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Analyzing the transition to electric drive vehicles in the U.S.

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ABSTRACT

Scenarios of the transition to electric drive passenger cars and light trucks are created using the same model, technology and market behavior assumptions used in the recent National Research Council study, *Transitions to Alternative Vehicles and Fuels*. The transition is assumed to begin in California and the other U.S. states that have adopted California's Zero Emission Vehicle (ZEV) requirements. Five years after the ZEV standards take effect in 2015, the rest of the U.S. adopts polices strongly supporting the transition. After roughly a decade of net costs, market adoption of electric drive vehicles becomes self-sustaining. In the long run, the model implies that social benefits exceed excess costs by approximately an order of magnitude. Analysis of major energy transitions is characterized by deep uncertainty due to the long time constants for energy system change, the unpredictability of technological change and government policies, inadequate understanding of market processes, and the many important positive feedback mechanisms that create tipping points.

1. Introduction a new challenge for public policy

> "Without question a radical transformation of the present energy system will be required over the coming decades."
>
> "An effective transformation requires immediate action."
>
> "In all (sustainable, ed.) pathways conventional oil is essentially phased out shortly after 2050. Every scenario that achieves the sustainability goals essentially eliminates petroleum use."
>
> [1]

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 [2]. Transitioning to sustainable energy systems is perhaps the essential element of a physically and economically sustainable global society [3,4]. As the world's vehicle population grows toward 2 billion, motorized transportation is challenged to contribute to protecting of the global climate system, enhancing energy security and reducing the adverse health effects of local air pollution [5]. There is no single solution to these problems [6–9]. However, it is becoming increasingly clear that achieving sustainable transportation implies a transition from petroleum-based, internal combustion engines to nearly zero emission electric drive.

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How such a transition can be accomplished is a new conundrum for public policy. The time constants for such transitions are measured in decades [10]. The future progress of technology is inherently uncertain. Knowledge of how the market will respond to advanced vehicle technologies and fuels is meager. A genuinely sustainable energy system for transportation requires a sustainable energy supply chain from energy source to vehicle. How can society manage such a transition efficiently and effectively?

Bringing about a large scale energy transition for the public good requires a new paradigm for environmental policy. It is not just a matter of internalizing externalities and letting markets do the rest. Externalities are an important part of the problem but not all of the relevant social costs are externalities, e.g., monopoly power in the world oil market [11]. Major energy transitions take decades. On this time scale the difference between social and private discount rates becomes critical. The transition requires technological progress beyond the current state of the art, and that is inherently uncertain. Equally importantly, the transition creates network external benefits which are difficult for private agents to capture. Among these are, (1) the value of fuel availability to car buyers, (2) learning-by-doing spillover effects, (3) reduction of the majority of consumers' aversion to the risk of new products, (4) the value of choice diversity (which conflicts with the need for scale economies during the early stages of a transition) and (5) "deep uncertainty" about outcomes in the mid- to long-range future and the difference between social and private perceptions of and tolerance for risk.

An economic paradigm for large scale energy transitions can be constructed from the concepts of net present social value, network external benefits, and adaptation to an uncertain future (e.g., [12]). Net social benefits are 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 [10]. 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., [13]). Uncertainty is an inescapable dimension because future technologies and markets will undoubtedly surprise us.

2. Modeling the transition to electric drive

The transition to electric drive vehicles requires replacing an entrenched technology and its physical and human infrastructure with new technologies that deliver superior public goods. At present the new technologies are not superior in the eyes of most potential buyers. However, with continued technological progress they have the potential to become superior from a private perspective as well. Electric drive technologies thus face six major economic barriers that lock in petroleum powered internal combustion engine vehicles and lock them out.

(1) Current technological limitations of electric drive 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 electric drive vehicles.
(6) Lack of an energy supply infrastructure for hydrogen and a limited infrastructure for plug-in electric vehicles.

Each of these barriers is difficult to quantify and uncertain in the future. Yet much can be learned about the transition process by quantifying each of them using available information with the expectation that as knowledge improves and conditions change, assessments can 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, early adopters willing to purchase electric drive vehicles and entrepreneurs willing to manufacture them or to supply the new fuels they require reduce the barriers and generate positive feedback effects that benefit existing and future e-drive vehicle owners. Modern economics calls these positive feedback effects "network externalities", positive external benefits that one user of a commodity can produce for another [14]. Network external benefits have been extensively studied in the development of personal computer operating systems and cell phones. Similarly, when an innovator purchases one of the first hydrogen fuel cell vehicles, it reduces the risk for all other buyers who may now consider buying a slightly less novel technology, and it lowers prices via scale economies and learning by doing.[3] When a city installs a public recharging station it increases the value to the owners of every electric vehicle. 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 are essential to the transition to electric drive vehicles because they create important positive feedbacks that can eventually lead to a self-sustaining transition. The Light-duty Alternative Vehicle and Energy Transitions (LAVE-Trans) model developed for the International Council on Clean Transportation was designed to measure these external benefits, albeit imperfectly. Recognizing and measuring the value of early deployment of vehicles and infrastructure

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

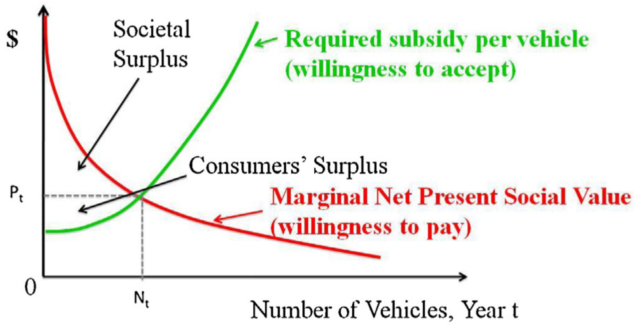


Fig. 1. Determination of an efficient quantity of vehicle sales in year *t* and an efficient subsidy.

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. Section 3 briefly describes the LAVE-Trans model; those interested in details can find them in the model documentation report ([6], Appendix H). Section 4 reviews the key assumptions about vehicle technologies, assumptions about fuel technologies and energy prices. Section 5 describes a scenario of successful transition to electric drive vehicles that by 2050 reduces greenhouse gas emissions from light-duty vehicles by 80 percent and nearly eliminates petroleum use. Uncertainty about future market acceptance of advanced technologies is the subject of Section 6. Many of the key factors that will determine the ultimate outcome of large-scale energy transitions are not well understood. Thus, the goal of this paper is as much to explore 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.

3. The economics of sustainable energy transitions

In any given year, increasing the number of electric drive vehicles sold or expanding their refueling infrastructure will change social costs and benefits not only in that year but in succeeding years. Assuming that the transition can produce positive social benefits, for any given pattern of 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 the Net Present Social Value of the transition with respect to the number of alternative vehicles sold, N_{it}, other variables held constant.[4] A similar set of calculations could be made for infrastructure deployment.

The demand curve constructed in this way represents the maximum amount society would be willing to pay to insure that various quantities of e-drive vehicles were sold in year *t* (the Marginal Net Present Social Value curve in Fig. 1). 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 Fig. 1). The first few 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 group of 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 functions were known for every year in the future, one could identify an economically efficient transition pathway.

But energy transitions take decades [15,16] and because of this, deep uncertainty about technology and markets is unavoidable [10]. If, as a consequence, risk-averse decision makers strongly discount expected future benefits, the Marginal Net Present Value curve will be lower, reducing the efficient number of vehicles to be deployed in year *t*.

The scenario described in this paper does not represent an optimal transition that maximizes the net present social value 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 [10]. Instead, we have combined plausible policies that, given the numerous assumptions required, appear to be able to produce a sustainable transition to electric drive vehicles.

[4] 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.

