Journal of Power Sources 196 (2011) 530–540

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Advanced vehicles: Costs, energy use, and macroeconomic impacts

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ARTICLE INFO

Article history:
Received 28 May 2010
Accepted 4 July 2010
Available online 31 July 2010

Keywords:
Fuel cell vehicles (FCVs)
Battery electric vehicles (BEVs)
Plug-in hybrid electric vehicles (PHEVs)
Alternative transportation fuels
Macroeconomic analysis

ABSTRACT

Advanced vehicles and alternative fuels could play an important role in reducing oil use and changing the economy structure. We developed the Costs for Advanced Vehicles and Energy (CAVE) model to investigate a vehicle portfolio scenario in California during 2010–2030. Then we employed a computable general equilibrium model to estimate macroeconomic impacts of the advanced vehicle scenario on the economy of California. Results indicate that, due to slow fleet turnover, conventional vehicles are expected to continue to dominate the on-road fleet and gasoline is the major transportation fuel over the next two decades. However, alternative fuels could play an increasingly important role in gasoline displacement. Advanced vehicle costs are expected to decrease dramatically with production volume and technological progress; e.g., incremental costs for fuel cell vehicles and hydrogen could break even with gasoline savings in 2028. Overall, the vehicle portfolio scenario is estimated to have a slightly negative influence on California's economy, because advanced vehicles are very costly and, therefore, the resulting gasoline savings generally cannot offset the high incremental expenditure on vehicles and alternative fuels. Sensitivity analysis shows that an increase in gasoline price or a drop in alternative fuel prices could offset a portion of the negative impact.

1. Introduction

Advanced vehicles and alternative fuels could play an important role in environmental protection. Conventional vehicle emissions contribute a lot to urban air pollution [1]. In contrast, advanced vehicles could substantially reduce greenhouse gas (GHG) emissions [2] and improve urban air quality [3,4]. Moreover, alternative vehicles could also reduce oil use and change the economy structure. Ogden et al. [5] estimated societal lifecycle costs of fuel cell vehicles. However, few such studies have examined the macroeconomic impacts of advanced vehicles – fuel cell vehicles, battery electric vehicles, and plug-in hybrid electric vehicles – on the statewide economy [6].

The next few decades are expected to be an important period of transitioning to alternative transportation technologies [7,8]. California has enacted aggressive zero emission vehicle (ZEV) policies to transition to a low carbon economy. Thus, it is meaningful to examine the potential market trajectory of advanced vehicles in the on-road vehicle stock over the time period 2010–2030. Taking this a step further, the study also estimates total energy use and gasoline displacement or savings resulting from alternative vehicle penetrations.

To estimate the steady-state costs for non-conventional vehicles and fuels in California, we developed a Costs for Advanced Vehicles and Energy (CAVE) model. Much uncertainty exists in forecasting costs for future electric drive vehicles, and estimates of advanced vehicle cost depend heavily on market penetration scenarios [9]. By employing learning curve techniques, the vehicle cost trajectory associated with a portfolio scenario is determined. Using a California-specific economic model, we eventually estimate the macroeconomic impacts of advanced vehicles on the economy of California.

2. Costs for Advanced Vehicles and Energy (CAVE) model

This study is focused on the time period 2010–2030, which is critical for the transition of advanced vehicles. However, there are no or few such vehicles today on the road in California and in the US. As with other studies, this analysis generally assumes non-conventional future cars have a comparable or higher performance than today's cars. Only passenger cars are considered; other light duty vehicles such as pickup trucks, sports utility vehicles (SUVs), and vans are not included in the study. Below are a few important modeling steps in CAVE.

2.1. Vehicle market penetration

The on-road fleet of passenger cars is based on projections of California's mobile emission factor model, EMFAC2007. New car

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doi:10.1016/j.jpowsour.2010.07.009

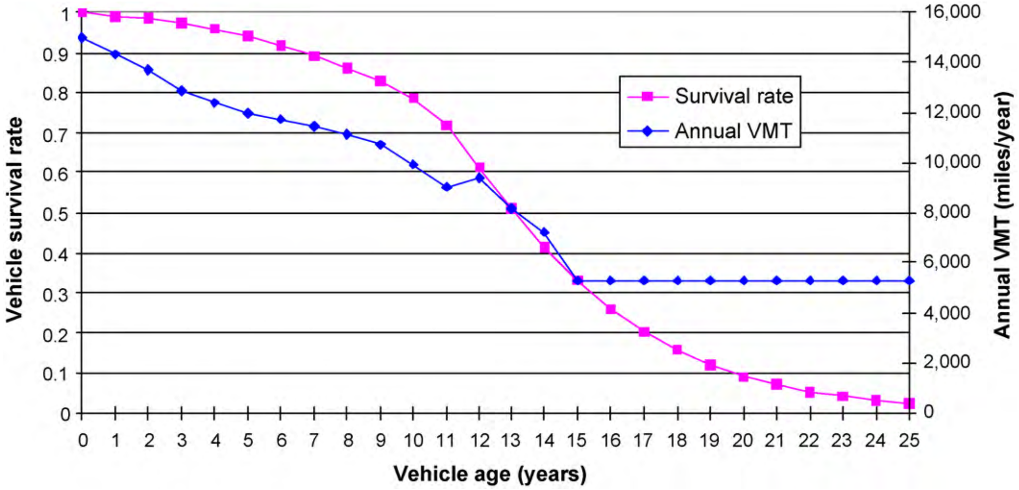

Fig. 1. Annual VMT of a typical car and vehicle survival rate [13].

sales each year account for 6.3% of the on-road fleet of that year [10]. We developed a portfolio scenario of new sales of advanced vehicles. The rationale is that there is no "silver bullet" solution – no single vehicle/fuel pathway – can help California meet its long-term climate change mitigation targets, i.e., reducing GHG emissions to 80% below 1990 levels by 2050 [2]. Advanced vehicle penetration into the market occurs at the national level. It is extremely important to note that, within the context of the entire US market for advanced vehicles, California is assumed to account for 50% of new sales in 2010 and linearly down to 20% in 2030. New car sales are composed of the following five types of vehicles.

Fuel cell vehicles (*FCVs*). Hydrogen FCVs are assumed to take off in 2020–2027, spanning eight years. California has been long interested in developing hydrogen refueling infrastructure, e.g., the California Hydrogen Highway project. On the other hand, fuel cell technology has been making rapid progress and, in 2008, fuel cell system costs dropped to $\$73\,\mathrm{kW}^{-1}$ at high volume, say, $500{,}000\,\mathrm{units\,year}^{-1}$ [11]. As with another study [7], a representative FCV is an 80 kW fuel cell "engine" with 5 kg of compressed hydrogen gas stored onboard.

Battery electric vehicles (*BEVs*). BEVs are expected to take off in 2018–2025, spanning eight years. This analysis assumes BEVs to have almost comparable performance as the other advanced or conventional vehicles, including driving range and battery durability.

Plug-in hybrid electric vehicles (*PHEVs*). PHEVs are assumed to take off in 2018–2025 too, like BEVs, as battery is the most critical limiting factor for both. However, PHEVs are expected to have much higher volume than BEVs to reflect the current "hot" interest. This study uses PHEV-30, a plug-in hybrid with an all electric range (AER) of 30 miles per charge, as a representative vehicle.

