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Energy saving and cost projections for advanced hybrid, battery electric, and fuel cell vehicles in 2015-2030

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Abstract

In this paper, the fuel savings, relative initial costs, and breakeven gasoline prices for mid-sized passenger cars utilizing advanced powertrains in 2015-2045 are compared to those using conventional and advanced engine/transmission power trains that would be available in the same time periods. The advanced powertrains considered are hybrid-electric (HEV and PHEV) and all-electric (EV) powered by batteries alone or by a hydrogen fuel cell. Large fuel savings compared to 2007 conventional passenger cars are projected by 2030 for all the advanced powertrains ranging from 45% with advanced engines in conventional vehicles to 60% in hybrid-electric vehicles (HEVs). The energy savings (combined gasoline and wall-plug electricity) for the PHEVs were 62% for the PHEV-20 and 75% for the PHEV-40. The energy saving for the FCHEV was 72% and for the BEV was 79%.

The cost analyzes of the various advanced powertrains compared to the 2007 baseline vehicle indicated the most cost-effective was the HEV with a breakeven gasoline price of $2.50-3.00/gal gasoline for a five year payback period, 4% discount rate, and 12,000 miles/year. This was even lower than that for the conventional vehicles using the same advanced, high efficiency engine.

The economics of battery-powered, 100 mile range vehicles were analyzed for battery costs between $300-700/kWh. The breakeven gasoline prices for the BEVs are higher than for the other advanced vehicles being $4-5/gal even for the $300/kWh batteries. The economic results for the FCHEVs indicate that target fuel cell costs of $30–50/kW, 10-year life, and hydrogen prices in the $2.50–$ 3.00/kgH2 range make fuel cell vehicles cost competitive with HEVs and ICE vehicles using advanced engines.

Keywords: HEV, BEV, PHEV, FCHEC, fuel economy, cost

1 Introduction

A key question in comparing advanced and conventional vehicles is how much of a reduction in fuel consumption can be expected from new technologies. It is also of interest to compare the alternative advanced vehicle technologies in terms of their costs relative to conventional and advanced engine/transmission power trains that would be available in the same time periods.

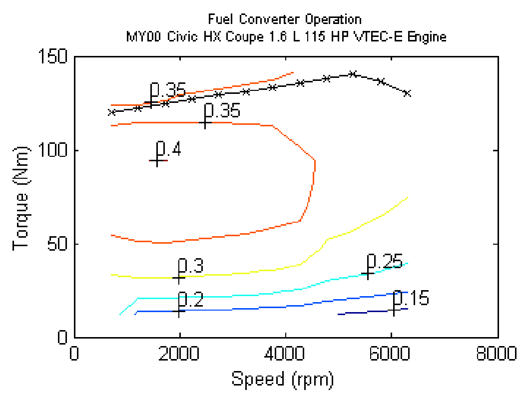
One approach to answering these questions is to run computer simulations of the operation of advanced vehicles on different driving cycles using the best component models available and control strategies intended to maximize the driveline efficiency. In these simulations, the vehicle and component characteristics can be varied to reflect projected improvements in technologies in the future. In this paper, simulations are run for a midsize passenger car for the time period 2015 to 2045. The baseline vehicle is a conventional vehicle marketed in 2007. The technologies compared are advanced, higher-efficiency engines, hybrid-electric vehicles, and electric-drive battery and fuel cell–powered vehicles. The simulation results are given in terms of the equivalent gasoline consumption of the various vehicle designs and the projected fuel savings. The vehicle inputs and simulation results are then utilized to analysis the initial costs and breakeven gasoline prices for the various alternative vehicle designs. The results obtained in this study are then compared with those presented in previous studies at MIT [1], the U.S. Department of Energy (DOE) [2], and the National Research Council (NRC) [3].

2 Vehicles and technologies considered

Three types of power trains—conventional internal combustion engine/transmission (ICE), hybrid-electric (HEV and PHEV), and all-electric powered by batteries alone or by a hydrogen fuel cell are compared. The ICE vehicles studied used an automatically shifted multi-speed transmission with increasing mechanical efficiency. The efficiency of the transmission was assumed to be a constant value varying from 92 percent in 2015 to 95 percent in 2045.

