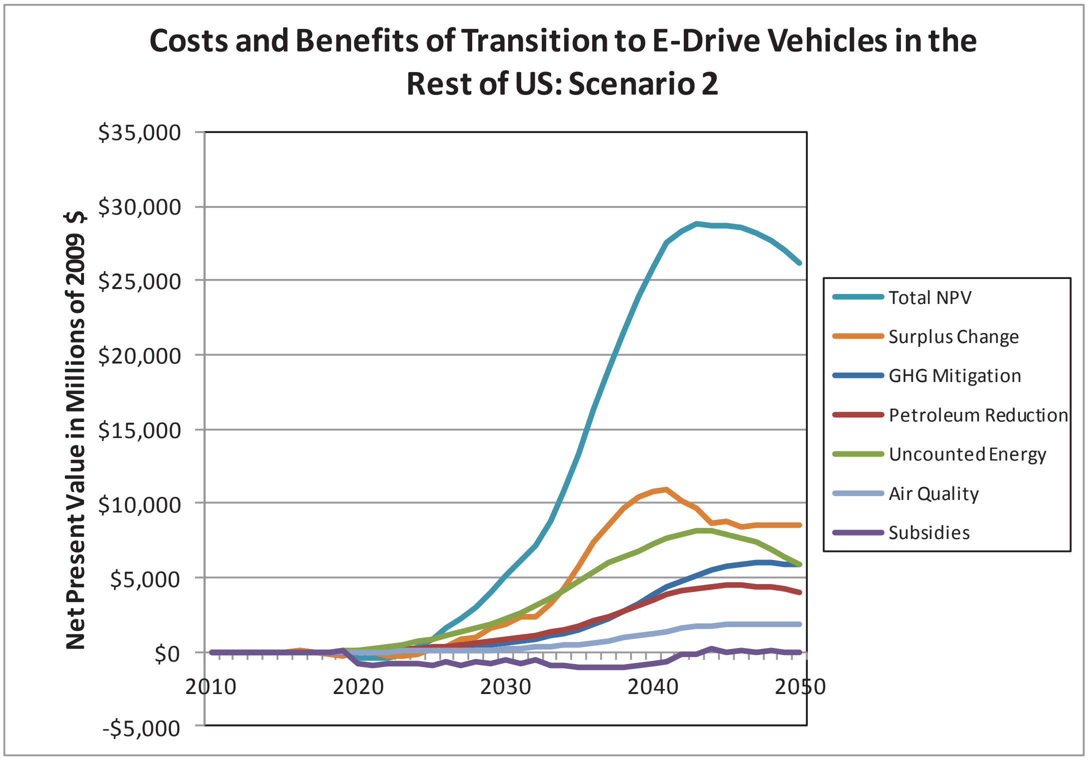

Figure 19b. Costs and Benefits of Transition to E-Drive Vehicles in the Rest of the US: Scenario 2

The effect of the ZEV program and subsequent federal policies on the marketability of fuel cell vehicles is illustrated in figure 20 and battery electric vehicles in figure 21. The figures illustrate quantitatively some of the network external benefits generated by the early, subsidized vehicle sales. Each factor graphed in the figures is a monetized component of the representative consumer's utility function, the function that determines vehicle choices in the LAVE-Trans model. The values shown should not be considered precise since much remains to be learned about how consumers value such factors as limited fuel availability or how much innovators are willing to pay to own zero emission vehicles. Rather, the graphs illustrate the effect of the positive feedbacks produced by network external benefits and how they gradually create competitive products that can hold their own in the market without continued support.

Initially priced at about $50,000 per vehicle including subsidies, the hydrogen fuel cell vehicle is also burdened by low volume production, lack of fuel availability, lack of a diverse array of makes and models to choose from, and for the majority of consumers, the perceived risk of being among the first to purchase a novel technology. The early placement of hydrogen refueling stations greatly reduces the estimated cost of lack of fuel availability from over $20,000 to less than a $5,000 per vehicle penalty. Subsidies by manufacturers required to sell ZEVs further reduce the price to potential buyers. But it is not until after 2030 that the cost of limited fuel availability becomes smaller than $1,000 per vehicle. The majority's risk aversion and the lack of diverse choices of makes and models take even longer to overcome.

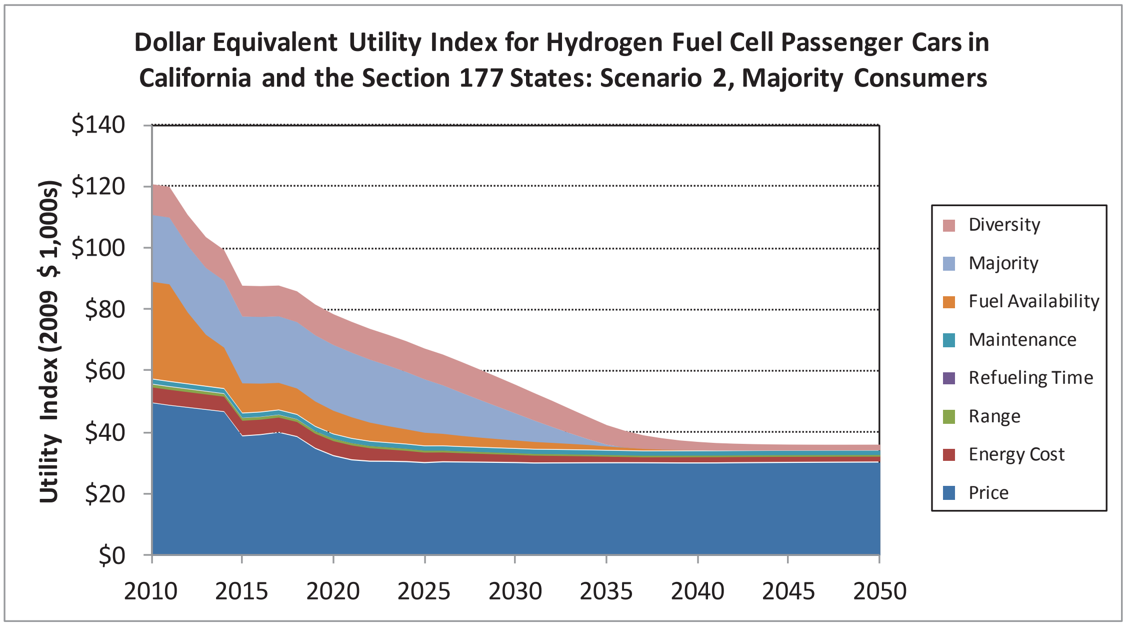

Figure 20. Dollar Equivalent Utility Index for Hydrogen Fuel Cell Passenger Cars in California and the Section 177 States: Scenario 2, Majority Consumers.