Hybrid electric vehicles (*HEVs*). HEVs began to penetrate the market a decade ago and are now commercially mature. Regular hybrids account for about 5% of current new car sales in California, and are expected to grow linearly to 17% in 2030 in the portfolio scenario.

Internal combustion engine vehicles (*ICEVs*). The remaining new sales are all conventional ICEVs included as a point of comparison.

Only ICEVs and HEVs make up the current fleet mix and sales mix. Note that advanced vehicles, or called electric drive vehicles, include FCVs, BEVs, and PHEVs. Pure ZEVs include only FCVs and BEVs.

2.2. Vehicle cost: learning-by-doing and technological advance

Several recent studies applied a composite learning curve approach to estimate the cost of fuel cell vehicles in the hydrogen transition [7,9] and the cost of plug-in hybrids [8]. In fact, there is no better way to project future cost of new technology in an accurate manner, especially for the complicated transportation technologies. Similarly, we also employ the learning curve techniques to estimate likely cost trajectories of new, advanced vehicle technologies.

For each doubling of cumulative capacity, unit cost of manufacturing will drop by a percentage, typically, 80% [12]. For a given year, a general learning-by-doing function is shown in Eq. (1):

$$C_N = C_1 \times N^b \tag{1}$$

where C_1 is the cost for the first unit; C_N refers to the cost required to produce the Nth unit; N is the number of units produced, e.g., the number of cars made; and $b = \log_2(p) = -0.322$ for a typical progress ratio $p = 0.80$.

However, the original equipment manufacturer (OEM) cost of building the first vehicle in 2030 makes no sense to remain the same as making the first vehicle of model year 2010. In order for the learning approach to accommodate the varying effects of different-year technologies, the cost required to produce the first unit is expected to drop with year, reflecting technological advance during the period 2010–2030, as shown in Eq. (2):

$$C_1(T) = C_1(2010) \times e^{-\lambda(T-2010)} \tag{2}$$

where T is any calendar year in 2010–2030; $C_1(2010)$ is the cost for the first unit in 2010; $C_1(T)$ refers to the cost for the first unit in year T; and λ is a constant; e.g., $\lambda = 0.0112$ represents that the cost of the first unit, on average, declines by 1% with year.

The total cost is derived by applying the unit cost equation as many times as needed and then summing all the values. The average cost is the total cost divided by the number of units produced. Note that the average cost of each advanced vehicle is estimated in the context of the entire US advanced vehicle market, where California is assumed to account for 50% of the new sales in 2010 and linearly down to 20% in 2030. However, the aggregate vehicle costs correspond to the California fleet only, as this study is focused on statewide (not national) impacts.

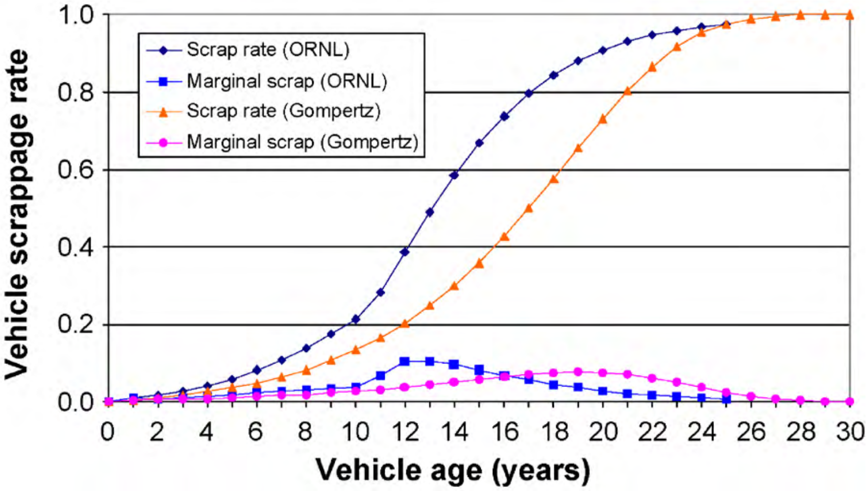

Fig. 2. Comparison of two sets of vehicle scrappage rates.

2.3. Annual VMT

This study employs vehicle miles traveled (VMT) of a typical car in the US. Fig. 1 shows the average annual VMT, based on the Transportation Energy Data Book [13], which generally drops with vehicle age, especially in the beginning years. Note that at ages of 15 years and older, a typical car travels 5300 miles year^{-1}.

2.4. Vehicle scrappage

2.4.1. Gompertz function approach

Vehicle survival rates are estimated by using the Gompertz function approach. This exponential relationship is shown as Eq. (3):

$$s(t) = e^{-B(e^{Ct}-1)} \tag{3}$$

where t is vehicle vintage, $t = 0, 1, 2, \ldots$; $s(t)$ refers to vehicle survival rate at age t; and B and C are constants: this study assumes $B = 0.02$ and $C = 0.21$.

By definition, the vehicle scrappage rate and the survival rate sum to one. The scrappage rate at a certain vehicle age, based on the Gompertz approach, is shown in Fig. 2.

Expected vehicle lifetime can be calculated as Eq. (4):

$$\bar{t} = \frac{\sum_{t=0}^{30} MSR_t \times t}{\sum_{t=0}^{30} MSR_t} \tag{4}$$

where $\bar{t}$ is expected vehicle lifetime; t is vehicle vintage, $t = 0, 1, 2, \ldots, 30$. Vehicles older than 30 years could be left out of the calculation because of their small fleet share; and MSR_t stands for the marginal scrappage rate at age t, which equals the scrappage rate at age t minus the scrappage rate at age $t-1$.

The Gompertz function approach gives an expected vehicle lifetime of 16.8 years, which is consistent with 16.9 years of passenger cars' life [14]. The Oak Ridge National Laboratory (ORNL) study also presents data on US vehicle survival rates (see Fig. 1), which are not used for our vehicle stock model as they are calculated to have an expected vehicle lifetime of 13.5 years. Fig. 2 compares the scrappage rate estimates (Gompertz) and the ORNL scrappage rates. In reality, the scrappage rate or vehicle lifetime, more or less, depends on the resale price of old vehicles and their scrap value.

2.4.2. Vehicle stock

Theoretically, the on-road vehicle stock in calendar year T can be estimated as Eq. (5):

$$\begin{aligned}\text{Veh\_Stock}\,(T) = {} & \text{Veh\_Stock}\,(T-1) + \text{New\_Sales}\,(T)\\ & -\text{Veh\_Scrappage}\,(T)\end{aligned} \tag{5}$$

For vehicles of the same model year at age t, vehicle scrappage is calculated as Eq. (6):

$$\text{Veh\_Scrappage}\,(t) = \text{New\_Sales}\,(t=0) \times \text{Scrappage\_Rate}\,(t) \tag{6}$$

In practice, we estimate the vehicle stock, accounting for scrappage, by using Eq. (7):

$$VS(T) = \sum_{i=0}^{t} NS(2010+i) \times SR[T-(2010+i)] \tag{7}$$

where T is any calendar year within 2010–2030; t is vehicle vintage, $t = T - 2010$; i is an integer for calculation purposes only; VS stands for the on-road vehicle stock in year T; NS stands for the number of new sales of vehicles, e.g., FCVs; and SR stands for vehicle survival rate.