All the vehicle simulations were performed using gasoline, spark-ignition (SI) engines. The engine characteristics (efficiency maps as a function of torque and RPM) used in the simulations are based on those available in ADVISOR and PSAT (vehicle system modeling tools developed and supported by the National Renewable Energy Laboratory and Argonne National Laboratory, respectively). This included engines currently in passenger cars (such as the Ford Focus engine and the Honda i-VTEC engine) and more advanced engines like those employing an Atkinson cycle (Prius 2004), variable valve timing (An-iVTEC), and direct injection (An-GDi). The maximum engine efficiencies in the simulations for future years were based on expected significant improvements in engine efficiencies using future technologies. Modifying the engine maps in this way does not include the effects of changes in the basic shape of the contours of constant efficiency, which would likely show even more drastic increases in efficiency at low engine torque/power. The uncertainty in the engine maps is one of the largest uncertainties in the inputs needed to perform the simulations.

Map of the advanced i-VTEC engine used in the vehicle simulations



The electric motor/controller efficiency maps were scaled from the map for the 15 kW permanent magnet AC motor in the hybrid Honda Civic and Accord. The maximum efficiency of these motors is presently quite high—in the 92 to 96 percent range—so large improvements are not expected in future years.

Table 1: characteristics of the batteries used in the simulations

Vehicle Configuration	2015				2030–2045			
	Battery Type	Ah	Wh/kg	Resist. mOhm	Battery Type	Ah	Wh/kg	Resist. mOhm
HEV	Li Titanate	4	35	1.1	Li Titanate	4	42	.9
PHEV-20	Ni MnO2	15	120	1.5	Ni MnO2	15	135	1.3
PHEV-40	Ni MnO2	50	140	.8	Ni MnO2	50	170	.65
FCHEV	Li Titanate	4	35	1.1	Li Titanate	4	42	.9

Notes: Ah = ampere-hour; Wh/kg = watt hours per kilogram; Resist. mOhm = electrical resistance in milliohms

The power trains for all the hybrid vehicles (HEVs and PHEVs) used a single-shaft, parallel arrangement with clutches that permit on/off engine operation at any vehicle speed and the engine to be decoupled and coupled in an optimum manner. The same engine maps and maximum efficiencies were used for the hybrids as for the ICE vehicles. The HEVs operated in the charge-sustaining mode and utilized the "sawtooth" control strategy [4-6] for splitting the power demand between the engine and the electric motor. This strategy results in the vehicle operating in the electric mode when the power demand is low; when the vehicle power demand is higher, the engine is turned on, providing power to meet the vehicle demand and to recharge the batteries or ultracapacitors. It is likely that engines designed to operate primarily at the high torque conditions, such as the Atkinson cycle engines, will have higher efficiency than the standard designs used in ICE vehicles. The effects of engine redesign have not been included in the present study.

Characteristics of the batteries used in the simulations are shown in Table 1. The battery models for the various battery chemistries were based on test data taken in the battery laboratory at UC Davis [7-9]. Modest improvements in both energy density and resistance are projected in future years. These improvements should not significantly affect the fuel economy projections, as all the batteries used in the simulations have high power capability and thus high round-trip efficiency.

For the PHEVs, the batteries were sized (in terms of useable kWh) for either a 10–20 mile or a 40–60 mile range with all-electric operation on the Federal Urban Driving Schedule (FUDS) and Federal Highway Driving Schedule (FHWDS) in the charge-depleting mode. After the batteries were depleted to their minimum state-of-charge, the PHEVs operated in the charge-sustaining mode using the same sawtooth strategy used for the HEVs. The same single-shaft, parallel hybrid power train arrangement used in the HEVs was used in the PHEVs with the larger battery.

The power train arrangement for the fuel cell–powered vehicles (FCHEVs) consisted of a PEM fuel cell and a lithium-ion battery. The battery is connected to the DC bus by a DC/DC converter that controls the output power of the battery such that the output power of the fuel cell is load leveled [10-12]. This control strategy greatly reduces the voltage fluctuations of the fuel cell and should significantly increase its life expectancy. The peak efficiency of the fuel cell is increased in future years. The batteries used in the FCHEVs are the same as those used in the HEVs.

The batteries used in the all-electric battery powered vehicles were the same as those used in the PHEV-40. The range of BEVs was about 100 miles (160 km). The characteristics of the mid-size passenger car were selected to give performance similar to the Nissan Leaf. The BEVs with a range of 100 miles are not all-purpose vehicles unless the batteries have fast charge capability of 10 minutes or less.