The attractiveness of BEVs to future buyers is also enhanced by policy-induced sales from 2015 to 2025. Fuel availability is a relatively minor issue, however. The value of public recharging infrastructure is unfortunately invisible in figure 20 because it is a negative cost (benefit); it grows from less than $100 per vehicle in 2025 to $400 per vehicle in 2050. The EVs limited range and longer recharging time remain significant cost factors through 2050 (BEVs are assumed to be designed with a 100 mile range in all years). The greater early sales volumes for BEVs erode the majority’s risk aversion more quickly than for FCVs, so that by 2030 BEVs are no longer seen as a risky new technology by majority consumers. Because BEVs’ market share does not exceed 20%, limited diversity of make and model choice remains somewhat of an issue through 2050.

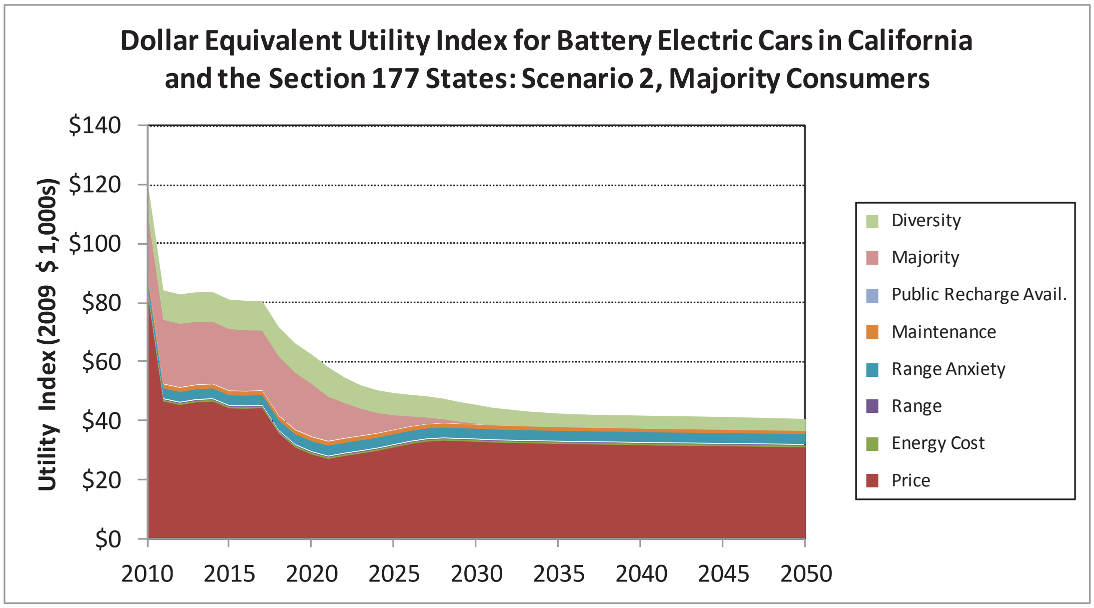

Figure 21. Dollar Equivalent Utility Index for BEV Cars in California and the Section 177 States: Scenario 2, Majority Consumers.

Still, sales to majority consumers are essentially zero during the early years of market development; innovators and early adopters are virtually the only purchasers (figure 22), according to the assumptions used in the LAVE-Trans model.[14] Innovators and early adopters generate network external benefits not only for future California and Section 177 state buyers but spillover benefits for the rest of the country, as well. The spillover benefits allow the transition to proceed more rapidly and permit a less intense policy effort to succeed outside of California. The earliest buyers of fuel cell vehicles produce indirect network external benefits by creating a market for hydrogen that expands the hydrogen refueling infrastructure. According to the LAVE-Trans model's estimates, the early placement of infrastructure cuts the cost of fuel availability more than in half, from just over $30,000 per vehicle in 2011 to less than $15,000 per vehicle by 2014. Sales of the first FCVs to the earliest adopters between 2015 and 2020 reduce fuel availability costs by another estimated $5,000 per vehicle. Sales required by the ZEV mandates and by the federal program also reduce costs via scale economies and learning-by-doing by an estimated $25,000 per vehicle by 2025.[15] From this perspective, subsidies to the first purchasers of electric drive vehicles are more than justified by the network external benefits they create for subsequent purchasers. Of course, this interpretation depends critically on the ultimate success of the transition such that present value benefits exceed present value costs by a substantial amount.

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[14] In fact, the number of innovators and early adopters, their willingness to pay for e-drive technologies, and how that willingness to pay will decline with increasing sales is not well understood. This is just one of many areas where a better quantification of market behavior would enable better analysis for decision making.

[15] Unlike indirect network external benefits, the benefits generated via scale economies and learning are pecuniary external benefits, that is, they are reflected in market prices in a competitive market.

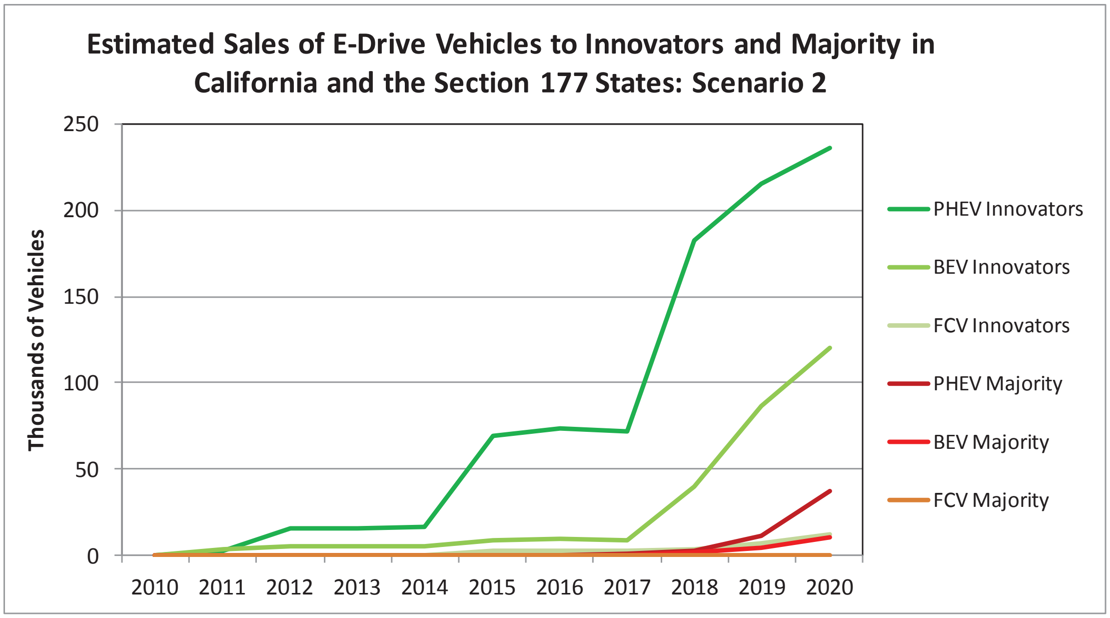


Figure 22. Estimated Sales of E-Drive Vehicles to Innovators and Majority in California and the Section 177 States: Scenario 2.