2.5. Fuel economy

Fuel economy employed is based on the EPA combined city/highway drive cycle: 55% city driving and 45% highway driving. We assume faster growth rates for conventional ICEVs in the 2010–2020 time frame to reflect California's Clean Car Standards (Pavley): "Pavley I" standards are in place for model years 2009–2016, and "Pavley II" for 2017–2020. Thereafter fuel economy would increase at a slower rate through 2030. Fig. 3 shows the trends in future improvements of passenger car fuel economy, in miles per gallon of gasoline equivalent (mpgge).

For model year 2010, FCV could be operated with fuel economy of 72 miles per gallon (mpg) [15], BEV with 105 mpg [16], and ICEV with 31 mpg [16].

While the 2010 model Toyota Prius (4 cylinders, 1.8 L) has a combined fuel economy rating of 50 mpg, almost all other regular hybrids are EPA-rated far below this. This study uses an average fuel economy number of 42 mpg for composite OEMs starting from the 2010 model [16].

PHEV-30 typically corresponds to a utility factor of 0.50, which means 50% of aggregate VMT occurs in charge depleting (CD) mode,

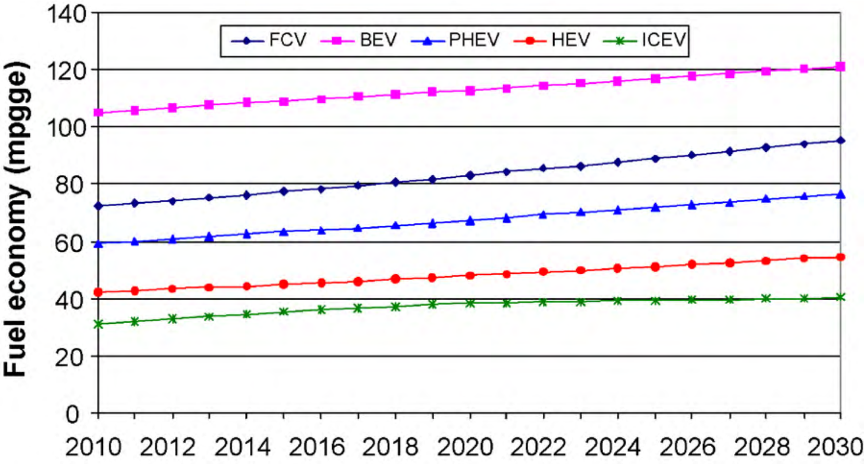

Fig. 3. Trends in future improvements of passenger car fuel economy.

i.e., all-electric driving [17]. On a gasoline gallon equivalent (gge) basis, PHEV-30 consumes a total of 71% of energy use in HEV: gasoline accounts for 50% and electricity 21% [17]. Therefore, an HEV-based estimate of 59 mpg applies to PHEV-30 in 2010.

Those pre-2010 vehicles are expected to be instrumental in satisfying travel demand in the subsequent decades, even in the case that advanced vehicles start to penetrate the market shortly after 2010 (see Fig. 6). In the time window 2010–2030, pre-2010 vehicles are relatively old and, on average, travel less than a typical fleet composed of both old and new vehicles. For simplicity, pre-2010 cars are assumed, on average, to travel 10,000 miles per year at 27 mpg.

2.6. Transportation fuel demand

Fuel demand of vehicles is calculated as Eq. (8):

$$FC(T) = \sum_{i=0}^{t} \frac{NS(2010+i) \times SR[T-(2010+i)] \times VMT[T-(2010+i)]}{MPG(2010+i)} \quad (8)$$

where T is any calendar year within 2010–2030; t is vehicle vintage, $t = T - 2010$; i is an integer for calculation purposes only; FC stands for fuel consumption in gallons of gasoline equivalent (gge) in year T; NS stands for the number of new sales of vehicles, e.g., FCVs; SR stands for vehicle survival rate; VMT refers to annual vehicle miles traveled; and MPG represents vehicle fuel economy in miles per gallon of gasoline equivalent (mpgge).

On a lower heating value (LHV) energy basis, 1 kg of hydrogen = 1 gallon of gasoline = 34 kWh of electricity. The HEV-based estimates indicate that about 70% of energy used by the PHEV-30 is from gasoline, and 30% from grid electricity. These relationships make it possible to estimate alternative fuel demand.

Note that the portion of gasoline still consumed in plug-in or regular hybrids should be taken into account to estimate the eventual gasoline savings. Generally, gasoline displaced by alternative fueled vehicles is estimated as Eq. (9):

$$GD(T) = \sum_{i=0}^{t} \frac{NS(2010+i) \times SR[T-(2010+i)] \times VMT[T-(2010+i)]}{MPG_0(2010+i)} \quad (9)$$

where GD stands for gasoline displacement in gallons in year T; and MPG_0 represents fuel economy, in miles per gallon (mpg), of the reference vehicle, i.e., ICEV.

2.7. Gasoline and electricity price forecasts

Retail gasoline prices over the period 2010–2030 are based on the California Energy Commission (CEC) high price forecast, which uses the Annual Energy Outlook (AEO) 2009 Reference Case crude oil prices [18]. Plug-in hybrids rely heavily on grid-connected electricity; typically, 50% of VMT associated with PHEV-30 is driven by electricity. CEC also projected the grid electricity price for vehicle use in California and its high price forecast is used in this study. Fig. 4 shows price forecasts for California retail gasoline and transportation electricity.

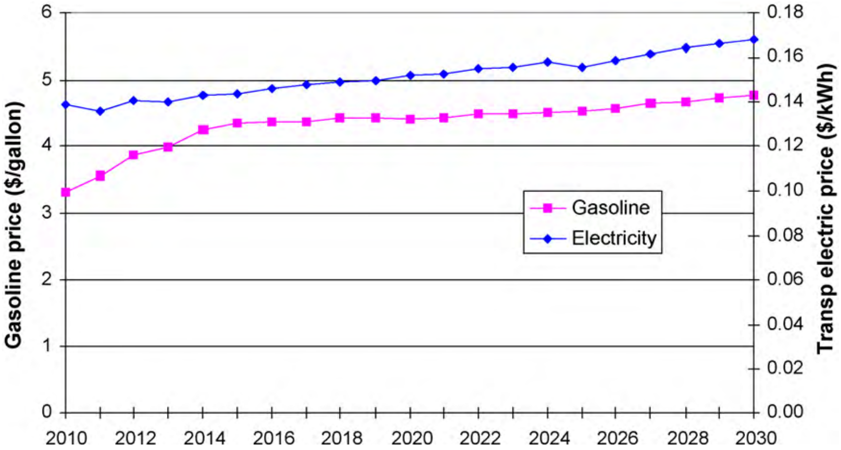

Fig. 4. California retail gasoline and transportation electricity price forecasts [18].