3 Vehicle simulation results and energy savings

In this paper, the simulation results for mid-size passenger cars using the various powertrain technologies are presented and discussed. More complete results for other types of vehicle are given in [13, 14]. The inputs used for the simulations are given in Table 2 for each the future years. These inputs were used to obtain the fuel economy results for ICE, HEV, and BEVs given in Table 3 and for PHEVs given in Table 4.

Table 2: Input parameters for the mid-size passenger cars simulations

Vehicle Configuration	**Parameter**	**2015**	**2030**	**2045**
Vehicle Inputs	C_D	.25	.22	.20
	A_F m^2	2.2	2.2	2.2
	F_r	.007	.006	.006
Advanced ICE	Engine kW	105	97	97
	Max. engine efficiency %	39	40	41
	Vehicle test weight (kg)	1403	1299	1299
	DOE mpg FUDS/FHWDS	29/47	33/54	34/57
HEV	Engine kW	73	67	67
	Max. engine efficiency %	39	40	41
	Motor kW	26	24	24
	Battery kWh	1.0	.9	.9
	Vehicle test weight (kg)	1434	1324	1324
	DOE mpg FUDS/FHWDS	73/61	84/82	89/88
PHEV-20	Engine kW	75	69	68
	Motor kW	61	57	57
	Battery kWh	4.0	3.6	3.6
	Vehicle test weight (kg)	1475	1361	1354
PHEV-40	Engine kW	77	71	67
	Motor kW	63	59	59
	Battery kWh	11.1	9.8	9.4
	Vehicle test weight (kg)	1535	1415	1407
FCHEV	Fuel cell efficiency %	60	62	65
	Fuel cell kW	83	76	72
	Motor kW	103	100	99
	Battery kWh	.93	.85	.85
	Vehicle test weight (kg)	1516	1383	1366
	DOE mpg FUDS/FHWDS	70/79	102/114	114/130
BEV	Motor kW	80	72	70
	Battery kWh	24	28	32
	Vehicle curb weight kg	1521	1400	1350

Table 3: Fuel economy and fuel savings results for mid-size passenger cars

Year		Study By	FUDS mpg	FHWDS mpg	% Fuel Saved	US06 mpg	Accel. 0–30/0–60
Baseline 2007			26	42	0		
Adv. ICE	2015	UCD	41.4	62.3	33.5	37.5	4.3/9.7
		DOE	29	47	9		
		NRC			29		
	2030	UCD	47.4	73.3	42.8	44.0	4.7/10.3
		DOE	33*	54*	20.7		
		MIT	42	68	37.3	44	
	2045	UCD	48.9	77.1	45.2	46.1	4.6/10.3
		DOE	34*	57*			
HEV	2015	UCD	73.3	74.1	53.1	46.5	4.3/9.7
		DOE	73	61	48.5		
		NRC			44		
	2030	UCD	85.7	84	59.3	53.7	4.7/10.3
		DOE	84	82	41.6		
		MIT	95	88	62.2	58	
	2045	UCD	87.9	89.2	61.0	55.8	4.6/10.3
		DOE	89	88	61.0		
FCHEV	2015	UCD	82.6	90.8	60.2	61.3	
		DOE	70	79	53.7		
	2030	UCD	102.8	111.5	67.8	76.2	
		DOE	102	114	68.1		
	2045	UCD	108.9	119.5	69.8	82.3	
		DOE	114	130	71.7		

Year		Study By	FUDS Wh/mi / range	FHWDS Wh/mi / range	% Fuel Saved (1)	US06 Wh/mi / range	Accel. 0–30/0–60 mph
BEV	2015	UCD	220/ 75mi	206/ 82mi	76.1/40.1	400/ 45mi	3.4/11.1
	2030	UCD	198/ 97mi	184/ 104mi	78.6/46.3	365/ 54mi	3.2/10.5
	2045	UCD	194/ 122mi	176/ 122mi	79.3/48.0	352/ 63mi	3.1/10.2

(1) gasoline energy/ powerplant source energy; 90% charger effic., 40% powerplt. effic.
* The DOE fuel economy values for the Adv. ICEV in 2030 and 2045 do not properly reflect improvements in engine technology and as a result are too low.