If technology progresses as expected and national policies for fuel economy/emissions standards and renewable or low-carbon fuel standards continue, it seems most likely that the rest of the U.S. would follow California's lead, as in Scenario 2. Because Scenario 2 seems the most likely scenario, the effects of higher and lower oil prices, and an alternative strategy for meeting the ZEV standards that relies on a somewhat smaller number of BEVs and a somewhat greater number of FCVs was tested in the context of Scenario 2 (see appendix tables A.1 and A.2 for details of assumed vehicle sales).

d. Scenario 2: High and Low Oil Prices

The 2011 Annual Energy Outlook (2011) High and Low Oil Price projections were used to test the effect of oil prices on the market shares of e-drive vehicles in Scenario 2. As would be expected, higher oil prices are estimated to increase the ultimate success of the transition to e-drive vehicles but the effect is small: the market share of e-drive vehicles in 2050 in California and the Section 177 States is estimated to be 76% versus 75% using Reference Case oil prices. Implied subsidies during the transition are sighty lower as well. In contrast, in the Low Oil Price Case, the share of e-drive vehicles in 2050 is only 70%. In addition, the implied subsidies required to achieve the ZEV requirements between 2015 and 2020 are approximately $3,000 per vehicle higher than in the Reference Oil Price Case. Overall, GHG emissions are reduced by 73% over the 2005 level in the Low Oil Price Case and by 81% in the High Oil Price Case. The relatively small differences in these estimates can be partly attributed to the dramatic improvements in fuel economy that make energy costs a less important determinant of consumers' vehicle choices. They are also partly due to the assumption that consumers undervalue future fuel costs and consider only the first three years of fuel costs in their purchase decisions. But the policies assumed also matter: the Indexed Highway User Fee becomes an increasingly important, fixed component of energy costs (growing from $0.42/gallon in 2010 to $1.68/gallon in 2050), and manufacturers' internal pricing strategies driven by fuel economy/emissions constraints provide additional incentives to buy low-emission vehicles that do not use petroleum in both cases.

e. Scenario 2: More FCV-intensive ZEV Strategy: No Travel Provision

If the travel provision of the ZEV requirements, which allows fuel cell vehicles sold in California to count in Section 177 States and vice versa, were able to be eliminated in 2018 due to infrastructure availability in other states, it is likely that a transition to hydrogen fuel cell vehicles would take place earlier. Tables A.1 and A.2 provide the specific numbers of each type of vehicle required with and without the travel provision; in 2018 4,000 more FCVs are sold without the travel provision, 15,000 more in 2020 and 60,000 more in 2025. The result is a somewhat faster transition to FCVs: an increase in FCV market share in 2030 from 2% with the travel provision to 10% without it (figure 23). In 2035 the difference is greater: 13% with the travel provision, 37% without. However, by 2050 the market shares are identical. Increased sales of FCVs tend to reduce sales of PHEVs and BEVs: with the travel provision, the respective shares of PHEVs and BEVs in 2035 are 10% and 15% but they decrease to 7% and 11% when the travel provision is removed. Although the travel provision appears to make a small difference, there is substantial uncertainty in the model's estimates (as will be illustrated below) and the transition process also exhibits tipping points, so these results should be interpreted with caution.

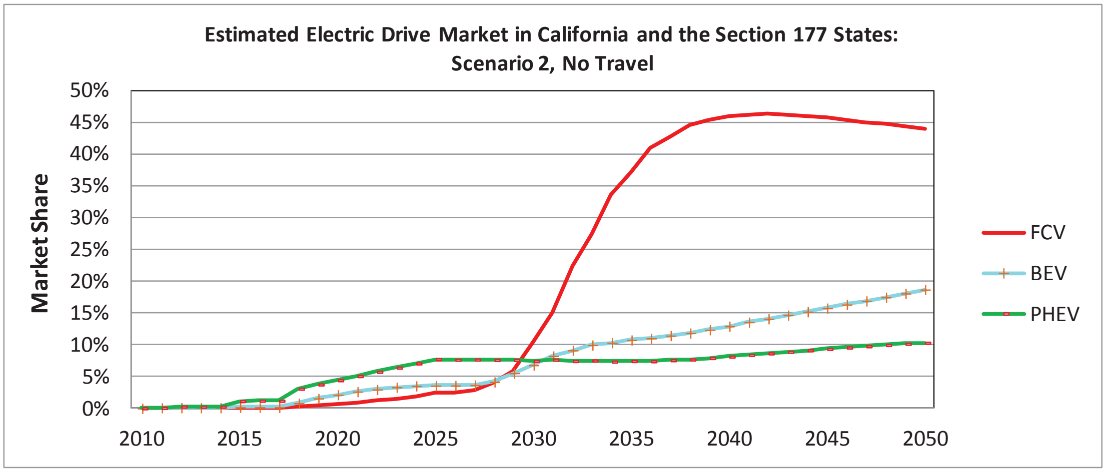


Figure 23. Estimated Electric Drive Market in California and the Section 177 States: Scenario 2, No FCV Travel Provision

f. Scenario 3: It's a Global Market

If California and the Section 177 states attempt a transition to electric drive vehicles and the rest of the U.S. does not, but countries like Germany, Japan, Korea and China do, it is very likely that the transition will not only be successful in California but in the rest of the US as well, provided that some early hydrogen infrastructure is deployed in the rest of the U.S. Scenario 3 is the only one that attempts to analyze the effects of world vehicle markets on the e-drive transition in the U.S.

Producing and selling electric drive vehicles outside of the US will generate some network benefits for the U.S.: scale economies and learning by doing throughout the supply chain, as well as breaking down the risk aversion of majority consumers, to some degree. It will not, however, create diversity of choice within the U.S. market nor create infrastructure for refueling and recharging. That requires selling vehicles and deploying hydrogen stations in the U.S. In scenario 3, the world market evolution illustrated in figure 11 is connected to the U.S. market to generate scale economies and learning by doing. The ZEV program proceeds in California and the Section 177 states as usual but the rest of the U.S. takes no action to induce a transition to electric drive vehicles.