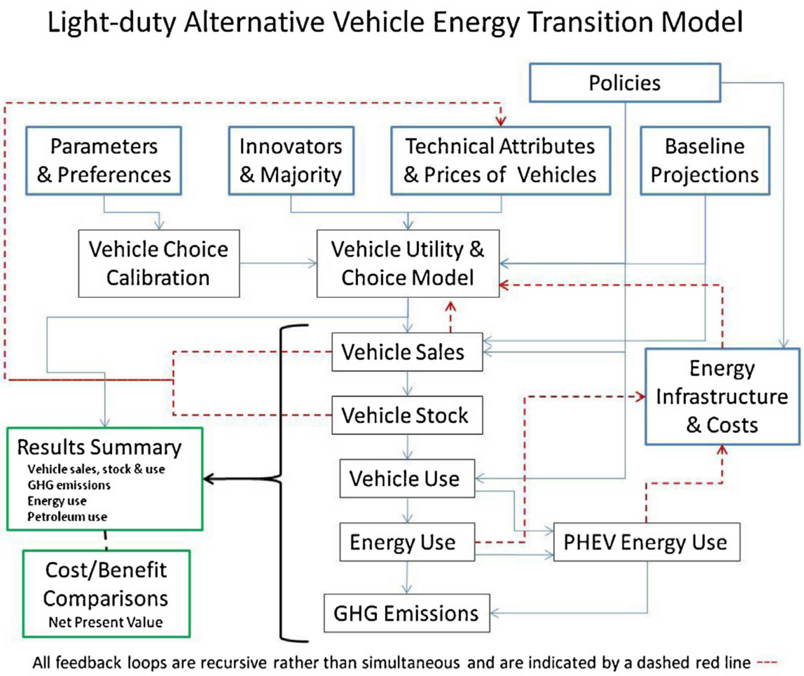


Fig. 2. Diagrammatic representation of the LAVE-Trans model. (For interpretation of the references to color in this text, the reader is referred to the web version of the article.)

4. The Light-Duty Alternative Vehicle and Energy Transitions (LAVE-Trans) Model[5]

The analysis of the transition to electric drive vehicles presented in this paper was constructed using the Light-duty Alternative Vehicles Energy Transitions (LAVE-Trans) model. The model was used by the National Research Council's study, *Transitions to Alternative Vehicles and Fuels* ([6], Appendix H[6]). That study's assumptions about the future progress of vehicle and fuel technologies, as well as the parameters describing the market's response, are also used in the this paper.

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. Fig. 2 illustrates the relationships between the major components of the model. Exogenous inputs to the model are shown as blue boxes. Consumers' choices are estimated using a representative consumer, nested multinomial logit model (e.g., [17–19]). 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. Projections of vehicle sales and energy prices to 2050 come from the U.S. Energy Information Administration's *2011 Annual Energy Outlook* [20].

The LAVE-Trans model includes several feedback loops through which adoption of alternative vehicles and fuels generates network external benefits that drive down costs and increase the acceptability to consumers of the novel technologies and fuels. For example, consumers are 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 eroded. As more electric drive vehicles are sold, more electric recharging and hydrogen refueling stations are built. As more stations are built, the attractiveness of electric drive vehicles increases. At the same time, as more vehicles are sold, costs approach long-run, high volume levels through the benefits of scale economies and learning-by-doing (e.g., [21]).

Given a starting sales projection, the Vehicle Choice model estimates changes to new vehicle purchases, as well as the shares of internal combustion engine (ICE), hybrid electric (HEV), plug-in hybrid (PHEV), battery electric (BEV) and fuel cell vehicle (FCV) technologies for passenger cars and light trucks for both Innovator/Early-adopter and Majority market segments. Sales are passed to the Vehicle Stock model 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 vehicle scrappage functions [22]. Vehicle kilometers by age and vehicle type vary with fuel prices and energy efficiency and are calculated in the Vehicle Use module (also calibrated to [22]). In the Energy Use module energy use is calculated by multiplying vehicle kilometers by number of vehicles and by energy consumption per kilometer. Well-to-wheel greenhouse gas, NO_x, HC, and PM10 emissions factors are applied to calculate total emissions.

[5] The model is named after the late economist Charles Lave who in collaboration with Kenneth Train was the first to apply the multinomial logit model to analyzing automobile choice [42].

[6] Model documentation can be found on line at http://www.nap.edu/openbook.php?record_id=18264&page=331.

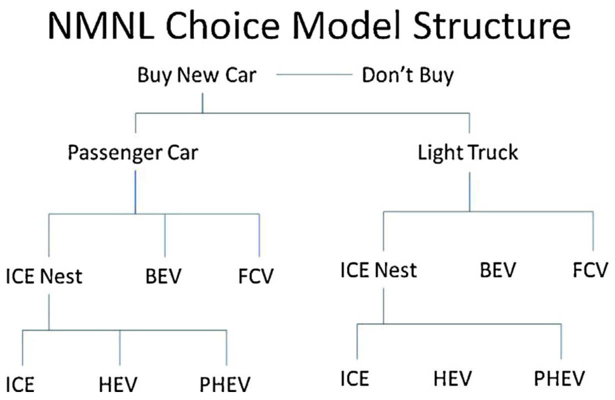


Fig. 3. Choice structure of the Nested Multinomial Logit model.

The structure of the nested multinomial logit choice model is shown in Fig. 3. Consumers evaluate the three kinds of drive-trains that include internal combustion engines (ICE, HEV, PHEV) and compare the internal combustion alternatives collectively 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.

There are several important feedback loops in the model. 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. Current sales also determine the numbers of different makes and models, i.e., the diversity of choices available to consumers for both advanced and conventional ICE technologies.

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 [23]. Because the remaining fuel costs have economic value, they are calculated separately and added to the cost/benefit calculations.

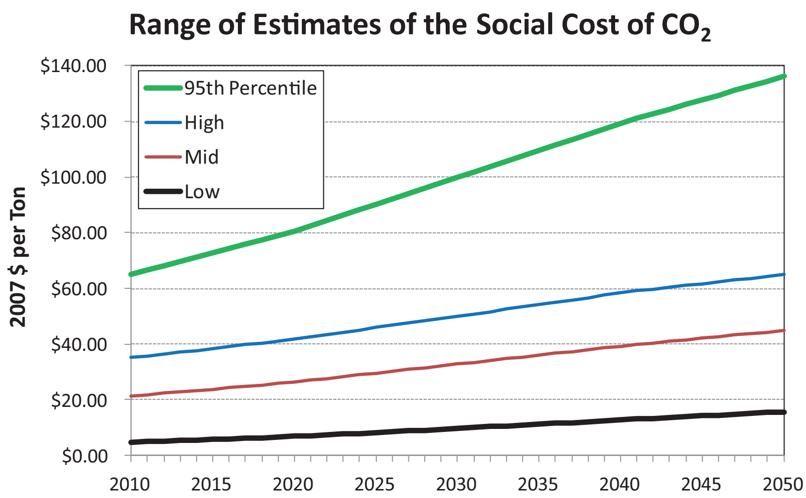


Fig. 4. Range of estimates of the social cost of CO_2 Emissions [24].