Table 4: Simulation results for PHEV mid-size passenger cars

Year		Driving Cycle	Electric Range mi	Charge-depleting mpg	Charge-depleting Wh/mi (at battery)	Charge-sustaining mpg
PHEV-20	2015	FUDS	17	All-elec	163	70.0
		FHWDS	17	All-elec	165	69.6
		US06	10	1570	280	45
	2030	FUDS	17	3333	143	77
		FHWDS	17	7500	145	84
		US06	11	1500	234	53
	2045	FUDS	18	All-elec	140	85.6
		FHWDS	19	All-elec	134	87.8
		US06	11	1400	233	52.8
PHEV-40	2015	FUDS	46	All-elec	167	69.1
		FHWDS	45	All-elec	171	71.7
		US06	31	800	251	46.2
	2030	FUDS	49	All-elec	141	84.6
		FHWDS	48	All-elec	143	86.0
		US06	32	1495	218	54.5
	2045	FUDS	49	All-elec	135	87.8
		FHWDS	49	All-elec	134	92.5
		US06	32	1731	205	59

The simulation results indicate that large improvements in the fuel economy of conventional midsize passenger cars can be expected in 2015 to 2020. Further improvements are projected for 2030 and 2045. These improvements relative to 2007 models for midsize cars are 50 percent (2015) to 70 percent (2030) for fuel economy and 33 percent (2015) to 43 percent (2030) for fuel savings. These improvements result from the combined effects of decreases in weight and drag coefficient and increases in engine efficiency. Projected increases in engine efficiency have the largest effect for the FUDS cycle (see Table 5). Hence, even without large changes in the basic power train technology, large improvements in fuel economy can be expected in the next 10 to 20 years.

Large improvements in the fuel economy of HEVs are projected for midsize passenger cars resulting in fuel savings of 50–60 percent compared to the 2007 baseline vehicles. Relatively large fuel economy improvements are projected for HEVs compared to advanced conventional vehicles using the same engine technologies (see Table 6).

Table 5: fuel economy Improvements in ICE Vehicles

Midsize passenger cars

Technology	2015 FUDS mpg	2015 FHWDS mpg	2030 FUDS mpg	2030 FHWDS mpg
2007 engine (baseline)	27	42	28	43
Without weight and C_D reduction	39	56	42	61
Engine power reduction only	29	45	30	46
All improvements	43	63	48	72

Table 6: Improvements (as ratios) in the fuel economy of HEVs compared to advanced ICE vehicles

Vehicle	2015 FUDS	2015 FHWDS	2030 FUDS	2030 FHWDS
Midsize passenger car	1.65	1.15	1.79	1.21

Two types of PHEVs were simulated—one with a small battery and an all-electric range of 10–20 miles and one with a larger battery and a range of 40–50 miles (see Table 4). There is not a large reduction (only about 15 percent) in electrical energy usage (Wh/mi) in the all-electric mode projected for 2015 to 2045, and the fuel economy of the various vehicle designs in the charge-sustaining mode is similar to the corresponding HEV. As a result, one would expect the energy usage (electricity plus gasoline) of the 10–20 mile PHEV would decrease by a greater fraction in the future than the 40–50 mile PHEV, which would travel a greater fraction of miles on electricity. The split between electricity and gasoline depends on its usage pattern (average miles driven per day and number of long trips taken).

Fuel cell–powered vehicles use hydrogen as the fuel. As with gasoline-fueled hybrids, the batteries are recharged onboard the vehicle from the fuel cell and not from the wall plug. The fuel economies calculated for FCHEVs are gasoline equivalent values but are easily interpreted as mi/kg H_2 since the energy in a kilogram of hydrogen is close to that in a gallon of gasoline. Hence the fuel savings shown for the fuel cell vehicles can be interpreted as the fraction of energy saved relative to that in the gasoline used in the baseline 2007 conventional vehicle. Fuel cell technology would thus reduce energy use by 60 percent (2015) to 72 percent (2030) for the midsize passenger car.

Battery-powered vehicles are recharged with electricity from the wall-plug. The energy use of the BEVs is given as Wh/mi from the battery. The gasoline equivalent can be calculated from $(gal/mi)_{gas.equiv.}$ = (kWh/mi)/33.7. The energy saved depends on the battery charging efficiency and the efficiency of the powerplant generating the electricity. For 2030 BEV, the gasoline energy equivalent saved is 79% from the wall-plug and 45% at a 40% efficient powerplant compared to the 2007 baseline ICE mid-size car. Compared to a 2030 HEV, the gasoline equivalent saved is only 47% from the wall-plug and there are no savings at the powerplant until the efficiency of the powerplant exceeds about 55%.

The fuel savings projected for the various technologies are summarized in Table 7.