The world transition to e-drive creates a more favorable scenario than Scenario 1; implicit subsidies are smaller and can be ended sooner and the transition begins earlier and ultimately achieves a larger FCV market share than in Scenario 1: 23% versus 15% (figure 24a compared with figure 14a). However, without early infrastructure or subsidies for e-drive vehicles no fuel cell vehicles are sold in the rest of the U.S. (figure 25a). On the other hand, if only a small number of stations are installed after 2020, the Rest of the U.S. begins a transition to FCVs by 2025, and market shares in California and the Rest of the U.S. reach 45% by 2050 (figures 24b and 25b).

Global market interactions are far more complex than can be accurately represented in a highly generalized model like LAVE-Trans. Still, the global market interactions are analogous to the California-Rest of U.S. interactions. Network external benefits created in one region are transferred to other regions, reducing the overall cost and difficulty of the transition without diminishing its benefits.

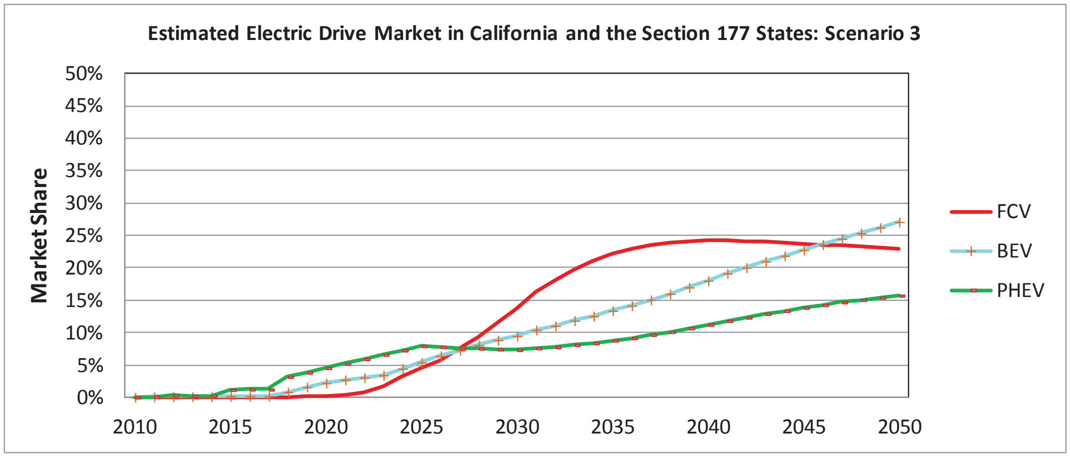
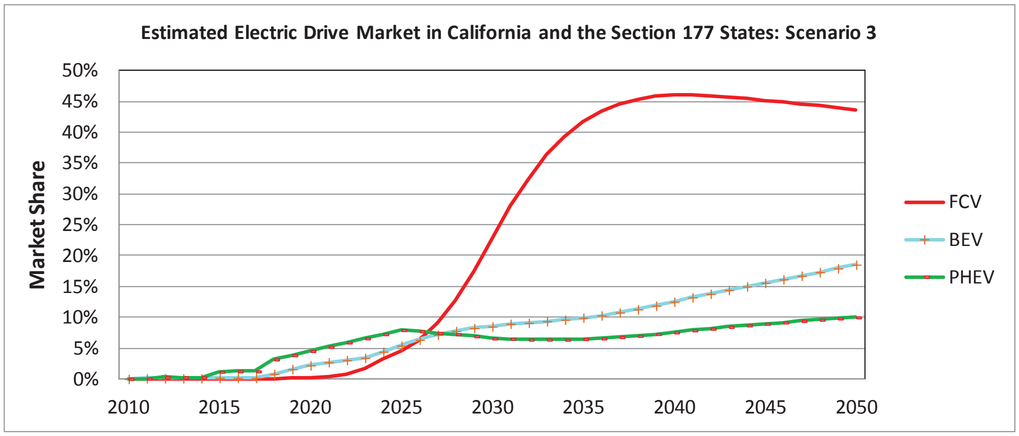
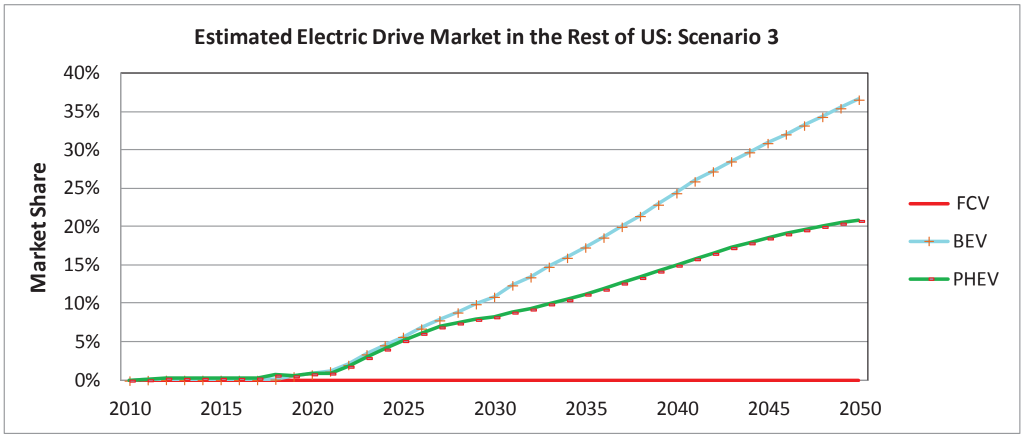


Figure 24a. Estimated Electric Drive Market in California and the Section 177 States: Scenario 3, World Transition Without Hydrogen Stations In the Rest of the U.S.



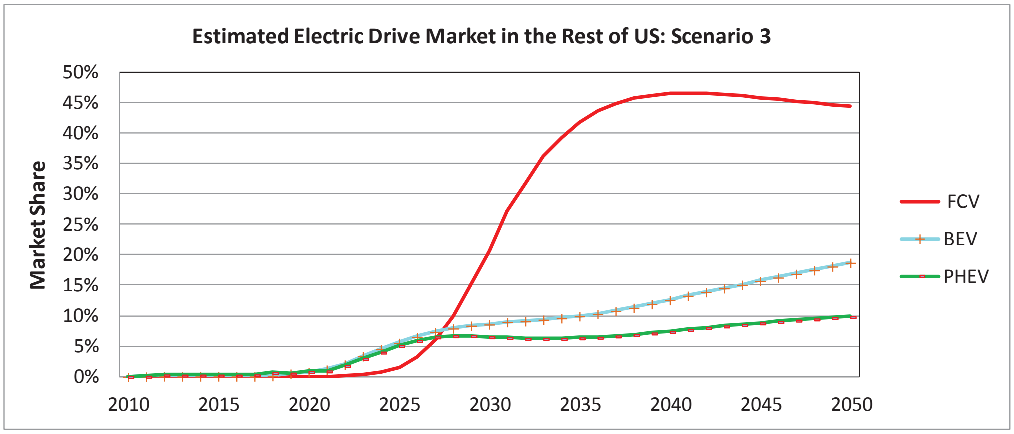
24(b)

Figure 24b. Estimated Electric Drive Market in California and the Section 177 States: Scenario 3, World Transition With 50 Hydrogen Stations Deployed in the Rest of the U.S. by 2022.