Table 1
Hydrogen supply options and levelized costs of hydrogen delivered to the users.

Electrolysis	Delivered price ($ kgH_2^{-1})	Size (TPD)	Efficiency	Efficacy (kWh kgH_2^{-1})	Elec price ($ kWh^{-1})	Elec cost ($ kgH_2^{-1})	Elec cost share
Current tech	8.50	1.5	74%	45	0.10	4.50	53%
Future tech	6.72	1.5	74%	45	0.10	4.50	67%
Onsite SMR	Delivered price ($ kgH_2^{-1})	Size (TPD)	Efficiency	Efficacy (mmBTU kgH_2^{-1})	NG price ($ mmBTU^{-1})	NG cost ($ kgH_2^{-1})	NG cost share
Current tech	3.86	1.5	72%	0.158	8.00	1.26	33%
Future tech	3.08	1.5	72%	0.158	8.00	1.26	41%
Central SMR	Delivered price ($ kgH_2^{-1})	Size (TPD)	Efficiency	Efficacy (mmBTU kgH_2^{-1})	NG price ($ mmBTU^{-1})	NG cost ($ kgH_2^{-1})	NG cost share
Current tech	3.41	379	74%	0.154	8.00	1.23	36%
Future tech	2.96	379	74%	0.154	8.00	1.23	41%

2.8. Hydrogen supply and costs

Over the next two decades, hydrogen made from natural gas via steam methane reforming (SMR) is expected to play a major role in the hydrogen economy transition. The rationale is that SMR technology is commercially mature and is one of the least-cost supply options [19,20]. However, onsite SMR and electrolysis could phase in first and meet hydrogen fuel demand at small scales, and then central production appears after the fuel market builds up [19,21]. This study includes three hydrogen supply options: onsite electrolysis, onsite SMR, and central SMR with pipeline delivery.

Table 1 presents hydrogen supply costs for the three options, on both a current and future technology basis. These data are derived from a recent hydrogen transition study where industrial prices of electricity and natural gas (NG) are used for hydrogen generation analysis [7], accounting for inflation and difference in feedstock costs. A typical central SMR is at a production volume of 379 tonnes per day (TPD), and both onsite SMR and distributed electrolysis at 1.5 TPD [9,19]. This study assumes future technology applies to year 2020 and beyond.

3. EDRAM model

To estimate macroeconomic impacts of advanced vehicle penetrations, we employ the Environmental Dynamic Revenue Analysis Model (EDRAM), a computable general equilibrium (CGE) model. EDRAM captures the fundamental economic relationships between producers, consumers, and government in California [6,22]. At equilibrium, the quantity supplied (which is a function of price) is equal to the quantity demanded (which is also a function of price) in the market. Using nonlinear optimization, EDRAM solves for the equilibrium price that clears the market.

For simplicity, California producers are aggregated into over 100 industrial sectors, and each sector is modeled as a competitive firm [6,22]. For example, the output of all of California's agricultural firms is modeled as coming from a single entity—the agriculture sector. Note that CGE models are not forecasting models. In contrast, EDRAM is an economic optimization model, although it is calibrated to exactly reproduce the economic conditions of the base year 2003 [6].

4. Results and discussion

4.1. Sales mix and vehicle stock

This study developed a portfolio scenario to simulate the likely vehicle market penetrations and, to the greatest extent possible, to reflect ZEV policies in California. Fig. 5 shows projected new car sales in California, representing the vehicle portfolio scenario.

Fig. 5 indicates that 4500 FCVs account for 0.5% of new sales in 2015, and 25,000 FCVs account for 2.5% in 2020. Followed by eight years take-off over 2020–2027, hydrogen cars will eventually account for 20% of new sales and reach 222,000 in 2030. Similarly, BEVs account for 0.3% of new sales at an annual production volume of 2500 BEVs in 2015, 2% of new sales and 20,000 BEVs in 2020, and eventually 13% of new sales and 144,000 in 2030. In contrast, PHEVs are expected to account for 1% of new sales and reach 9000 PHEVs in 2015, 5.5% and 54,000 vehicles in 2020, and eventually 25% of new sales and 277,000 in 2030.

Fig. 6 shows the estimated vehicle stock in the portfolio scenario. Although ICEVs are expected to only account for 25% of sales in 2030 and, as a result, alternative vehicles take the major sales share, alternative vehicles will still play a minor role in the on-road vehicle stock. Due to slow fleet turnover, pre-2010 vehicles,

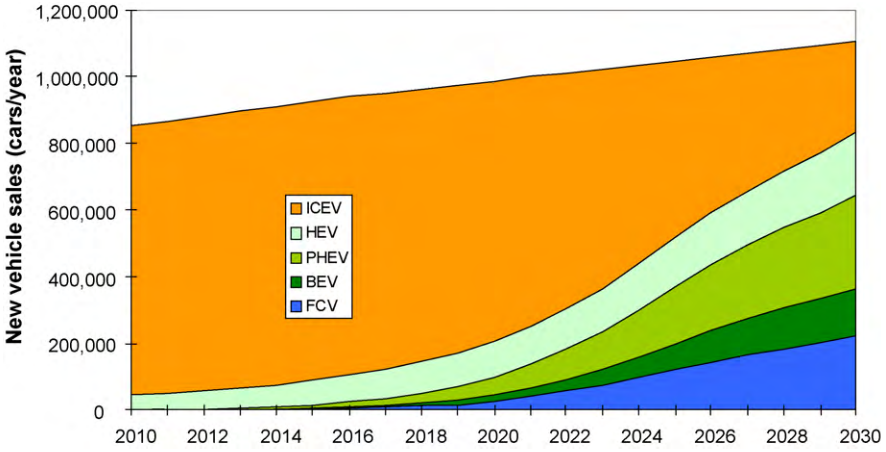

Fig. 5. Projected vehicle sales in the portfolio scenario.

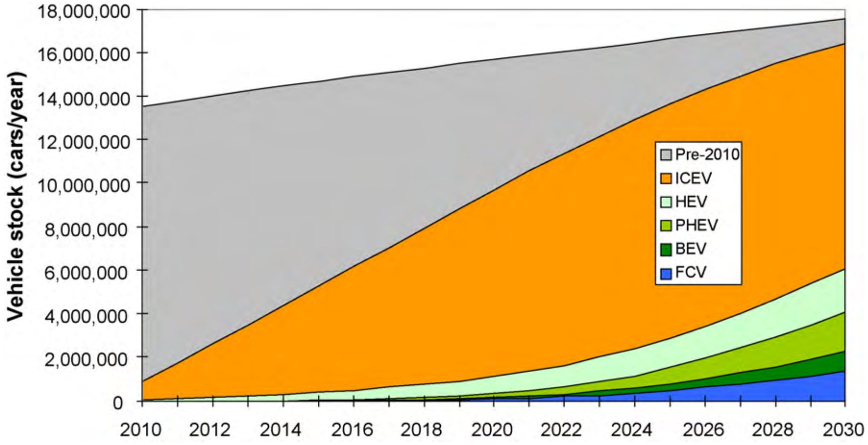

Fig. 6. Estimated vehicle stock in the portfolio scenario.

mostly conventional ICEVs, are expected to continue to account for a substantial fraction of the on-road fleet, especially in the early 2010s. Conventional vehicles – newly introduced ICEVs and pre-2010 vehicles – are expected to play a major role over the time period studied, and collectively account for about 65% of the vehicle stock in 2030 (with pre-2010 vehicles still accounting for 6.8% in 2030). Put another way, advanced vehicles and regular hybrids can only slightly outweigh one third of the on-road stock at the end of the study period.