Table 7: Summary of the fuel savings (%) for the various advanced technologies

Technology	Midsize passenger car
Advanced ICE vehicle	33–45 (tank) *
HEV	53–61 (tank)
PHEV-20	62% (wall-plug, tank)
PHEV-40	75% (wall-plug, tank)
FCHEV	60–72 (tank)
BEV	79% (wall-plug) 45% (powerplant)

* a/b 2015/2045

4 Cost analysis approach

The costs of the for each of the power train combinations simulated were analysed using a spreadsheet cost model that permitted the quick analysis of the economics of the vehicle designs operated in North America, Europe, and Japan. The analysis was done as a function of fuel price, usage pattern (driving cycle and miles/year), and discount rate.

The key inputs to the cost analysis are the fuel economy projections for each of the vehicle/driveline combinations and the unit costs of the driveline components. The costs of the engine/transmission and electric motor/electronics are calculated from the maximum power rating of the components and their unit cost ($/kW). The component power (kW) and energy storage (kWh) ratings for the calculations of the component costs were taken from Table 2. In all cases, the values for 2030 were used in the cost projections. The input values for the fuel economy projections were taken from Table 3 and 4. The fuel economy values shown in the tables correspond to the EPA chassis dynamometer test data and have been corrected to obtain real-world fuel economy using the .9 and .78 factors used by EPA to obtain the fuel economy values given in their Fuel Economy Guide. The real-world fuel economy values are used in all the economic study calculations.

Considerable uncertainty currently surrounds the costs of electric driveline components—the electric motor, power electronics, batteries, and fuel cell. This is especially true of the cost of the batteries and the fuel cell. For this reason, a range of values for the unit costs of those components were used. There is a smaller uncertainty about the costs of advanced conventional engine components, so a single unit cost values were used for those components. The values we used were based on information in [15]. In all cases, it was assumed that the vehicles and driveline components are manufactured in large volume for a mass market. The inputs to the spreadsheet were selected to match the specific vehicle designs for this study (Tables 2-4).

In the case of PHEVs, the fuel economy used was the equivalent value based on the sum of the electricity and gasoline usage for the usage pattern (fraction of miles driven in the all-electric, charge-depletion mode). This value of equivalent fuel economy was applicable to both the urban (FUDS) and highway (FHWDS) driving cycles. In the case of FCHEVs, the gasoline equivalent of the hydrogen consumption (kgH2/mi) was used to determine the equivalent gasoline break-even price. In the case of the BEVs, the electrical energy cost for the operation of the vehicle was determined using the Wh/mi value from the simulations assuming an electricity price of 8 cents/kWh.

In estimating the retail or showroom cost of vehicles, a markup factor of 1.5—that is, the retail price is 1.5 times the OEM (original equipment manufacturer) cost of the component. The cost of reducing the weight and the drag of the vehicle is included as a fixed cost based on values given in [3]. Additional input values to the cost model include the price of the fuel, the annual mileage use of the vehicles, the years over which the analysis is to be done, and the discount rate. Values of all the input parameters can be changed by the user from the keyboard as part of setting up the economic analysis run. Key output parameters are the average composite fuel economy for the vehicle in real world use, differential driveline cost, fraction of fuel saved, and actual and discounted breakeven fuel price ($/gal). All vehicle costs and fuel prices are in 2007–2010 dollars.

5 Cost results and discussion

The results of the economic analysis of the various advanced vehicle cases for a midsize passenger car for 2030 are given in Tables 8 and 9. The energy saved and cost differentials are relative to the 2007 baseline vehicle using a port fuel-injected (PFI) engine. The break-even gasoline price is calculated for a vehicle use of 12,000 miles per year and time periods of 5 or 10 years. The 5-year period is used for the ICE vehicles and the HEVs because it is commonly assumed that new car buyers would desire to recover their additional purchase cost in that period of time. Both the 5-year and 10-year periods are used for the PHEVs, BEVs, and FCHEVs since the lifetimes of the batteries and the fuel cells are uncertain at the present time and it seems reasonable to recover the high cost of those components over their lifetimes. Discount rates of 4 and 10 percent are used for the 5- and 10-year periods, respectively. These discount rates are likely more appropriate for society as a whole than for individual vehicle buyers. The economic calculations were made for ranges of battery and fuel cell costs because those costs are particularly uncertain and sure to change significantly over the next 10 to 20 years.