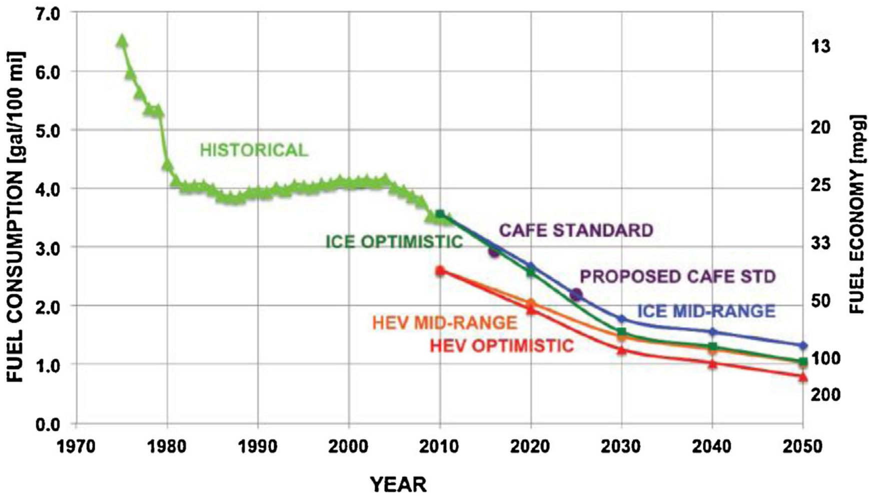


Fig. 5. Energy efficiency projections of the NRC's [6].
Transitions to Alternative Vehicles and Fuels (Fig. 2.1), reprinted with permission of the National Academies Press, Washington, DC.

The value per ton of GHG emissions avoided is based on the IWGSCC [24] High case which discounts future costs at a 2.5% rate. It rises from \$35/ton CO_2 equivalent in 2010 to \$65/ton in 2050 (Fig. 4). The value of reducing petroleum consumption is based on the EPA/NHTSA [25] 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 [26] guidance for cost-effectiveness analyses.

Two versions of the LAVE-Trans model, one representing California and the “Section 177” states[7] 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.

5. Advanced vehicle technology scenarios

The future costs and energy efficiencies of advanced vehicle power-trains, both conventional and alternative, are of central importance to the transition to electric drive. The technology projections of the NRC [6] “Transitions” 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.[8] The resulting energy efficiency estimates (in gallons per 100 miles) are compared with historical data for new light-duty vehicles in Fig. 5 [6]. The data displayed in Fig. 5 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 0.83 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 2005–2030 rate. Only the committee's mid-range estimates are used in the scenario presented below. Vehicles in 2050 are highly efficient, about 70 miles per gallon for a typical ICE passenger car and 90 MPG for an HEV.

The NRC [6] assessment is one of the few that projects technological progress to 2050 and 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.). 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.

The NRC *Transitions* study's longer time frame and focus on load reduction produced a novel conclusion. Because the cost of battery-electric and fuel cell drive-trains scale more directly with power than ICE drive-trains, load reduction is of greater value to these technologies. As a result, unlike previous assessments extending to 2035 (e.g., [27]), after 2040 BEVs and FCVs

[7] 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).
[8] Detailed documentation can be found in the National Research Council [6] report *Transitions to Alternative Vehicles and Fuels*, Chapter 2 and Appendix F.

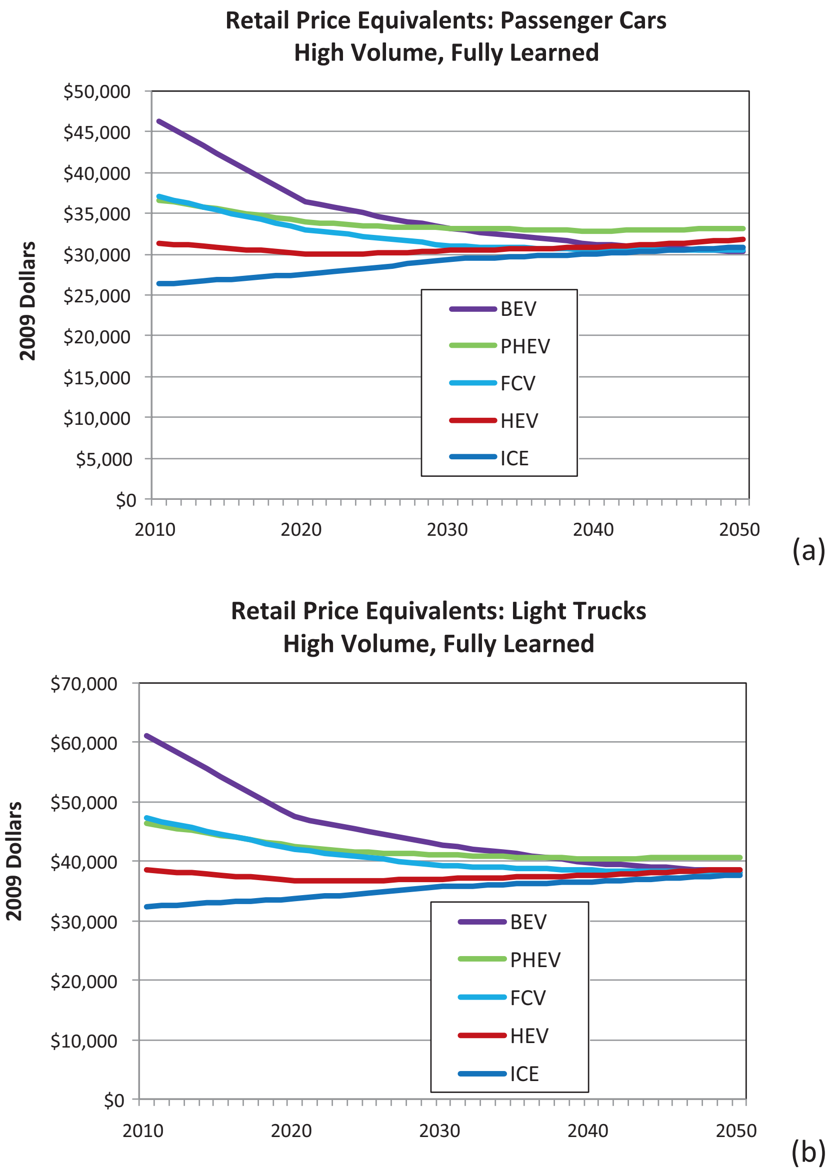


Fig. 6. (a and b) Retail price equivalents (long-run average costs) of advanced technologies at high volume and fully learned, mid-range and optimistic estimates: passenger cars [6].

become less costly than comparable ICEs or HEVs. PHEVs, on the other hand, remain a few thousand dollars more expensive through 2050 (Fig. 6a and b) because they require a powerful electric motor, internal combustion engine and a substantial battery pack. Other studies have projected the narrowing of cost differences over time (e.g., [28–30]) 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 Fig. 6a and b assume fully-learned, high-volume production (at least 200,000 units per year). In the LAVE-Trans model, these costs must be approached over time through cumulative production and the growth of market demand. Costs in the early years of a transition will be far higher than those shown in Fig. 6a and b.

Battery and fuel cell system costs are key to the projections. The estimated costs of batteries are consistent with NHTSA and EPA [25] estimates for 2025, reaching $160/kWh for battery electric vehicles by 2050, and $650/kWh for hybrid electric vehicles. The fuel cell system costs for 2010 are consistent with high-volume, fully-learned cost estimates by James [40,41]. The reductions in high volume production costs are generally consistent with other projections of high-volume costs over the next 15–20 years (e.g., [21]). The range of battery electric vehicles is held constant over time at 100 miles, so that battery cost reductions translate directly into vehicle cost reductions. Plug-in hybrids were designed for a 25 miles real-world all-electric driving range.