In the portfolio scenario, ICEVs will hit the maximum sales at 836,000 cars in 2015. However, the on-road ICEV stock will reach the maximum of 11 million cars in 2027. On one hand, new sales of advanced vehicles are in very small quantity before 2015. On the other hand, an average vehicle life of 16.8 years limits fleet modernization.

Of all non-ICEVs, regular hybrids are expected to remain the largest vehicle stock each year and reach 11% of the on-road fleet in 2030. This is mainly because HEVs have been sold for a decade and recently reached a sales share of 5%. It also benefits from the assumption that regular hybrids will account for an increasingly important share of the new sales, growing linearly to 17% in 2030.

4.2. Fuel consumption and gasoline displacement

Fig. 7 presents annual fuel demand of passenger cars on the road in California. Total fuel consumption is expected to peak at 5.61 billion gge in 2017 and thereafter substantially drop with year. That is because more efficient advanced vehicles phase in and take off in 2018, the next year following the peak. As expected, alternative fuels will play an increasingly important role. FCVs, BEVs, and PHEVs collectively account for about 15% of energy consumption in 2030, whereas they account for 23% of vehicle stock.

The remaining pre-2010 fleet, the carryover of vehicle stock from previous years to 2010–2030, is a major energy consumer, especially in the early years, because of its huge population and less efficient operation. This "legacy fleet" even still accounts for about 11% of energy consumption in 2030, the end year of analysis. Over the next two decades, gasoline is the major transportation fuel and conventional gasoline vehicles are dominant in the on-road fleet.

Fig. 8 shows that advanced vehicles, especially alternative fueled vehicles, are a good path leading to gasoline savings. FCVs running on hydrogen contribute the most to gasoline displacement. Although HEVs are more efficient than conventional ICEVs, these regular hybrids are not expected to save much gasoline, despite that their population outweighs any other advanced vehicles in the portfolio scenario.

Fig. 9 shows California hydrogen demand and the trajectory of market penetrations of the three hydrogen supplies on a daily basis. Onsite SMR and distributed electrolysis will take the lead to penetrate the market in an equally important manner, because of their small scale and no delivery requirement. As hydrogen demand

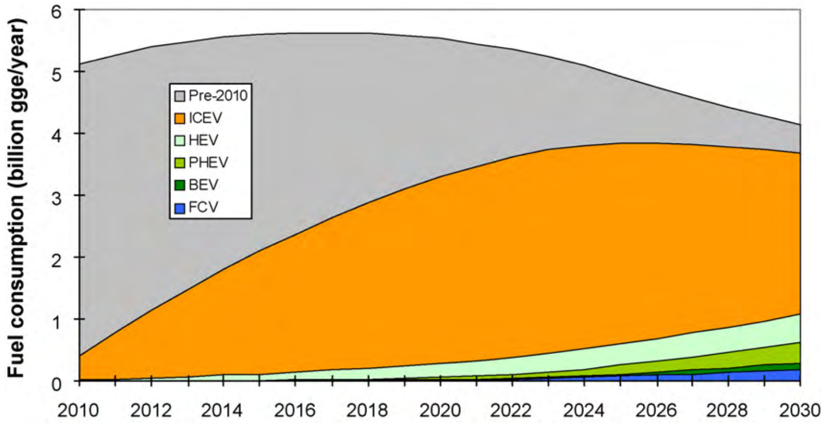

Fig. 7. Annual fuel demand of on-road passenger cars in California during 2010–2030.

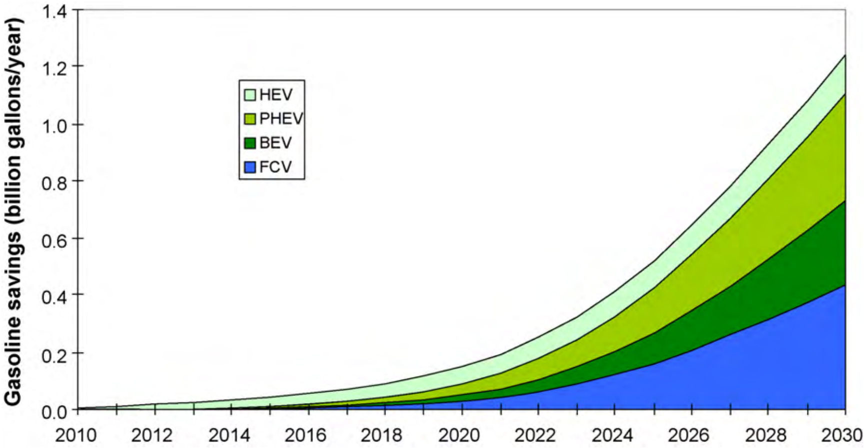

Fig. 8. Gasoline displaced or saved by non-ICEVs for the vehicle portfolio scenario.

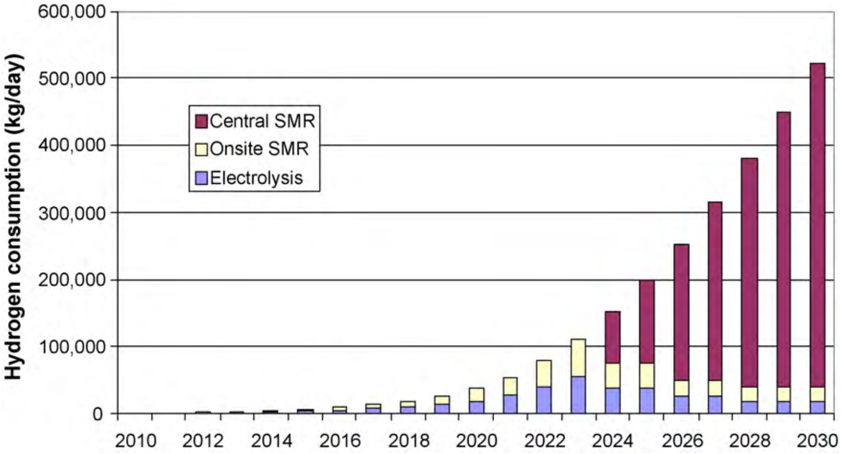

Fig. 9. Daily hydrogen demand and supply market build-up.

builds up, central SMR as a less expensive supply option will enter and dominate the supply market; meanwhile, the other two alternatives will phase out as a result of relatively high costs of hydrogen supply.