First consider the economic results for the ICE and HEV vehicles. The fractional energy savings are .43 and .62 for the ICE vehicle using advanced engines and the HEV using the same engine technology, respectively. The corresponding discounted break-even gasoline prices ($/gal) are $3.62 for the ICE vehicle and $2.30–$2.60 for the HEV. The gasoline price is lower for the HEV than for the ICE vehicle because the fuel economy of the HEV is significantly higher. These results indicate the economic attractiveness of the HEV even at battery costs of $1000/kWh. It appears that both the advanced ICE and the HEV will make economic sense even at the gasoline prices in 2012 and with a 5-year payback period.

Next consider the economic results for the PHEVs. The fractional energy savings are .65 and .79 for the PHEV-20 (small battery, AER =10–20 miles) and PHEV-40 (large battery, 40–50 miles), respectively. The energy used by the PHEVs includes both gasoline fuel and the gasoline equivalent of the electrical energy from the battery. The cost differentials of the PHEVs are relatively high compared to those of the HEVs and depend markedly on the cost of the batteries. As would be expected, the differential costs and break-even gasoline prices are significantly higher for the large-battery PHEV than for the small-battery PHEV, which is significantly higher than for the HEV with about the same energy savings. In the case of the PHEV with the small battery, the break-even gasoline price is in the same range as that of the HEV only when the retail battery cost is about $400/kWh and the time period of the calculation is 10 years, the assumed lifetime of the battery. For the PHEV with the large battery, a retail battery cost of $300/kWh and at least a 10-year life is needed to make the vehicle cost competitive with either the small-battery PHEV or the HEV. However, the fuel and energy savings using the large-battery PHEV are the highest among the advanced vehicles considered.

Table 8: Summary of Cost Results for a Midsize Passenger Car in 2030

Component cost assumptions (changes in retail price of the vehicle):
Added vehicle cost to reduce drag and weight, $1,600
Advanced engine/transmission, $45/kW
Standard engine/transmission, $32/kW
Electric motor and electronics, $467 + $27.6/kW
Batteries $/kg = $/kWh x Wh/kg /1000
Fuel cell, $30/kW–$75/kW

Vehicle Configuration	**Real-World mpg**	**Battery Inputs**			**Energy Saved**	**Vehicle Cost Differential**	**Discounted Break-even Gas Price**
		$/kWh	**Wh/kg**	**$/kg**			
Baseline vehicle 2007	27.1						
Adv. ICE	47.8				.43	$3095	$3.62/gal[1]
HEV	71.1	1000	70	70	.62	$3204	$2.61/gal[1]
		800	70	56		$3003	$2.45/gal[1]
		600	70	42		$2802	$2.29/gal[1]
PHEV-20	75.3[4]	800	100	80	.65	$6409	$5.03/gal[1]
							$3.64/gal[2]
		600	100	60		$5605	$4.40/gal[1]
							$3.19/gal[2]
		400	100	40		$4801	$3.77/gal[1]
							$2.73/gal[2]
PHEV-40	127[5]	700	150	105	.79	$10,228	$6.58/gal[1]
							$4.77/gal[2]
		500	150	75		$8218	$5.29/gal[1]
							$3.83/gal[2]
		300	150	45		$6208	$3.99/gal[1]
							$2.89/gal[2]
FCHEV	89.8						
$75/kW FC		800	70	56	.70	$7549	$5.47/gal[1]
							$3.31/gal[3]
$50/kW FC		800	70	56		$5549	$4.02/gal[1]
							$2.43/gal[3]
$30/kW FC		800	70	56		$3949	$2.86/gal[1]
							$1.73/gal[3]
Battery electric BEV	Equiv. 176						
Range 100 mi.		$700	170	119	.77 wall plug	20294	10.72 (1) 8.09 (3)
		$500	170	85		14694	7.90 (1) 6.04 (3)
		$300	170	47		9094	5.06 (1) 3.99 (3)

Notes:
1. 5 years and 4% discount rate, 12,000 miles/yr
2. 10 years and 10% discount rate, 12,000 miles/yr
3. 10 years and 6% discount rate, 12,000 miles/yr
4. Equivalent (includes gallon equivalent of gasoline for electricity used in the all- electric operation) including electricity, 20% of vehicle miles on electricity
5. Equivalent (includes gallon equivalent of gasoline for electricity used in the all- electric operation) including electricity, 65% of vehicle miles on electricity
6. Hydrogen equivalent kg/mi
The PHEV-20 has a small battery (25–33 kg, all-electric range or AER of 10–20 mi); the PHEV-has a large battery (55–80 kg, AER 40–60 mi).