Reference energy prices are based on the Energy Information Administration's 2011 Annual Energy Outlook [20]. Low carbon energy prices are from the NRC [6] *Transitions* study. Prices of gasoline, electricity and hydrogen for highway use are shown in Fig. 7a–c. Regional prices were calculated by weighted averaging of prices for relevant Census Regions, provided in

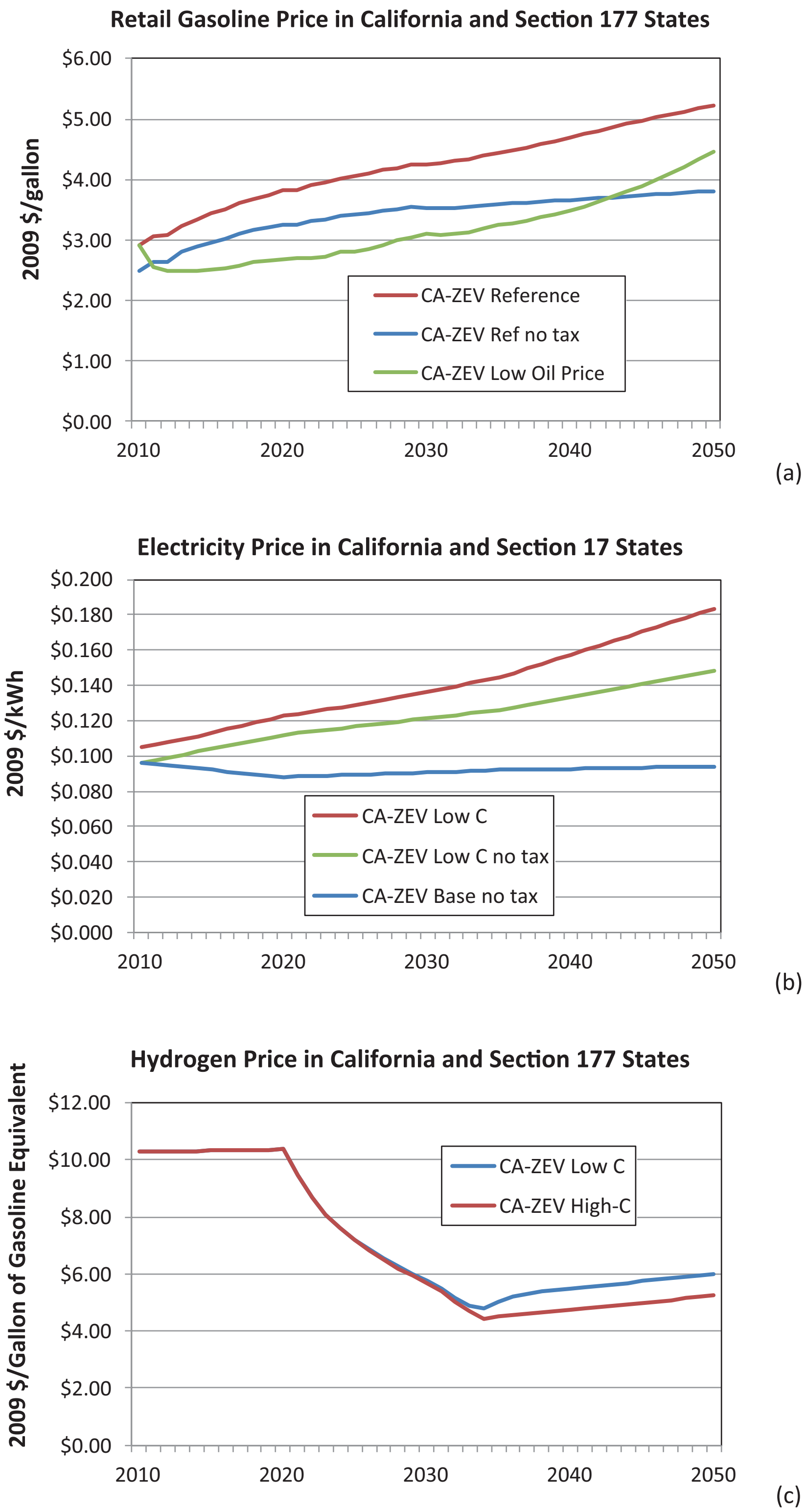


Fig. 7. (a–c) Energy prices used in the LAVE-Trans model runs.

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 IHUF assigns the motor fuel tax to all forms of energy used by light-duty vehicles and indexes the fee to the average energy efficiency 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 [31]. 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 (Fig. 7a). Approximately \$1 of that increase is due to the increase of the IHUF. 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 incremental cost of low carbon electricity increases gradually to about 5 cents per kWh

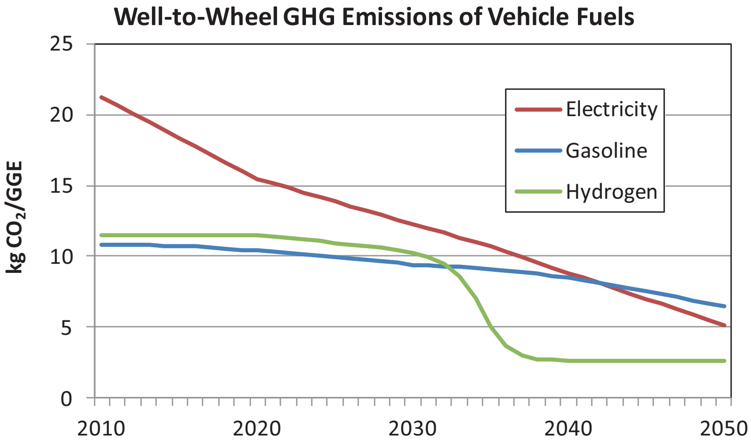


Fig. 8. Well-to-wheel greenhouse gas emissions from vehicle fuels, U.S. averages.

in 2050. The retail price of hydrogen is initially above \$10 kg^{-1} due to the high cost of supplying hydrogen in small volumes and the high cost of operating refueling outlets below design capacity. Lower 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 from the NRC [6] *Transitions* study.

The scenario presented in the following section assumes 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 [6] 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 13.5 billion gallons of gasoline with synthetic gasoline derived from biomass via pyrolysis and refining. U.S. average emissions are shown in Fig. 8; 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.

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.

6. Transitioning 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 [10]. 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 necessarily a policy recommendation. Current vehicle subsidies continue until 2015 when they are assumed to 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, energy suppliers and consumers by means of regulatory requirements.

Two key policies are assumed to remain in effect and be strengthened over time: (1) fuel economy and GHG 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 [6] *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–\$4 per gallon, before tax. Production grows to 13.5 billion gallons in 2030 and remains at that level through 2050 unless fewer gallons are demanded ([6], 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 [32]. The latest Air Resources Board staff estimates suggest that in the initial phase in years 2015–2017, manufacturers are likely to sell 6500–7000 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

Table 1
Station deployment and expected FCV sales in California: ARB and CAFCP estimates.

Station deployment and expected vehicles sales in California				CAFC sales	Estimated minimum ZEV sales requirement
Year	Start of year station total	Added stations	CAFCP number of vehicles on the road		
2012	4	4	312	100	0
2013	8	9	430	118	0
2014	17	20	1389	959	0
2015	37	31	10,000	8611	2134
2016	68	Market needs	20,000	10,000	2269
2017	*84*	Market needs	53,000	33,000	2297
2018	*100*	Market needs	*95,000*	*42,000*	2943

Sources: [33], Table 5; ICCT estimates.
Numbers in italics have been approximated based on lower bounds given in CAFCP Table 5.

the other Section 177 states, and vice versa. Through 2025, the ARB estimates sales of nearly 1 million TZEVs, about 385,000 BEVs and approximately 170,000 FCVs. Detailed assumptions about vehicles sales under the ZEV scenarios can be found in Appendix Table A.1.

Hydrogen infrastructure deployment is based on California's plan for deploying hydrogen refueling stations. It begins with the strategic placement of 68 stations in five linked clusters [33,34] during a pre-commercial period from 2012 to 2014 (Table 1). 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 and 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. 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 California Fuel Cell Partnership's (CAFCP) 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 which have been used in the scenarios presented below.

The current and planned deployment of recharging infrastructure is much farther advanced. The California Plug-in Electric Vehicle Collaborative [35] reported that installation of more than 7500 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 1000 BEVs sold.