25(a)

Figures 25a. Estimated Electric Drive Market in Rest of U.S.: Scenario 3 Without Hydrogen Stations in the Rest of the U.S.



25(b)

Figures 25b. Estimated Electric Drive Market in Rest of U.S.: Scenario 3 With 50 Hydrogen Stations Deployed in the Rest of the U.S. by 2022.

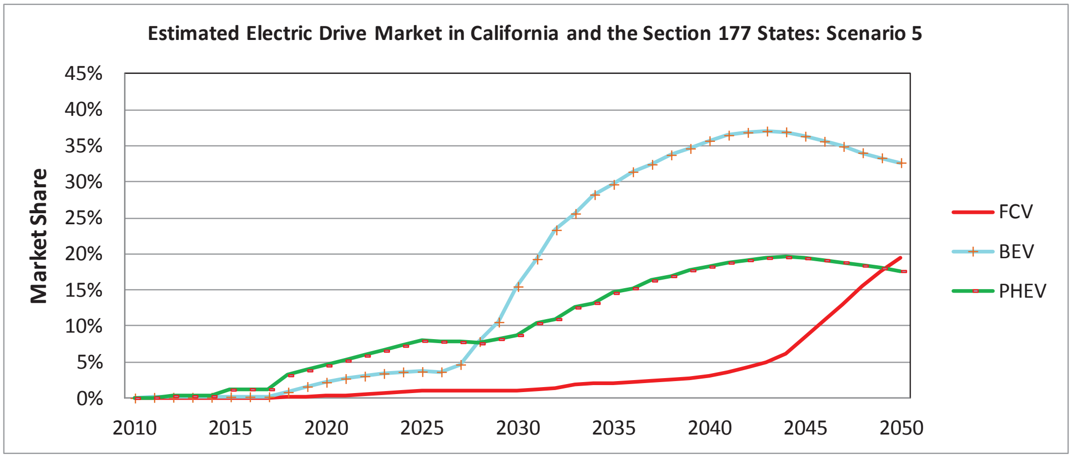
g. Scenario 4: No Early Hydrogen Infrastructure

The existence of tipping points in the transition to low-carbon vehicles and fuels in particular has been recognized previously (Struben and Sterman, 2008), as has the tendency for positive feedbacks to create path dependence (Köhler et al., 2006; Arthur, 1990). For example, if hydrogen refueling infrastructure is not put in place in advance of 2015, the same implicit subsidies and infrastructure deployments that enabled the ZEV requirements to be met and induced a national transition to fuel cell vehicles in Scenario 2 fail to produce a transition to fuel cells. Even if the Rest of the U.S. deploys the same 324 hydrogen stations that are assumed to be deployed in Scenario 2, the failure to provide early hydrogen infrastructure in California derails the transition to FCVs elsewhere in the U.S. The Scenario 2 implicit subsidies in California and the Section 177 states and the Scenario 2 infrastructure and implicit subsidies in the Rest of the U.S. could not induce a transition to FCVs; the advance provision of hydrogen infrastructure in California is a tipping point that either enables or derails the transition to hydrogen nationwide. In the absence of competition from hydrogen FCVs, BEVs and PHEVs gain market share but the combined e-drive market share is 52%, compared to 72% when hydrogen infrastructure is provided in advance.

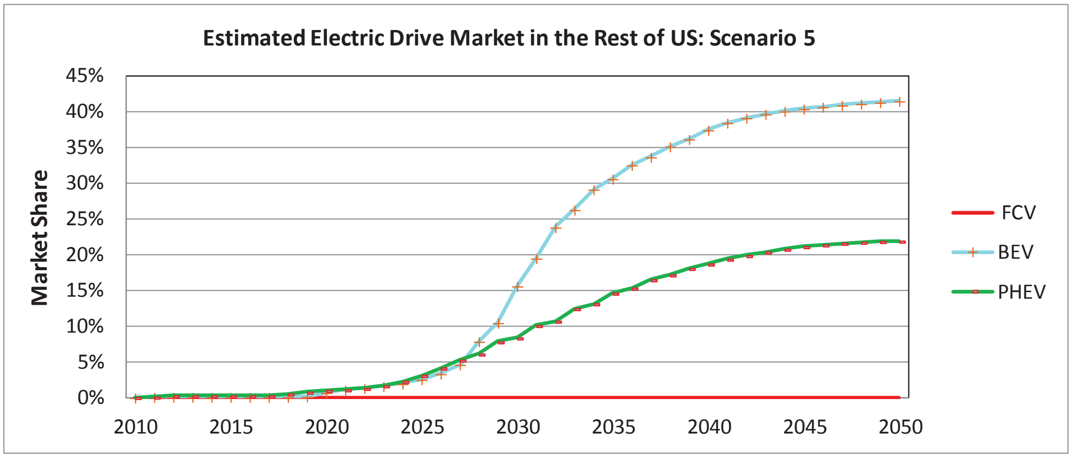
However, without early hydrogen infrastructure, the implicit subsidies of Scenario 2 would be insufficient to meet the ZEV requirements. Meeting the ZEV requirements would necessitate much larger incentives. Lack of infrastructure has a modest effect on the subsidies for plug-in vehicles but a very large impact on the implicit subsidies required to sell hydrogen FCVs. With early infrastructure, the estimated implicit subsidies for FCVs to meet the ZEV targets begin at about $10,000 per vehicle in 2015 and decline to less than $2,000 per vehicle by 2025. Without any early refueling stations, the implicit subsidies are $31,000 per vehicle in 2015 and $7,500 per vehicle in 2025. These subsidies are in addition to the federal tax credit of $7,500 still in effect in 2015 and the CAFE-induced feebates that take effect in 2017. Total subsidies from 2020 to 2025 in California and the Section 177 states are about $2 billion higher if the initial 68 hydrogen refueling stations are not deployed. While these estimates are by no means precise, they are indicative of the value of even a modest number of stations installed in advance of marketing vehicles. It is apparently very much in the interest of vehicle manufacturers faced with the ZEV requirements to have even a modest number of hydrogen refueling stations in place by 2015.

h. Scenarios 5 & 6: Better Technology, Better Transitions

Things may turn out better (or worse) than expected. If electric drive technology progresses more rapidly than in the expected (mid-range) technology assumptions, the transition process becomes easier and the rewards increase. Scenario 5 is Scenario 1 (no U.S. transition policy) using optimistic technology assumptions. Scenario 6 is Scenario 2 with optimistic technology. In Scenario 5 the key difference is the earlier and greater market success of battery electric vehicles (figure 26a). Sales begin to take off shortly after 2025 and peak at 35% of the market. Implied subsidies are also lower by $2,000 to $3,000 per vehicle and none are required after 2026 for BEVs. By 2050, e-drive vehicles achieve a combined market share of 65% in Scenario 1 with expected technology and 70% in Scenario 5 with optimistic technology assumptions. In the Rest of the U.S., with no early hydrogen infrastructure deployment no FCVs are sold but PHEV and HEV sales increase to 64% of the market, compared with 58% in Scenario 1.