The break-even gasoline prices do not include the effect of possible battery replacement. It was assumed that the batteries will last through at least the time period of the calculation (5 years or 10 years). Results for the PHEVs are shown for 5 years at a 4-percent discount rate and 10 years at a 10-percent discount rate. The break-even gasoline prices are lower for the longer time period, even using the higher discount rate, and only get into a reasonable range for the lowest battery costs assumed. The short discount period (5 years) corresponds to the time we expected the first owner of the vehicle to own the car, and the 10-year period corresponds to the expected lifetime of the batteries. In all cases, the economics are more attractive for the longer time period, indicating a leasing arrangement for the batteries seems to make sense. The cost of the electricity to recharge the batteries was included in the calculations using the equivalent fuel economy, which was determined by adding the gasoline equivalent of the electricity (kWh) used in the all-electric charge-depleting mode to the gasoline used in the charge-sustaining mode. This approximation is almost exact for electricity costs of 6–10 cents/kWh.

Table 9: Cost analysis of battery and fuel cell powered vehicles compared to advanced ICE and HEV vehicles

Vehicle design		2030 Breakeven fuel price $/gal gasoline equiv.					
		2007 ICE baseline		**Adv. ICE baseline**		**HEV baseline**	
Battery electric *							
5 yr at 4% disc	**battery cost $/kWh**	**w/o disc.**	**with disc.**	**w/o disc.**	**with disc.**	**w/o disc.**	**with disc.**
	700	9.57	10.72	14.43	16.16	21.50	24.08
	500	7.05	7.90	9.97	11.17	14.91	16.70
	300	4.52	5.06	5.50	6.17	8.28	9.27
10 yr at 10% disc	**battery cost $/kWh**	**w/o disc.**	**with disc.**	**w/o disc.**	**with disc.**	**w/o disc.**	**with disc.**
	700	4.99	8.09	7.58	12.28	11.31	18.30
	500	3.72	6.04	5.35	8.67	7.99	12.94
	300	2.46	3.99	3.12	5.05	4.63	7.50
PHEV large battery **							
5 yr at 4% disc	**battery cost $/kWh**	**w/o disc.**	**with disc.**	**w/o disc.**	**with disc.**	**w/o disc.**	**with disc.**
	700	5.6	6.27	8.07	9.04	14.1	15.79
	500	4.55	5.10	6.0	6.72	10.45	11.70
	300	3.51	3.93	3.9	4.37	6.8	7.62
10 yr at 10% disc	**battery cost $/kWh**	**w/o disc.**	**with disc.**	**w/o disc.**	**with disc.**	**w/o disc.**	**with disc.**
	700	2.94	4.76	4.32	7.00	7.54	12.22
	500	2.42	3.92	3.27	5.30	5.71	9.25
	300	1.89	3.06	2.22	3.60	3.88	6.29
Fuel cell HEV***							
5 yr at 4% disc	**fuel cell cost $/kW**	**w/o disc.**	**with disc.**	**w/o disc.**	**with disc.**	**w/o disc.**	**with disc.**
	75	5.07	5.68	6.48	7.26	9.62	10.77
	50	4.16	4.66	4.88	5.47	7.25	8.12
	30	3.44	3.85	3.61	4.04	5.36	6.00
10 yr at 10% disc	**fuel cell cost $/kW**	**w/o disc.**	**with disc.**	**w/o disc.**	**with disc.**	**w/o disc.**	**with disc.**
	75	3.06	4.96	4.17	6.76	6.19	10.02
	50	2.61	4.23	3.37	5.46	5.00	8.10
	30	2.25	3.64	2.73	4.42	4.06	6.58

* electric cost 8¢/kWh; 12000 miles/yr.

** 65% of miles on electricity, 12,000 miles/yr.

*** fuel cell cost includes hydrogen storage at $10/kWh, 4 kg H2; $3.5/kg H2

The economic calculations for the FCHEVs were done for a range of fuel cell unit costs ($30–75/kW). An intermediate battery cost ($800/kWh) was used for all the calculations. The break-even fuel cost (hydrogen equivalent) becomes comparable to that of the HEV when the fuel cell unit cost is less than $50/kW. This is especially the case when the time period of the analysis is 10 years. The energy savings of the fuel cell vehicles (70 percent) are intermediate between those of the HEV and the large-battery PHEV. The break-even fuel cost represents the gasoline ($/gal) and hydrogen ($/kg) prices for which the vehicle owner would recover the differential vehicle cost in the time period of the calculation. If the price of the hydrogen is lower than the break-even gasoline price, the vehicle owner would recover more than the vehicle price differential from fuel cost savings compared to the baseline ICE vehicle. These economic results for the FCHEVs indicate that target fuel cell costs of $30–50/kW, 10-year life, and hydrogen prices in the $2.50–$ 3.00/kgH2 range should make fuel cell vehicles cost competitive with HEVs and ICE vehicles using advanced engines.