For the purpose of calculating costs and benefits, the scenario has a base case that includes identical assumptions about technologies' energy efficiencies and costs. The base case assumes that fuel economy/emissions standards are in effect and that Highway Trust Fund revenues are maintained by means of the IHUF.[9] Beginning in 2018 the strict fuel economy and emissions standards necessary to drive the dramatic improvements in fuel economy shown above in Fig. 5 are assumed to induce manufacturers to price the alternative technologies to reflect the social costs of their greenhouse gas emissions and petroleum use.[10] 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 a potential availability of 13.5 billion gallons of low-carbon gasoline produced from biomass via thermo-chemical conversion processes plus 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 even without a transition to electric drive vehicles. 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.

The transition scenario ("California Leads, U.S. Follows") assumes that the rest of the U.S. follows the California and 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 explores what might happen if the rest of the U.S. did not follow California's lead and did not adopt policies to induce a transition to electric drive. None of the scenarios

[9] 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.

[10] 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.

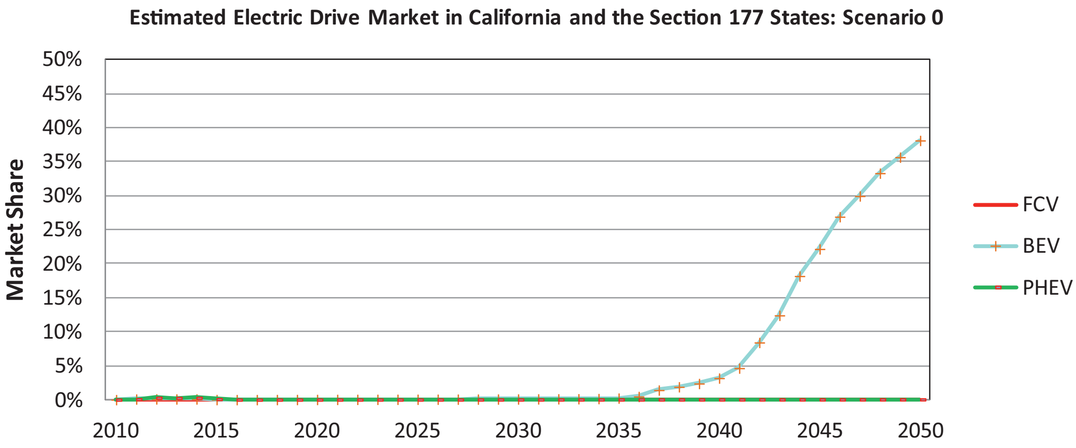


Fig. 9. Estimated electric drive market in California and the Section 177 states: scenario 0.

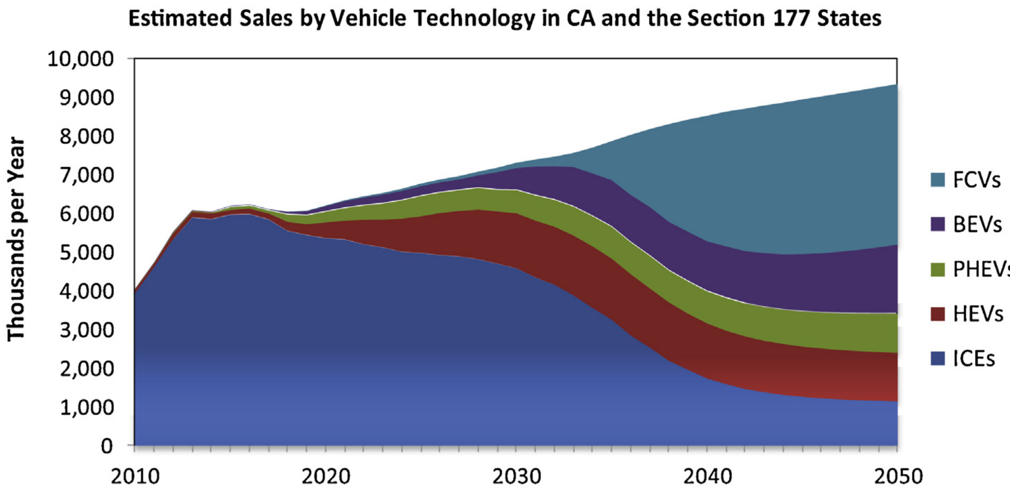


Fig. 10. Estimated sales by technology in California and the Section 177 states: scenario 2.

reflects uncertainty about the market's response to alternative vehicles and fuels. Instead, a sensitivity analysis was carried out for the principal scenario using Monte Carlo simulation to illustrate the implications of uncertainty about consumers' preferences.

Not only are the transition scenario and its variants conditional on many assumptions about technological progress and market behavior but the modeling of energy transitions is still in an early stage of development. Still it may provide useful insights about the nature of the transition, the factors on which its success is 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.

A ''No-Transition'' case is the base case to which the scenario is compared. Although it assumes no ZEV requirements, it still includes very significant policy actions. California and federal fuel economy and emissions standards are continuously tightened to produce the fuel economy improvements shown above and these are assumed to induce manufacturer pricing that favors electric drive vehicles. The No-Transition case includes the Indexed Highway User Fee on all vehicle energy use, as well as 13.5 billion gallons gasoline equivalent of drop-in biofuels. These actions have enormous impacts, reducing 2050 petroleum use by an 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, appear to be 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 (Fig. 9). After that point, sales take off, eventually capturing an estimated 38% of the market in California and the Section 177 states in 2050.

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.

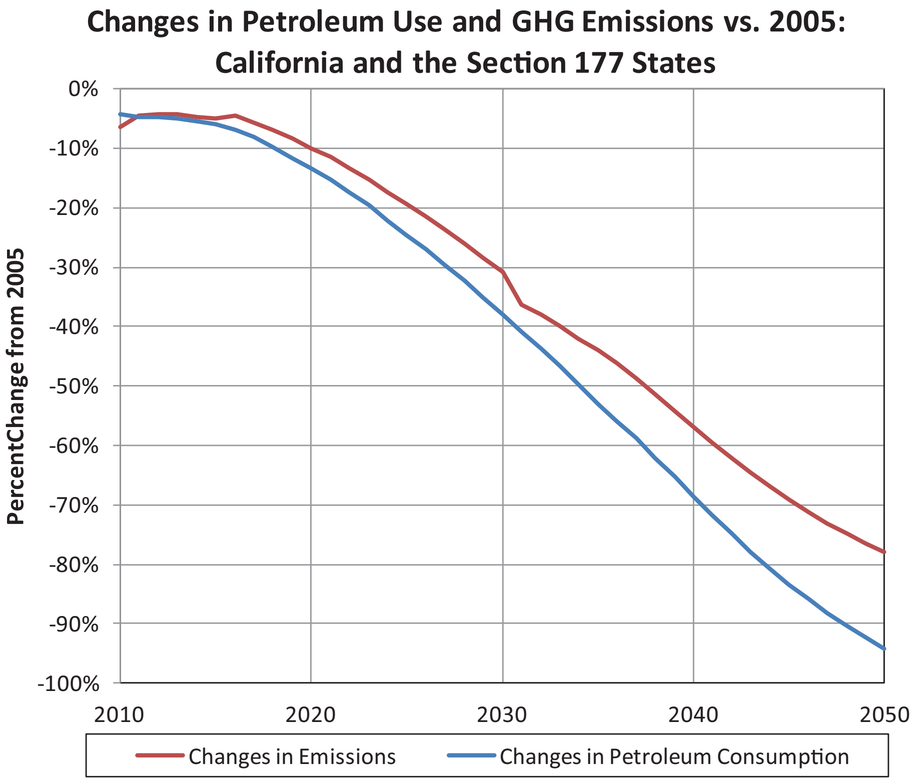


Fig. 11. Changes in petroleum use and GHG emissions vs. 2005 in California and the Section 177 states.

