SUSTAINABLE TRANSPORTATION ENERGY PATHWAYS

A Research Summary for Decision Makers

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Chapter 4:
Comparing Fuel Economies and Costs of Advanced vs. Conventional Vehicles

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A key question in comparing advanced and conventional vehicles is how much of a reduction in fuel consumption we can expect from new technologies. One approach to answering this question 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 we can vary the vehicle and component characteristics to reflect projected improvements in technologies in the future.

This chapter describes simulations run for a midsize passenger car and a small/compact SUV for the time period 2015 to 2045. The baseline vehicle is a conventional vehicle marketed in 2007. Technologies we compared are advanced, higher-efficiency engines, hybrid-electric vehicles, and electric-drive battery and fuel cell-powered vehicles. We present the results of our simulations in terms of the equivalent gasoline consumption of the various vehicle designs and the projected reductions in fuel usage, and we compare our results with those presented in previous studies at MIT, the U.S. Department of Energy (DOE), and the National Research Council (NRC). We also 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.

THE SIMULATION TOOLS WE USED

Studies directed toward projecting the performance of vehicles using various advanced power train technologies have been performed at the UC Davis Institute of Transportation Studies since about 2000.[1] A number of computer models have been developed to simulate advanced vehicles.[2] For this chapter, we performed the conventional and hybrid (HEV and PHEV) vehicle simulations using the UC Davis version of ADVISOR,[3] which includes special power train schematic and control strategy files.

The computer program we used to simulate fuel cell vehicles is a modification of the program developed previously at UC Davis[4] that permits scaling of the fuel cell stack and accessories and improves the treatment of system transients, particularly those due to the compressed air system. In addition, we added control strategies using batteries or ultracapacitors that permit operation of the fuel cell in either the load-leveled or power-assist mode. These simulation tools allow us to calculate the fuel consumption of advanced vehicles on various driving cycles.

To the extent possible, the results of the simulation programs have been validated by comparing simulation results for vehicles currently being marketed with EPA dynamometer test data[5] for vehicles using the same power trains / engines. In all cases, the comparisons are reasonable, as shown in the following table.

Model/Year	Engine	Driveline Type	City mpg	Highway mpg
Ford Focus/2010 simulation	Focus	conventional	28	44
EPA test 2007/ Ford Focus	Focus	conventional	30	44
Honda Civic simulation	i-VTEC	conventional	33	45
EPA test 2007/ Honda Civic	i-VTEC	conventional	33	50
Honda Civic simulation	i-VTEC	hybrid	56.5	62.5
EPA test 2007/ Honda Civic	i-VTEC	hybrid	54.4	65.4
Toyota Prius simulation	Atkinson	hybrid	68	67.5
EPA test 2007/Toyota Prius	Atkinson	hybrid	66.6	65.4
EPA test 2007/Honda Accord	4 cyl. 140 kW	conventional	26.6	43.6
EPA test 2007/Toyota Camry	4 cyl. 140 kW	conventional	26.6	42.3

Note: EPA test results from U.S. Department of Energy and U.S. Environmental Protection Agency, "Fuel Economy Guide—2007," are corrected by 1/.9 for the Federal Urban Driving Schedule (FUDS) and 1/.78 for the Federal Highway Driving Schedule (FHWDS) to obtain the dynamometer test data. The .9 and .78 values are the factors used by EPA to relate their test data for the vehicles on the city and highway cycles, respectively, to the fuel economy values given in the Fuel Economy Guide for those test cycles.

Fuel Economy and Energy Savings Simulation Inputs

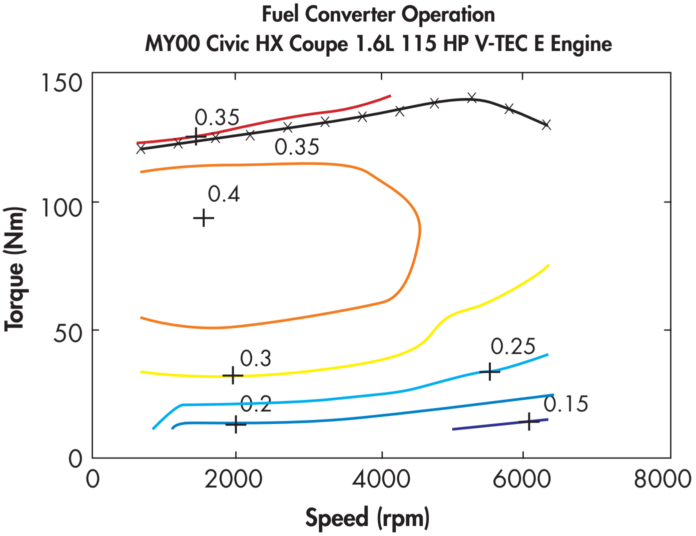
The primary challenge in simulating vehicle operation is to come up with the vehicle and power train inputs to be used in the simulations. If the inputs are realistic, the simulation results should be a reliable estimate of the performance and fuel consumption of vehicles in the future. There is, of course, considerable uncertainty in the inputs used in any study, particularly regarding when specific improvements in the technologies will be achieved. Thus, results can also be interpreted as representing the fuel savings that would result if vehicles are marketed having the vehicle and power train characteristics assumed in the inputs. This makes the simulation results useful in setting design targets for future development programs for advanced vehicle technologies. Similarly, component costs assumed in our economic estimates are useful as targets for future pricing.