The economics of battery-powered, 100 mile range vehicles were analyzed for battery costs between $300-700/kWh. The differential costs of the BEVs are greater than any of the other vehicle designs being $20294 for batteries costing $700/kWh and $9094 for $300/kWh. The breakeven gasoline prices for the BEVs are also higher than for the other advanced vehicles being $4-5/gal even for the $300/kWh batteries. Based on the energy equivalent of the wall-plug electricity to recharge the batteries, the BEVs have an energy savings of 77 %, but much less savings if the powerplant efficiency is included. In that case, the energy savings are only 40%.

All the breakeven gasoline prices considered thus far (Table 8) were determined for differential costs and fuel savings relative to the 2007 baseline vehicle. It is of interest to consider the breakeven gasoline prices of the BEV, PHEV-40, and FCHEV using the Advanced ICE and HEV vehicles as the baseline. These comparisons (Table 9) indicate that none of the electric drive vehicles with large batteries, even at the lowest battery cost of $300/kWh, are economically attractive relative to the Adv. ICE and HEV vehicles. This is especially true of the BEVs. As expected the breakeven gasoline prices are highest when the HEV is used as the baseline. The FCHEV is the most attractive of the electric drive vehicles when compared to the HEV.

6 Summary and Conclusions

In this paper, the fuel savings, relative initial costs, and breakeven gasoline prices for mid-sized passenger cars utilizing advanced powertrains in 2015-2045 are compared to those using conventional and advanced engine/transmission power trains that would be available in the same time periods. The advanced powertrains considered are hybrid-electric (HEV and PHEV) and all-electric powered by batteries alone or by a hydrogen fuel cell. Large fuel savings compared to 2007 conventional passenger cars are projected by 2030 for all the advanced powertrains ranging from 45% with advanced engines in conventional vehicles to 60% in hybrid-electric vehicles (HEVs). The energy savings (combined gasoline and wall-plug electricity) for the PHEVs were 62% for the PHEV-20 and 75% for the PHEV-40. The energy saving for the FCHEV was 72% and for the BEV was 79%.

The cost analyzes of the various advanced powertrains compared to the 2007 baseline vehicle indicated the most cost-effective was the HEV with a breakeven gasoline price of $2.50-3.00/gal gasoline for a five year payback period, 4% discount rate, and 12,000 miles/year . This was even lower than that for the conventional vehicles using the same advanced, high efficiency engine. In the case of the PHEV with the small battery, the break-even gasoline price is in the same range as that of the HEV only when the retail battery cost is about $400/kWh and the time period of the calculation is 10 years, the assumed lifetime of the battery. For the PHEV with the large battery, a retail battery cost of $300/kWh and at least a 10-year life is needed to make the vehicle cost competitive with either the small-battery PHEV or the HEV. However, the fuel and energy savings using the large-battery PHEV are the highest among the advanced hybrid vehicles considered.

The economics of battery-powered, 100 mile range vehicles were analyzed for battery costs between $300-700/kWh. The breakeven gasoline prices for the BEVs are higher than for the other advanced vehicles being $4-5/gal even for the $300/kWh batteries. The economic results for the FCHEVs indicate that target fuel cell costs of $30–50/kW, 10-year life, and hydrogen prices in the $2.50–$ 3.00/kgH2 range make fuel cell vehicles cost competitive with HEVs and ICE vehicles using advanced engines.

It is of interest to consider the breakeven gasoline prices of the BEV, PHEV-40, and FCHEV using the Advanced ICE and HEV vehicles as the baseline. These comparisons indicate that none of the electric drive vehicles with large batteries, even at the lowest battery cost of $300/kWh, are economically attractive relative to the Adv. ICE and HEV vehicles. This is especially true of the BEVs. As expected the breakeven gasoline prices are highest when the HEV is used as the baseline. The FCHEV is the most attractive of the electric drive vehicles when compared to the HEV.

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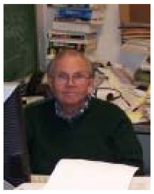

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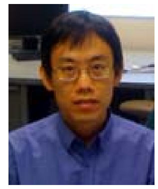

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