6.1. California and the Section 177 states lead, rest of US follows

If the ZEV program in California and the Section 177 states appears to be successful, it is likely to induce other states and the federal government to adopt similar transition policies. In the transition scenario, policies in the rest of the U.S. lag those in California by five years and begin in 2020. U.S. transition policies include both early infrastructure deployment and mandates or subsidies for ZEVs. However, the per-vehicle subsidies are lower than those required in the ZEV states because of the external benefits produced by the ZEV mandate. The result is a successful transition to ZEVs throughout the U.S. By 2050, 75% of new vehicle sales are FCVs, PHEVs or BEVs and most of the remainder are HEVs (Fig. 10). By 2050, 60% the light-duty vehicles on the road are estimated to be electric drive and another 15% are hybrid vehicles.

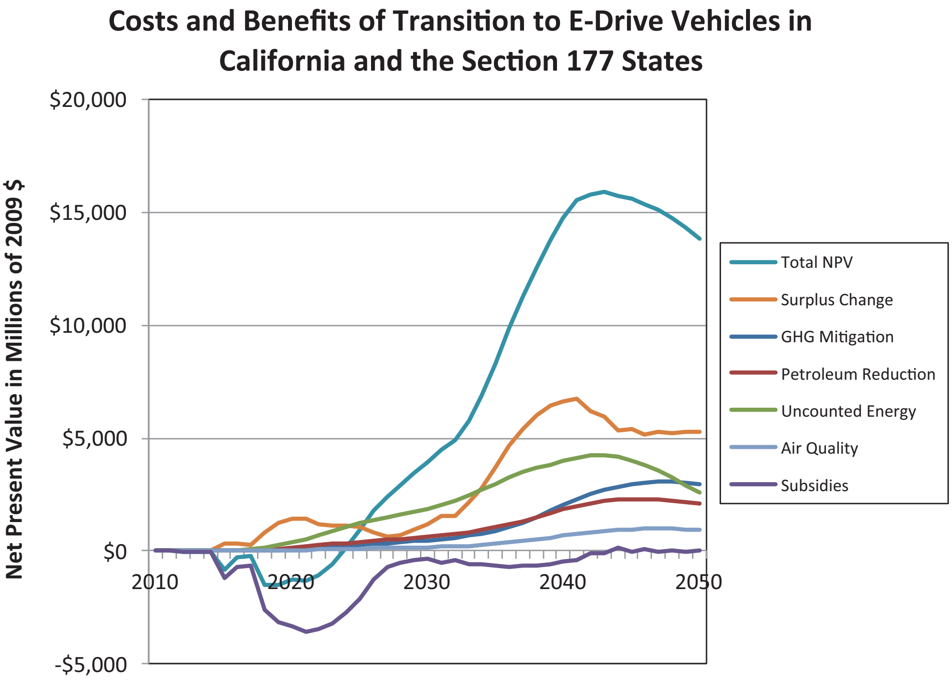
The transition to electric drive vehicles, combined with low-carbon electricity, hydrogen and gasoline, achieves a 79% reduction in GHG emissions[11] and virtually eliminates petroleum use by light-duty vehicles by 2050 (Fig. 11). In this scenario only 4.6 billion gallons or 35% of gasoline is produced thermo-chemically from biomass. This is considerably less than the 13.5 billion gallons included in the “No Transition” case because less gasoline is being consumed.

Although substantial costs must be borne up front, the net present value of the transition to e-drive vehicles appears to be very large (Fig. 12a). The present value of explicit and implicit subsidies for vehicles and infrastructure in California and the Section 177 states is estimated at $3.4 billion annually (present value) in the peak years and adds up to an estimated $36 billion total present value. This cost estimate is of the same general magnitude as excess transition costs estimated by NRC [36] and NRC [37]. Because costs must be paid up front, the total net present value is negative for almost a decade. Yet the overall net present value of the transition is estimated at more than a quarter of a trillion dollars ($294 billion). It is 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, plus smaller but still significant air quality benefits.

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 of California and the Section 177 states (Fig. 12b). The costs and benefits have been calculated relative to the base case that contains exactly the same assumptions about energy efficiency improvements, availability of low-carbon biofuels, and technological progress but omits the policies necessary to drive a transition to electric drive vehicles, such as the ZEV standards.

The effect of the transition policies on the marketability of fuel cell vehicles is illustrated in Fig. 13 and battery electric vehicles in Fig. 14. The figures illustrate quantitatively some of the network external benefits generated by the early,

[11] 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.



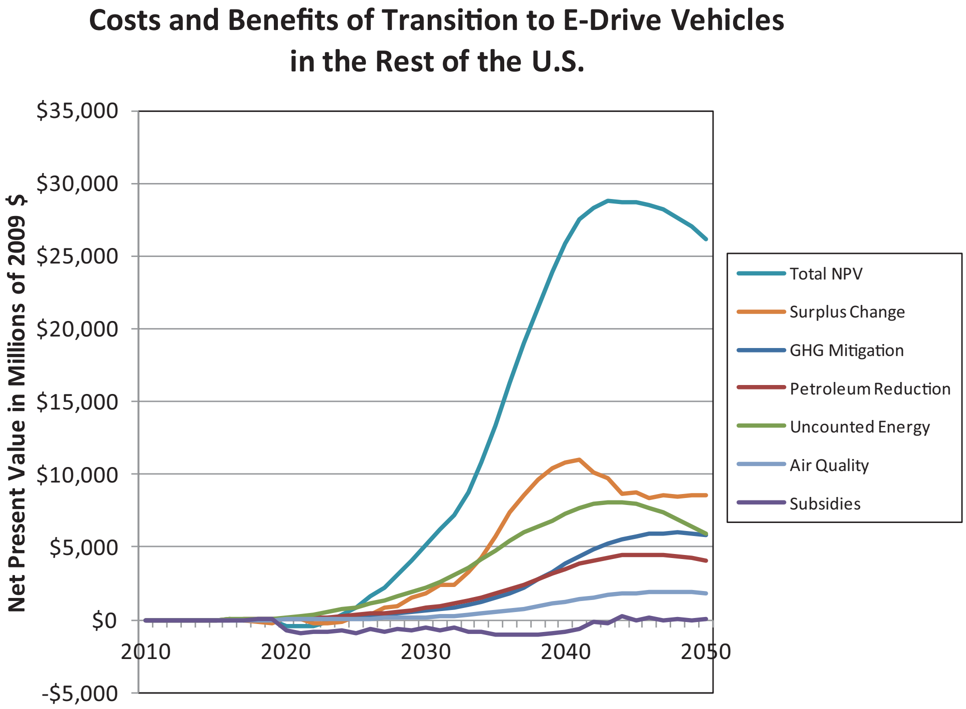


Fig. 12. (a) Costs and benefits of transition to e-drive vehicles in California and the Section 177 states. (b) Costs and benefits of transition to e-drive vehicles in the rest of the US.