4.3. *Learned-out price and learning curve*

Advanced vehicles in mass production are expected to reach the learned-out price level. In general, it is at production volumes of

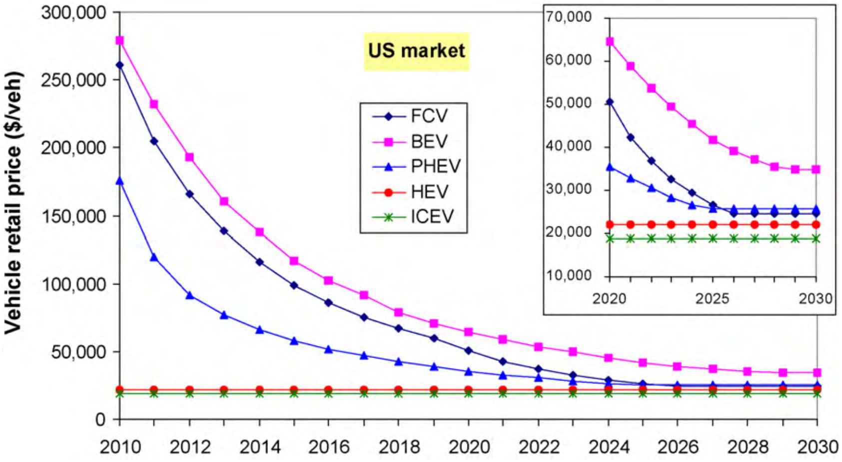

Fig. 10. Estimated learning curve for the average retail price of advanced vehicles.

Table 2
Learned-out price of advanced technology vehicles.

Vehicle technology	Incremental OEM cost (in 2005 $)[a]	Incremental price (in 2008 $)[b]	Retail vehicle price (in 2008 $)[c]
FCV	3600	5592	24,600
BEV	10,200	15,845	34,800
PHEV-30	4300	6680	25,700
HEV	1900	2952	22,000
Reference ICEV	0	0	19,000

[a] Incremental OEM costs are taken from an MIT study [17].

[b] The retail price is assumed to be 1.4 times the OEM cost to account for the other costs (e.g., marketing) and profits [7,8]. Note that the 2008 consumer price index (CPI) is 1.110 times the 2005 CPI in California.

[c] For benchmarking, a reference ICEV is included, assuming its retail price is $19,000 for a base model.

about half a million per year. Table 2 presents the final learned-out price of advanced vehicles.

Fig. 10 shows estimated learning curves for the average retail price of advanced vehicles, within the context of the entire US market. This study assumes HEVs have already learned out, as they entered the US market a decade ago and are today in mass production. Therefore, the price difference between regular hybrids and conventional cars remain constant over future years at about $3000 car^{-1}.

Note that these learning curves correspond to the specific vehicle market penetrations in the portfolio scenario. Retail prices are expected to drop dramatically with production volume and time for the three advanced technologies. Plug-in hybrids, fuel cell vehicles, and battery vehicles will meet the learned-out prices in 2025, 2026, and 2029, respectively.

The cost for PHEVs is relative low in the beginning penetration years, as they build on regular hybrid technologies; as a result, plug-in hybrids are expected to meet the learned-out level a little earlier (2025), compared to fuel cells and batteries. Despite the synergy of battery technology with PHEVs, BEVs require a battery of much improved performance, such as large capacity and long durability. Therefore, BEVs could be the most expensive of the three and are anticipated to reach the learned-out level in 2029. In contrast, fuel cell vehicles are costly in the beginning years, but after the 2020 market take-off they make rapid progress and in 2026 meet the learned-out price which is a little less expensive than PHEV-30.

4.4. Vehicle and fuel expenditures

Incremental expenditure on advanced vehicles and fuels, relative to the same number of conventional ICEVs, addresses the additional resource requirement of transitioning to electric drive vehicles. Figs. 11–13 show the annual cash flow in the time frame 2010–2030 for the vehicle portfolio scenario. Of the three advanced vehicles, only the penetration scheme of hydrogen cars could generate a zero or even negative net cash flow on an annual basis.

As the FCV fleet grows, demand for hydrogen fuel increases, too. However, the resulting expenditure on hydrogen is dwarfed by the great gasoline savings due to hydrogen use (Fig. 11). The aggregated incremental vehicle costs, on top of the equivalent conventional ICEVs, begin to drop a few years in advance of the learned-out

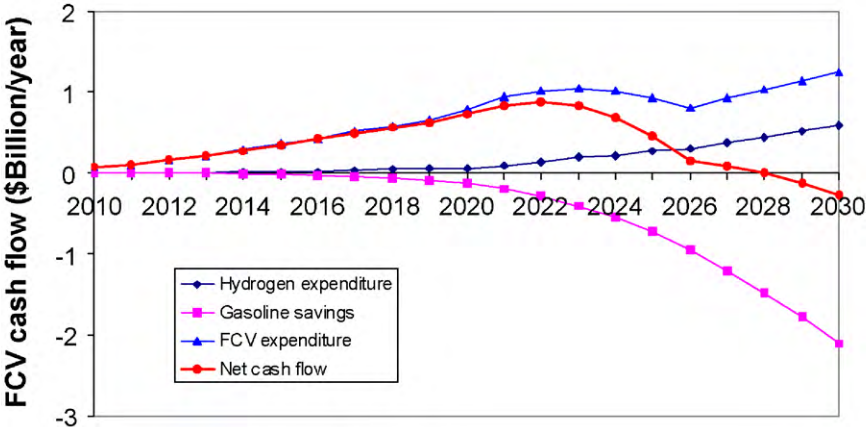

Fig. 11. Annual cash flow of fuels and vehicles: FCVs.

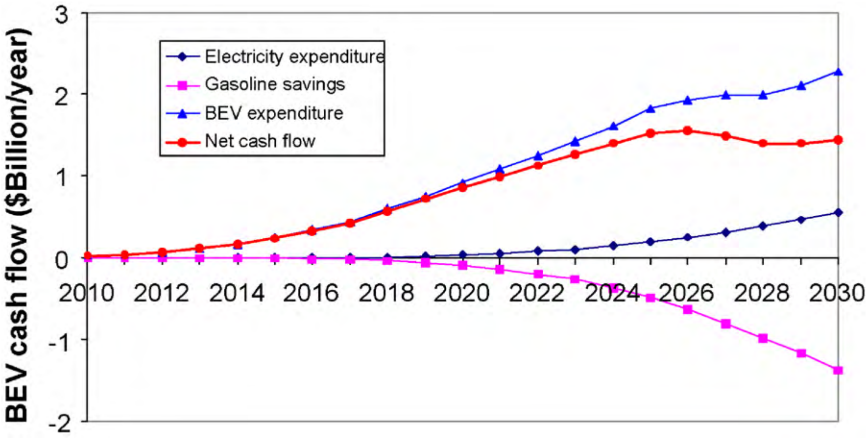

Fig. 12. Annual cash flow of fuels and vehicles: BEVs.

Table 3
Overall impacts of electric drive vehicles on the economy of California in 2030.

Macroeconomic indicator	BAU scenario	Portfolio scenario	Diff	% Diff
State output ($billion)	4932	4928	−3.3	−0.07%
Gross state product ($billion)	3468	3464	−4.5	−0.13%
State personal income ($billion)	2808	2802	−5.9	−0.21%
Employment (thousand)	19,250	19,245	−4.2	−0.02%

Table 4
Range of input variables for sensitivity analysis, in 2008 dollars.