26(a)



26(b)

Figures 26a and 26b. Estimated Electric Drive Market in California and the Section 177 States (a) and in the Rest of the U.S. (b): Scenario 5.

If the rest of the U.S. follows California and the Section 177 states in promoting a transition to electric drive vehicles (Scenario 6), FCVs come on earlier and take a greater share of the new vehicle market (figure 27). FCVs clearly take market share from BEVs and PHEVs but the combined market share of the three technologies reaches 75% by 2040 and 80% by 2050.

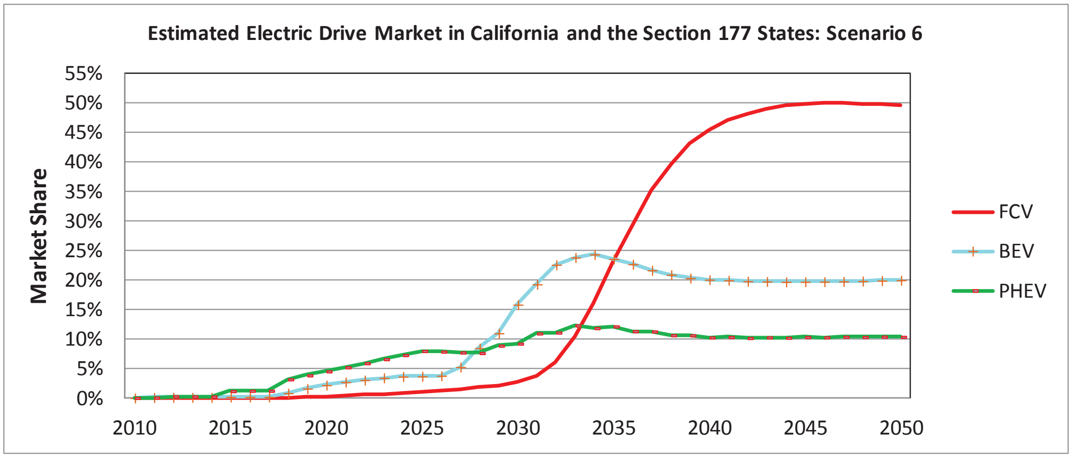


Figure 27. Estimated Electric Drive Market in California and the Section 177 States: Scenario 6.

By 2050, e-drive vehicles make up 70% of the on-road vehicle stock and account for 72% of vehicle miles, despite the fact that BEVs are assumed to be driven only 2/3 as much as other vehicle technologies. The greater success of electric drive vehicles reduces petroleum use in 2050 by 99%: essentially all fuel for internal combustion engine vehicles in California and the Section 177 states is provided by 4.6 billion gallons of drop-in biofuel. The combined effect of efficiency improvements driven by fuel economy standards, low-carbon liquid fuels, the energy user fee indexed to average vehicle fuel economy, and the transition to electric drive vehicles reduces light-duty vehicle greenhouse gas emissions by 89% not only for California but for the entire U.S., as well (figure 28).

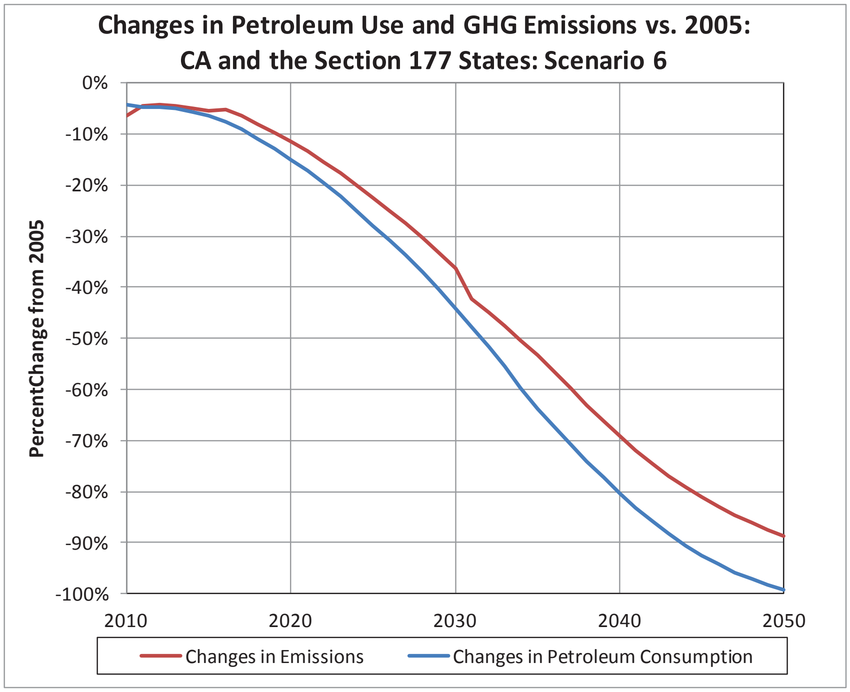


Figure 28. Changes in Petroleum Use and GHG Emissions vs. 2005: California and the Section 177 States, Scenario 6, Optimistic Technology

VI. Coping with Uncertainty

The estimates presented above are based on projections of technological progress over the next four decades, combined with our current understanding of how the market is likely to respond to alternative vehicles and fuels. Although care has been taken to use sound engineering analysis and the best available economic parameters, the future remains very uncertain. Because policy makers have no alternative but to cope with it, quantifying the uncertainties we face in managing a transition to sustainable vehicles and fuels is useful (Bastani et al., 2012). It provides insight into the value of research to reduce uncertainty about the chances for technological progress and the market's likely response to it. It also provides decision makers with a more realistic description of the challenges they face in attempting to bring about a transition to electrically powered vehicles.

To illustrate the magnitude of uncertainty, a Monte Carlo simulation consisting of 1,000 different model runs was carried out using the probability distributions for the 17 parameters shown in table A.4.[16] Each simulation selects a different set of 17 parameter values from the probability distributions and recalculates both the ZEV and rest of U.S. spreadsheets. The transition policies of Scenario 2 are held constant for all simulations. This means constant implicit subsidies for vehicles, which may or may not result in the ZEV standards being met in any particular run. This is not an optimal or even intelligent policy approach, since policies should adapt to market conditions. As a consequence, the frequency of failure to achieve a transition will be overestimated relative to an adaptive policy strategy. Nonetheless, the exercise is useful for describing market uncertainty from today's perspective.