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 be considered illustrative rather than precise since much remains to be learned about how consumers value such factors as limited fuel availability or how risk averse majority consumers are to purchasing early zero emission vehicles. The graphs illustrate the effect of the positive feedbacks produced by network external benefits and how they can 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 before 2015 greatly reduces the estimated cost of lack of fuel availability. But it is not until after 2030 that

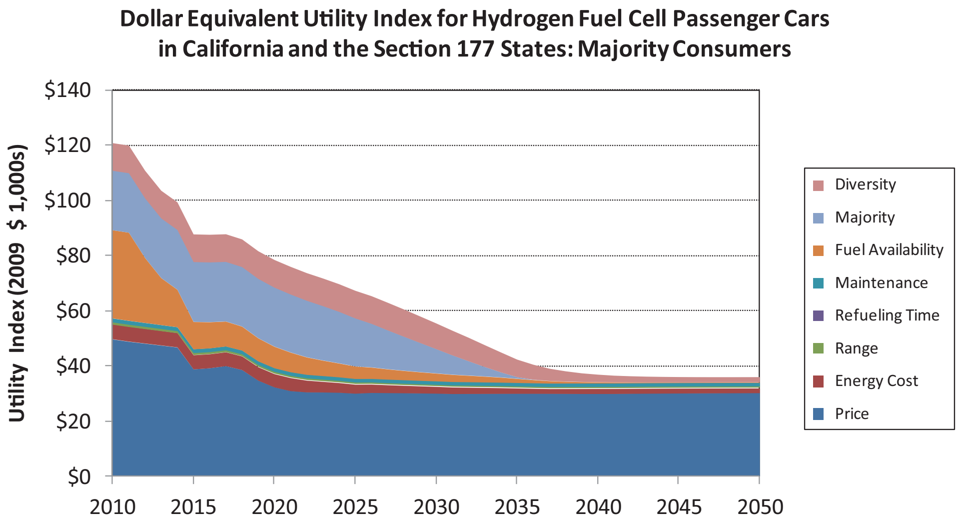


Fig. 13. Dollar equivalent utility index for hydrogen fuel cell passenger cars in California and the Section 177 states: majority consumers.

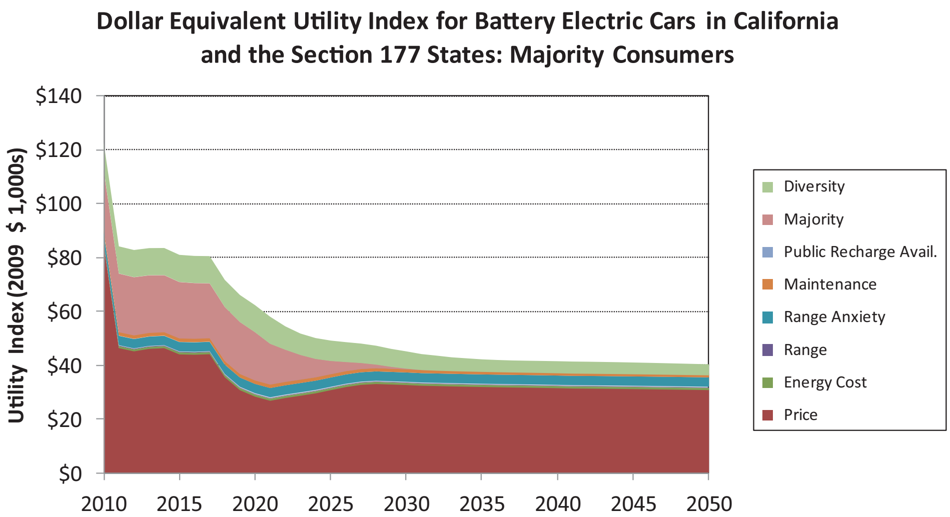


Fig. 14. Dollar equivalent utility index for BEV cars in California and the Section 177 states: majority consumers.

the cost of limited fuel availability becomes smaller than $1000 per vehicle. The majority's risk aversion and the lack of diverse choices of makes and models take even longer to overcome.

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, even initially. The value of public recharging infrastructure is unfortunately invisible in Fig. 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 EV's 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% even by 2050, limited diversity of make and model choice remains somewhat of a barrier.

The market's aversion to the risk of novel technology appears to be a major barrier. Sales to majority consumers are essentially zero during the early years of market development; innovators and early adopters are virtually the only purchasers (Fig. 15), according to the assumptions used in the LAVE-Trans model.[12] Innovators and early adopters are the ones who 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 are what allow the transition to proceed more rapidly with a less intense policy effort in the rest of the U.S. The earliest buyers of fuel cell vehicles create a market for hydrogen thereby

[12] 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.

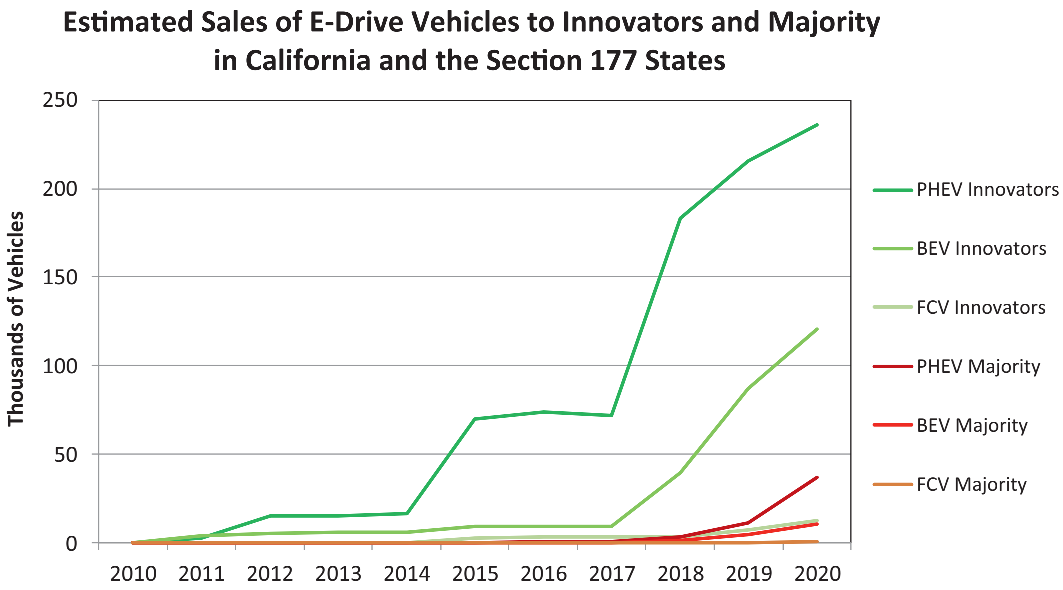


Fig. 15. Estimated sales of e-drive vehicles by risk group in California and the Section 177 states.

expanding 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 $5000 per vehicle. Sales required by the ZEV mandate and by the federal program also reduce costs by scale economies and learning-by-doing by an estimated $25,000 per vehicle by 2025.[13] From this perspective, subsidies to the first purchasers of electric drive vehicles could be more than justified by the network external benefits they create for subsequent purchasers. Of course, this justification depends critically on the ultimate success of the transition such that present value benefits exceed present value costs by a substantial amount.

6.2. Higher and Lower Oil Prices

A sustainable transition to electric drive vehicles appears achievable even with Lower Oil Prices. In the High Oil Price case the ultimate success of the transition to e-drive vehicles is increased 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 slightly lower as well. Using the Low Oil Price Case assumptions, 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 $3000 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.

6.3. No Early Hydrogen Infrastructure

The existence of tipping points in technology transitions in general and to low-carbon vehicles and fuels in particular has been recognized previously [19], as has the tendency for positive feedbacks to create path dependence [13,38]. 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 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 the transition scenario the failure to provide early hydrogen infrastructure in California derails the transition to

[13] 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.