Sensitivity variable	Base value	High value	Low value
Gasoline price ($ gallon^{-1})	4.777	6.210	3.344
Industrial NG price ($ mmBTU^{-1}): H_2 making	8.00	10.40	5.60
Industrial electricity price ($ kWh^{-1}): H_2 making	0.10	0.13	0.07
Transportation electricity price ($ kWh^{-1}): PHEV use	0.168	0.218	0.118
Ratio of variable to base value	1.00	1.30	0.70

year 2026, as the drop in vehicle cost more than offsets the growth of the fleet. Because the OEM cost of FCV remains constant in the learned-out year and beyond, the aggregated vehicle costs will go up thereafter. Incremental costs for FCVs and hydrogen will break even with gasoline savings in 2028, which results in a net annual cash flow of zero.

Similarly, the BEV phase-in causes increased vehicle/electricity expenditure, which however cannot be offset in the time window 2010–2030 by gasoline savings due to electricity use as the fuel (Fig. 12). Although plug-in hybrids are expected to result in obvious energy savings, especially when running as a “pure” electric vehicle in charge depleting mode, the incremental costs for vehicles/electricity outweigh gasoline savings throughout the period studied (Fig. 13). Different from the BEV scenario, the net cash flow for PHEVs, more or less, tends to be flat and even shows a decreasing trend toward 2030.

4.5. Statewide macroeconomic impacts

Technically, macroeconomic effects on California could be estimated, by using EDRAM, for any year during 2010–2030, given annual transaction flows shown in Figs. 11–13. However, the rollout of advanced vehicles takes time and they can only play a major role in decades. Thus, a statewide macroeconomic analysis is conducted for 2030 as an example to show the role of advanced vehicles in the economy of California.

Table 3 presents, for 2030, the overall impacts on California of the portfolio scenario of advanced vehicles, relative to the business-as-usual (BAU) scenario. The BAU scenario assumes no or few advanced vehicles; it is composed of only regular hybrids, accounting for 17% of new car sales in 2030, and conventional ICEVs, accounting for the remaining 83% of new sales. All four major macroeconomic indicators are taken into consideration: state output, gross state product (GSP), state personal income (SPI), and employment. These indicators are in real 2008 dollars or in physical units.

In conclusion, the portfolio scenario is estimated to have a slightly negative influence on California’s economy, which is mainly because advanced vehicles are very costly and, therefore, the resulting gasoline savings cannot offset the high incremental expenditure on vehicles and alternative fuels, especially for BEVs and PHEVs (see Figs. 12 and 13). For example, the portfolio scenario would cause 4200 job losses, relative to the BAU scenario. However, the economy of California is expected to grow substantially from today’s level; e.g., GSP is estimated to be around $3.5 trillion by 2030. Thus, the negative percentage impacts are expected to be very small, compared to such a big economy, and generally below −0.2%.

4.6. Sensitivity analysis

To test sensitivity of changes in each macroeconomic indicator to fuel prices, a 30% increase or drop from the base value is examined. Table 4 shows sensitivity variables and their three levels of value: base, high, and low.

Since all macroeconomic indicators show consistent, slightly negative effects of the portfolio scenario (Table 3), we only present sensitivity results of two indicators: changes in GSP and changes in employment, with respect to fuel prices (Figs. 14 and 15). Both indicators are the most sensitive to gasoline prices: an increase in gasoline price would clearly result in less losses of GSP and jobs associated with the vehicle portfolio scenario. The reasoning is that gasoline cars are still prevailing on the road in 2030 (Fig. 6), and the majority of car fuel is still gasoline (Fig. 7). Sensitivity results indicate that a high gasoline price could drive the transition to advanced vehicles and alternative fuels, from an economic perspective. Note that the portfolio scenario, however, still has a negative effect on the economy in the examined range of input variables.

As opposed to gasoline price, an increase in the price of electricity directly for PHEV use could result in more losses in GSP and jobs, although it is not as sensitive as gasoline price (Figs. 14 and 15). Technically, industrial NG and electricity prices have slightly negative impacts on the economy of California. However, because of the small hydrogen demand, macroeconomic indicators appear to be

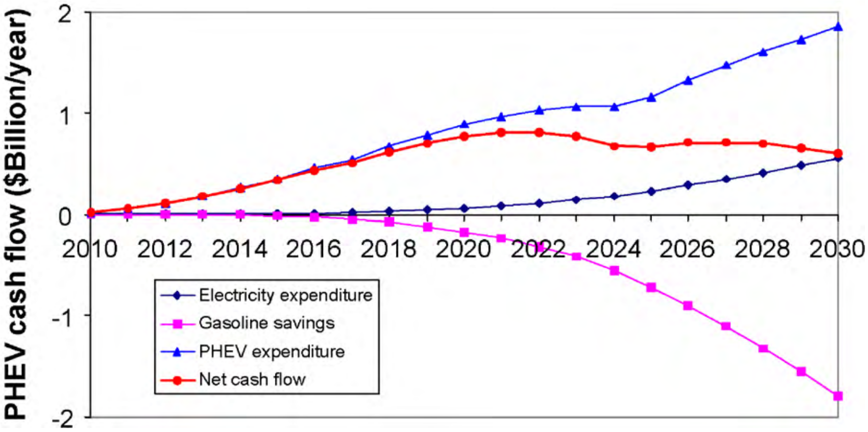

Fig. 13. Annual cash flow of fuels and vehicles: PHEVs.

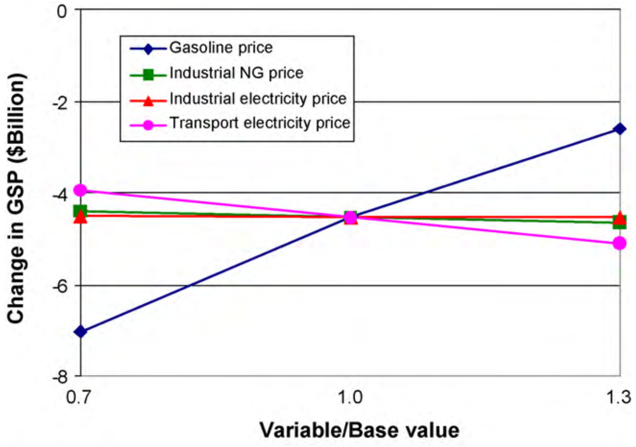

Fig. 14. Sensitivity of changes in GSP to fuel prices.

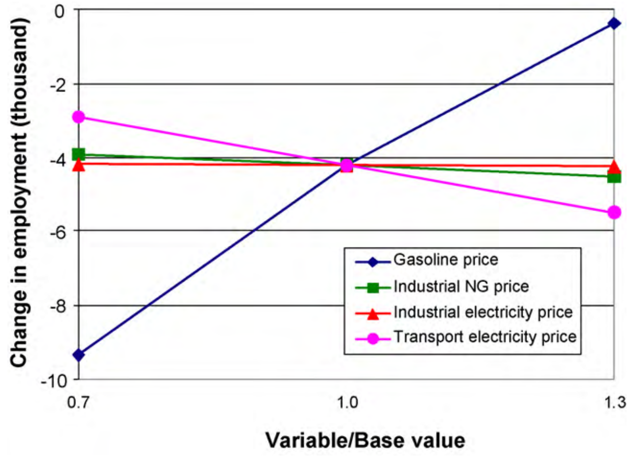

Fig. 15. Sensitivity of changes in employment to fuel prices.

insensitive to prices of industrial NG and industrial electricity for hydrogen-making purposes.