The simulated uncertainty about the market's response to electric drive vehicles is illustrated by figures 29 and 30, which show the frequency distributions for the market shares of BEVs and FCVs in 2050. Both have a "spike" at zero, indicating that the fixed transition policies failed to trigger the tipping points for transition under the market conditions of those simulations. The simulated probability is about 35% in the case of FCVs and 25% for BEVs but again, the simulation assumes no policy adjustments. BEV market shares range to 60%, with the greatest frequencies in the interval 5% to 30%. FCV market shares show a greater frequency at 0%, due to the importance of the fuel availability barrier but the greatest non-zero probability is between 30% and 60% of the light-duty market. The likelihood of zero market penetration in either case could be greatly reduced by adjusting the transition policies to suit market conditions either by increasing the implicit subsidies (e.g., so that the ZEV standards would be met in every case) or providing more refueling or recharging infrastructure. These simulations illustrate the magnitude of uncertainty about market conditions by simulating responses given a fixed policy strategy. The uncertainty is clearly very large and is comprised of lack of knowledge about important market parameters, as well as uncertainty about how market preferences may change in the future.

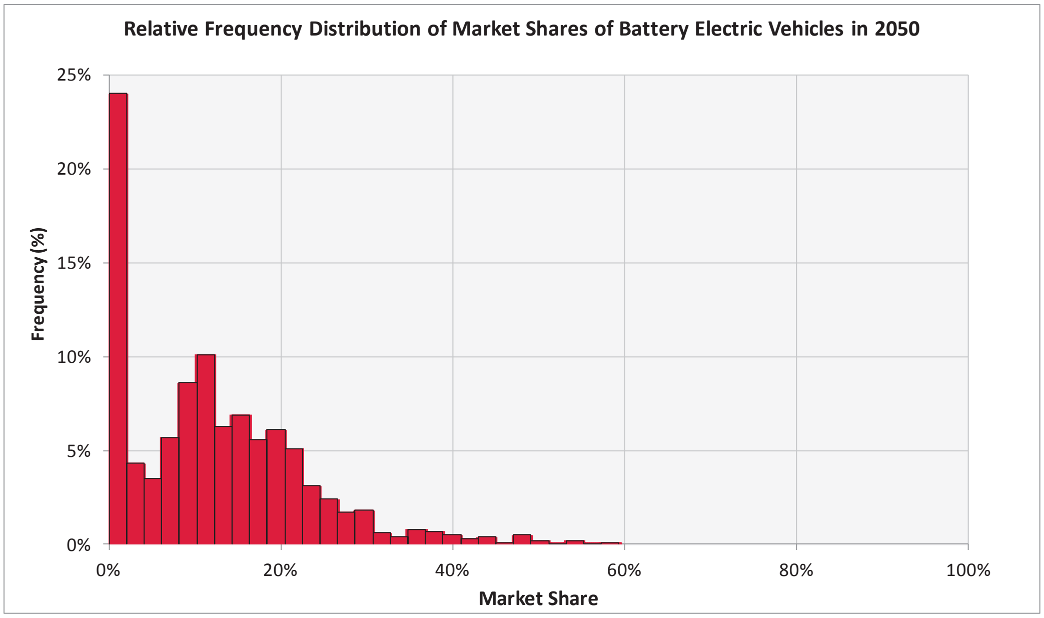


Figure 29. Relative Frequency Distribution of BEV Market Shares Generated by Monte Carlo Simulation.

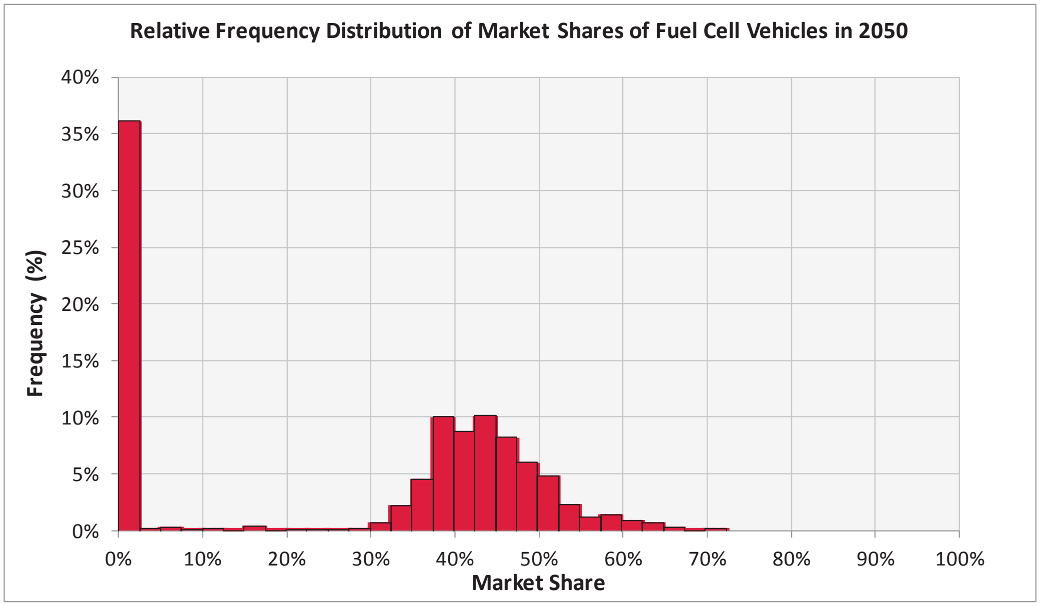


Figure 30. Relative Frequency Distribution of FCV Market Shares Generated by Monte Carlo Simulation.

The simulation analysis demonstrates two important points: 1) the future market for electric drive vehicles is highly uncertain and, 2) if policies do not adapt to market conditions there is a substantial likelihood of missing a tipping point that leads to a successful transition. The simulation has not considered the uncertainty of future technological progress, an important subject for future analysis.

VII. The Way Forward: Act, Learn, Adapt

This analysis of possible transitions to electric drive vehicles in California, the Section 177 states and the Rest of the United States has demonstrated the potential to produce benefits that exceed the costs of transition by an order of magnitude or more. It has done so in the context of a rational paradigm for public policy making to accomplish large-scale, long-term energy transitions for the public good. Constructing the paradigm and measuring the costs and benefits, even with great uncertainty, may be the study's most important contribution. The analysis has also shown that the future of electric drive vehicles is very uncertain, depending on the future evolution of e-drive technologies, the market's response to them and the implementation of effective, adaptable public policies. Analysis of decision making in the presence of great uncertainty has shown that adaptive strategies, strategies that change in response to future developments, are more robust and can perform almost as well as optimal strategies based on a full knowledge of future events (Groves and Lempert, 2007). There is little doubt that public policy will have to adapt in order to bring about a transition to sustainable, electric-drive vehicles.