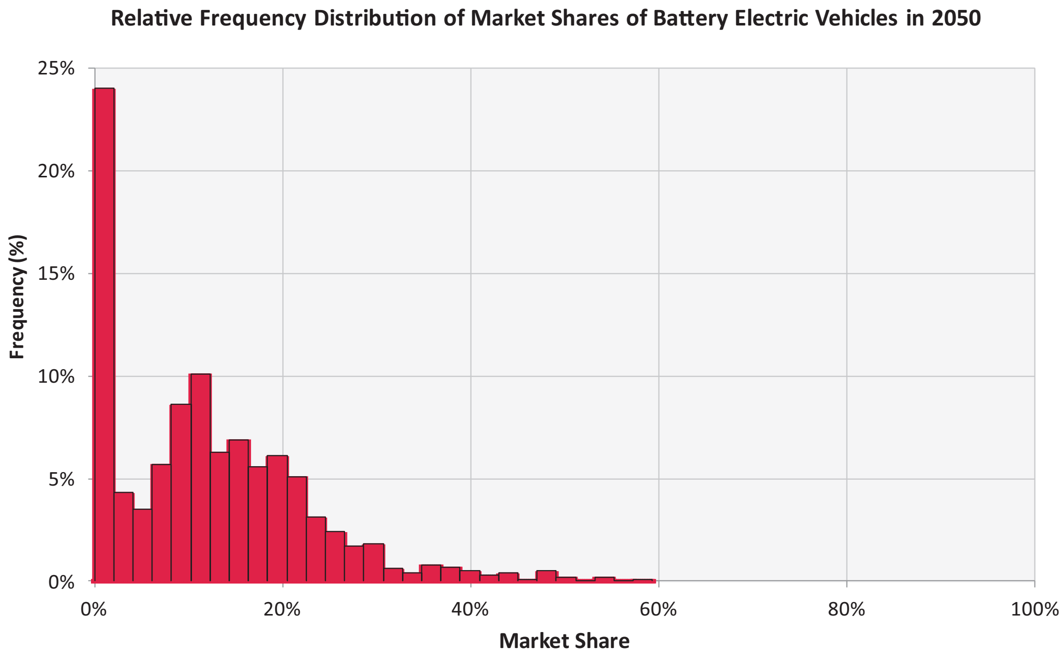


Fig. 16. Relative frequency distribution of BEV market shares generated by Monte Carlo simulation.

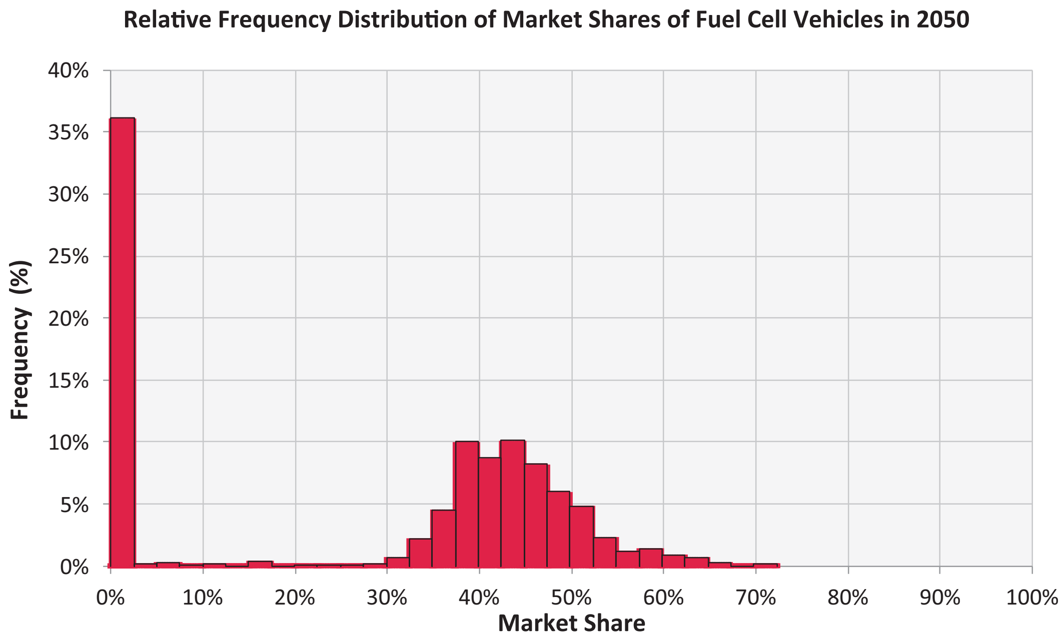


Fig. 17. Relative frequency distribution of FCV market shares generated by Monte Carlo simulation.

FCVs elsewhere in the U.S. The early provision of hydrogen infrastructure in California appears to be a critical tipping point. 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 the transition scenario 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 $2000 per vehicle by 2025. Without any early refueling stations, the implicit subsidies are $31,000 per vehicle in 2015 and $7500 per vehicle in 2025. These subsidies are in addition to the federal tax credit of $7500 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 estimated to be about $2 billion higher if the initial 68 hydrogen refueling stations are not deployed. Given that the stations are estimated to cost $1–$2 million to construct, deploying early infrastructure would seem to be very cost-effective. 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.

7. Coping with uncertainty

Although the NRC Transitions study committee took care to use sound engineering analysis and the best available economic parameters, the future remains very uncertain. Quantifying the uncertainties decision makers face in managing a transition to sustainable vehicles and fuels can be useful [42]. 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 a more realistic description of the challenges to accomplishing a transition to electrically powered vehicles.

To illustrate the magnitude of uncertainty, a Monte Carlo simulation consisting of 1000 different model runs was carried out using the probability distributions for the 17 parameters shown in Table A.3.[14] 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 are held constant for all simulations. This means constant implicit subsidies for vehicles and deployment of a fixed amount of early infrastructure, 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.

Figs. 16 and 17 illustrate 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 in those simulations. The simulated probabilities of failure are about 35% in the case of FCVs and 25% for BEVs but again, the simulation assumes no adaptation of policies. BEV market shares range to 60%, with the greatest frequencies in the interval 2–30%. 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 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.

8. Concluding discussion

The analysis indicates that it may be possible for a transition to electric drive vehicles to produce benefits that exceed the excess costs of a transition by an order of magnitude or more. Constructing a logical paradigm for understanding the economics of the transition and even imprecisely measuring the costs and benefits is intended to be a useful contribution. The future of electric drive vehicles is highly 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 optimal strategies 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 the optimal strategies based on a full knowledge of future events [39]. There is little doubt that public policy will have to adapt in order to successfully accomplish a transition to sustainable, electric-drive vehicles.

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

- 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. Reducing 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 in pursuit of an uncertain outcome.
- 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-

[14] The simulations were run using the @Risk® commercial software.

emission, electric drive vehicles. On the supply side, better understanding of firms' responses to risk, and quantifying scale economies and learning rates are also important.

This paper has described an 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.

Acknowledgments

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Appendix

See Tables A.1–A.3

Table A.1
Estimated 2015–2025 ZEV requirements 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	9999	10,518	10,267	48,428	94,446	132,892	167,434	191,548	217,543	235,105	242,539
FCV	3333	3506	3422	4280	8975	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
Lifetime emission rates for vehicles sold after 2009 (g/mi) and values of pollutant reduction per metric ton (2012 $).

	2010–2019			2020–2024			2025–2050		
	NO_x	HC	PM10	NO_x	HC	PM10	NO_x	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.3
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 ($/h)	Triangle	$10.00	$20.00	$40.00
Maximum value of public recharging to typical PHEV buyer	Uniform	$500	$1000	$1500
Cost of one day on which driving exceeds BEV range	Uniform	$10	$20	$30
Maximum value of public recharging to typical BEV buyer	Uniform	$0	$500	$1000
Importance of fuel availability relative to standard assumption	Triangle	0.67	1.00	1.67
Payback period for fuel costs (yrs.)	Triangle	2.0	3.0	5.0
Volume threshold for introduction of new models rel. to std. assumptions	Uniform	0.80	1.00	1.20
Optimal production scale relative to standard assumptions	Uniform	0.75	1.00	1.25
Scale elasticity relative to standard assumptions	Uniform	0.50	1.00	1.50
Progress Ratio relative to standard assumptions	Uniform	0.96	1.00	1.04
Price elasticities of vehicle choice relative to standard assumptions	Uniform	0.60	1.20	1.80
Percentage of new car buyers who are innovators	Triangle	5.0%	15.0%	20.0%
Willingness of innovators to pay for novel technology ($/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

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