In summary, an increase in gasoline price or a drop in alternative fuel prices could offset a portion of the negative impact that the advanced vehicle portfolio is estimated to have. The small market size of alternative fuels explains that, within the next two decades, the statewide economy of California is not as sensitive to alternative fuel prices as to gasoline price.

5. Conclusions

Advanced vehicles and alternative fuels could play an important role in reducing oil use and changing the economy structure. Using the learning curve approach, we developed the Costs for Advanced Vehicles and Energy (CAVE) model to investigate a vehicle portfolio scenario in California during 2010–2030 which highlights hydrogen fuel cell vehicles, battery electric vehicles, and plug-in hybrid electric vehicles. Conventional cars and regular hybrids are also included as a point of comparison. Then we employed the Environmental Dynamic Revenue Analysis Model (EDRAM) to estimate macroeconomic impacts of the advanced vehicle scenario on the economy of California.

Results indicate that, due to slow fleet turnover, conventional vehicles are expected to continue to be dominant in the on-road fleet and gasoline is the major fuel over the next two decades, even in the case that alternative vehicles account for the major share of sales in 2030. Total energy consumption is estimated to peak soon because more efficient advanced vehicles phase in and take off. Alternative fuels are expected to play an increasingly important role, and FCVs running on hydrogen contribute the most to gasoline displacement. Although regular hybrids are more efficient than conventional cars, they are not expected to save much gasoline.

Incremental costs for FCVs and hydrogen could break even with gasoline savings in 2028, which results in a net annual cash flow of zero. Similarly, the BEV phase-in causes increased vehicle/electricity expenditure, which however cannot be offset during 2010–2030 by gasoline savings due to electricity use as the fuel. Although plug-in hybrids are expected to result in energy savings, especially when running as a "pure" electric vehicle in charge depleting mode, the incremental costs for vehicles/electricity outweigh gasoline savings throughout the period studied.

The vehicle portfolio scenario is estimated to have a slightly negative influence on California's economy, which is because advanced vehicles are very costly and, therefore, the resulting gasoline savings generally cannot offset the overall incremental expenditure on vehicles and alternative fuels. However, an increase in gasoline price or a drop in alternative fuel prices could offset a portion of the negative impact. The small market size of alternative fuels explains that, within the next two decades, the statewide economy of California is not as sensitive to alternative fuel prices as to gasoline price.

References

[1] G. Wang, S. Bai, J.M. Ogden, Transport. Res. Part D: Transp. Environ. 14 (2009) 168–179.
[2] C. Yang, D. McCollum, R. McCarthy, W. Leighty, Transport. Res. Part D: Transp. Environ. 14 (2009) 147–156.
[3] G. Wang, J.M. Ogden, D. Sperling, Transport. Res. Part D: Transp. Environ. 13 (2008) 436–448.
[4] G. Wang, J.M. Ogden, D.P.Y. Chang, Atmos. Environ. 41 (2007) 8874–8890.
[5] J.M. Ogden, R.H. Williams, E.D. Larson, Energy Policy 32 (2004) 7–27.
[6] P. Berck, Macroeconomic Impacts for the State Alternative-fuels Plan, Prepared for California Energy Commission, Prepared by University of California at Berkeley, Consultant report, Contract No. 600-06-001, November 2007.
[7] National Research Council, Transitions to Alternative Transportation Technologies: A Focus on Hydrogen, National Academies Press, Washington, DC, 2008.
[8] National Research Council, Transitions to Alternative Transportation Technologies—Plug-in Hybrid Electric Vehicles, National Academies Press, Washington, DC, 2009.
[9] D.L. Greene, P.N. Leiby, B. James, J. Perez, M. Melendez, A. Milbrandt, S. Unnasch, M. Hooks, Analysis of the Transition to Hydrogen Fuel Cell Vehicles and the Potential Hydrogen Energy Infrastructure Requirements, March 2008, http://cta.ornl.gov/cta/Publications/Reports/ORNL_TM_2008_30.pdf. (accessed July 29, 2009).
[10] EMFAC2007, The California Motor Vehicle EMission FACtors (EMFAC) Model, 2007 (accessed June 19, 2007) http://www.arb.ca.gov/msei/onroad/latest_version.htm.
[11] TIAX, Direct Hydrogen PEMFC Manufacturing Cost Estimation for Automotive Applications, Presentation by J. Sinha, et al., September 2008, http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/fctt_pemfc_cost_review_0908.pdf (accessed August 6, 2009).
[12] L. Argote, D. Epple, Science 247 (February) (1990) 920–924.
[13] Oak Ridge National Laboratory, in: S.C. Davis, S.W. Diegel, R.G. Boundy (Eds.), Transportation Energy Data Book, 28th edition, Oak Ridge National Laboratory (ORNL), 2009 (accessed March 5, 2010) http://cta.ornl.gov/data/tedb28/Edition28_Full_Doc.pdf.
[14] D.L. Greene, Transport. Res. Part D: Transp. Environ. 14 (2009) 375–384.
[15] J.M. Ogden, J.M. Cunningham, M.A. Nicholas, Roadmap for Hydrogen and Fuel Cell Vehicles in California: A Transition Strategy Through 2017, Institute of Transportation Studies, University of California, Davis, 2010, Research Report UCD-ITS-RR-10-04.
[16] Energy Information Administration, Annual Energy Outlook 2009 with Projections to 2030, Full report, March 2009, http://www.eia.doe.gov/oiaf/archive/aeo09/pdf/0383(2009).pdf (accessed February 1, 2010).
[17] M.A. Kromer, J.B. Heywood, Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet, 2007 (accessed July 29, 2009) http://web.mit.edu/sloan-auto-lab/research/beforeh2/files/kromer_electric_powertrains.pdf.
[18] California Energy Commission, Transportation Fuel Price and Demand Forecasts: Inputs and Methods for the 2009 Integrated Energy Policy Report—Final Staff Report, 2009, http://www.energy.ca.gov/2009publications/CEC-600-2009-001/CEC-600-2009-001-SF.PDF (accessed February 9, 2010).

[19] B.D. James, P.O. Schmidt, J. Perez, HyPro: A Financial Tool for Simulating Hydrogen Infrastructure Development, Directed Technologies, Inc., Final Report. December 2008.

[20] H2A, Hydrogen Analysis (H2A) Project, U.S. Department of Energy, 2009 (accessed August 5, 2009) http://www.hydrogen.energy.gov/h2a_analysis.html.

[21] J.M. Ogden, Int. J. Hydrogen Energy 24 (1999) 709–730.

[22] P. Berck, E. Golan, B. Smith, Dynamic Revenue Analysis for California, California Department of Finance, 1996 (accessed March 8, 2010) http://www.dof.ca.gov/HTML/FS_DATA/dyna-rev/dynrev.htm.