Despite the deep uncertainty, this study has produced some useful insights.

KEY FINDINGS

- If technological progress proceeds as expected and strong, adaptive public policies are implemented, the additional public and private benefits of a transition to electric drive vehicles are likely to exceed the additional costs of inducing a transition to electric drive by approximately an order of magnitude.
- Substantial uncertainty remains about the rate and extent of technological progress as well as how the market will respond to electric drive vehicles. An on-going effort to reduce the uncertainties through technology assessment and market research is likely to be of great value to decision makers.
- Although the barriers to electric-drive vehicles are small relative to the potential benefits, they are large in absolute terms. The transition to a sustainable market for electric drive vehicles in the United States will require at least decade and probably more, as well as the expenditure of tens of billions of dollars.
- The chances of success for the California ZEV program are greatly increased and the costs reduced if the rest of the U.S. pursues similar policies. However, under a variety of conditions the ZEV program can succeed in the absence of federal transition policies.
- Motor vehicle markets are global. Developments in electric drive markets around the world could be as important to the success of electric drive vehicles in California as market developments in the rest of the U.S.
- The transition process contains important positive feedbacks that create tipping points. However, missing a tipping point need not be fatal provided that public policy perseveres, learns and adapts.

- Provision of refueling infrastructure in advance of commercial sales appears to be essential for hydrogen fuel cell vehicles and helpful but far less important to the success of plug-in electric vehicles.
- Uncertainty about the market’s response to electric drive vehicles remains profound. There is much to learn about sensitivity to price, differences in consumers’ preferences, the importance of fuel availability, limited range and extended recharging times, the value of diversity of choice, and the number of innovators and their willingness to pay for zero-emission, electric drive vehicles. On the supply side, better understanding of firms’ responses to risk, and quantifying scale economies and learning rates are equally important.
- The appropriate paradigm for policy making to achieve the large-scale energy transition to electric drive consists of cost/benefit analysis under deep uncertainty and numerous, important positive feedback loops. Internalizing external costs is helpful but not sufficient. In general, specific, temporary transition policies are needed to create network external benefits that can overcome the barriers to transition.

This report has described an initial effort to model the transition to electric drive vehicles, including measuring the costs and benefits, quantifying the transition barriers and network external benefits, and estimating the effects of public policies on the transition process. At present, many of the critical parameters in the process cannot be quantified with sufficient precision for the LAVE-Trans model to be used as a predictive tool. It is hoped that future research and analysis will narrow the uncertainties and develop improved tools to support public policy decisions.

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IX. Appendix

Table A.1 Estimated ZEV Requirements for 2015-2025 for California and the Section 177 States (vehicles)

	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
PHEV	70,929	74,614	72,832	187,113	228,247	275,005	322,658	371,215	419,599	470,505	524,792
BEV	9,999	10,518	10,267	48,428	94,446	132,892	167,434	191,548	217,543	235,105	242,539
FCV	3,333	3,506	3,422	4,280	8,975	15,618	23,255	32,864	42,300	53,645	67,372
Total	**84,261**	**88,638**	**86,522**	**239,821**	**331,667**	**423,515**	**513,347**	**595,627**	**679,442**	**759,255**	**834,703**

Table A.2 Estimated ZEV Requirements for 2015-2025 for California and the Section 177 States: No Travel Provision (vehicles)

	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
PHEV	70,929	74,614	72,832	187,113	228,247	275,005	322,658	371,215	419,599	470,505	524,792
BEV	9,999	10,518	10,267	48,428	94,446	132,892	167,434	191,548	217,543	235,105	242,539
FCV	3,333	3,506	3,422	10,273	21,540	37,482	55,811	78,873	101,520	128,748	161,693
Total	**84,261**	**88,638**	**86,522**	**245,813**	**344,233**	**445,380**	**545,903**	**641,636**	**738,662**	**834,358**	**929,024**

Table A.3 Assumed Lifetime Emission Rates for All Vehicles Sold After 2009 (g/mi) and Assumed Values of Pollutant Reduction per Metric Ton (2012 $).

	2010 - 2019			2020 - 2024			2025 - 2050		
	NOx	HC	PM10	NOx	HC	PM10	NOx	HC	PM10
ICE	0.164	0.141	0.0176	0.113	0.104	0.0130	0.090	0.086	0.0108
EV	0.028	0.007	0.0060	0.025	0.006	0.0055	0.026	0.006	0.0056
PHEV	0.109	0.087	0.0129	0.078	0.065	0.0100	0.065	0.054	0.0087
FCV	0.102	0.020	0.0001	0.097	0.019	0.0001	0.105	0.021	0.0001
Value ($/ton)	$17,080	$17,080	$341,600						

Table A.4 Probability Distributions for Market Response Parameters Used in Monte Carlo Simulation

Parameters	Distribution	Min	Mean	Max
Importance of diversity of makes and models to chose from	Triangle	0.50	0.67	1.00
Value of time ($/hr.)	Triangle	$10.00	$20.00	$40.00
Maximum value of public recharging to typical PHEV buyer	Uniform	$500	$1,000	$1,500
Cost of one day on which driving exceeds BEV range	Uniform	$10,002	$20,000	$30,000
Maximum value of public recharging to typical BEV buyer	Uniform	$0	$500	$1,000
Importance of fuel availability relative to standard assumption	Triangle	0.67	1.00	1.67
Payback period for fuel costs (yrs.)	Triangle	2.0	3.0	5.0
Volume threshold for introduction of new models rel. to std. assumptions	Uniform	0.80	1.00	1.20
Optimal production scale relative to standard assumptions	Uniform	0.75	1.00	1.25
Scale elasticity relative to standard assumptions	Uniform	0.50	1.00	1.50
Progress Ratio relative to standard assumptions	Uniform	0.96	1.00	1.04
Price elasticities of vehicle choice relative to standard assumptions	Uniform	0.60	1.20	1.80
Percentage of new car buyers who are innovators	Triangle	5.0%	15.0%	20.0%
Willingness of innovators to pay for novel technology ($/mo.)	Uniform	$100	$200	$300
Cumulative production at which innovators WTP is reduced by 1/2	Uniform	500,000	1,000,000	1,500,000
Majority's aversion to risk of new technology ($/mo.)	Uniform	-$900	-$600	-$300
Cumulative production at which majority's risk is reduced by 1/2	Uniform	500,000	1,000,000	1,500,000