Power train configurations and component characteristics

We compared 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. The ICE vehicles we studied used an automatically shifted multi-speed transmission with increasing mechanical efficiency; we made no attempt to optimize the transmission gearing or shifting strategy. 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). We increased the maximum engine efficiencies in the simulations for future years based on expected significant improvements in engine efficiencies using upcoming technologies.[6] 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 VTEC ENGINE USED IN THE ICE VEHICLE SIMULATIONS



The engines used in the ICE vehicle simulations were scaled from the four-cylinder Honda VTEC engine, for a maximum efficiency of 40 percent (value for 2030).

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.

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[7] 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[8] 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 the table below. The battery models for the various battery chemistries were based on test data taken in the battery laboratory at UC Davis.[9] Modest improvements in both energy density and resistance are projected in future years.[10] These improvements will result in lower vehicle weight and more efficient power train operation but 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.

CHARACTERISTICS OF THE BATTERIES USED IN OUR SIMULATIONS

	2015				2030–2045			
Vehicle Configuration	**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.

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) driving cycles 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.[11] 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.

Vehicle weight and road load characteristics

The most important and uncertain inputs used in the simulations are the vehicle characteristics—weight and road load characteristics (drag coefficient, frontal area, and tire rolling resistance). The weight and drag reductions assumed for the future are aggressive. The weights were reduced about 20 percent compared to 2007 models and the drag coefficients were reduced about 25 percent in 2030; hence the fuel consumption reduction projections should be considered to be reasonably optimistic. The tire rolling resistance was assumed to decrease only slightly from a baseline value of .007 due to the need to maintain traction for driving safety. The frontal area of the vehicles was not changed in future years. There is a marked difference in the drag characteristic, C_DA, between the passenger car and the SUV, which will have significant effects on the projected fuel consumption of the two classes of vehicles.

VEHICLE WEIGHT AND DRAG REDUCTIONS PROJECTED FOR ADVANCED ICE VEHICLES

Significant reductions in vehicle weight and drag are assumed for both the passenger car and the SUV. The values used are the same as assumed in S. Plotkin and M. Singh, "Multi-Path Transportation Futures Study: Vehicle Characterization and Scenarios," Argonne Lab and DOE Report (draft), March 5, 2009, and are not much different from those used for 2030 in E. Kasseris and J. Heywood, "Comparative Analysis of Automotive Powertrain Choices for the Next 25 Years," SAE paper 2007-01-1605, 2007. Nevertheless, whether the vehicles in the future will meet these targets for weight and drag reduction remains to be seen.

Year	**Midsize Passenger Car**		**Small/Compact SUV**	
	Test weight (kg)	**Drag coef. CD**	**Test weight (kg)**	**Drag coef. CD**
2007–10	1615	.30	1750	.40
2015	1403	.25	1629	.37
2030	1299	.22	1497	.35
2045	1299	.20	1497	.33

Note: Vehicle test weight = curb weight + 136 kg

SUMMARY OF INPUTS USED IN THE VEHICLE SIMULATIONS

Midsize passenger cars

Acceleration performance for all vehicles: 0–60 mph in 9–10 seconds, 0–30 mph in 3–4 seconds

Vehicle Configuration	Parameter	2015	2030	2045
	CD	.25	.22	.20
	AF m2	2.2	2.2	2.2
	Fr	.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

Small/compact SUVs

Acceleration performance for all vehicles: 0–60 mph in 10–11 seconds, 0–30 mph in 3–4 seconds

Vehicle Configuration	Parameter	2015	2030	2045
	CD	.37	.35	.33
	AF m2	2.9	2.94	2.94
	Fr	.0075	.007	.007
Advanced ICE	Engine kW	122	112	112
	Max. engine efficiency %	39	40	41
	Vehicle test weight (kg)	1629	1497	1497
	DOE mpg FUDS/FHWDS	24/34	27/38	28/39
HEV	Engine kW	89	81	81
	Max. engine efficiency %	39	40	41
	Motor kW	31	28	28
	Battery kWh	1.2	1.1	1.1
	Vehicle test weight (kg)	1669	1532	1530
	DOE mpg FUDS/FHWDS	55/46	61/51	63/54
PHEV-20	Engine kW	96	90	89
	Motor kW	66	62	61
	Battery kWh	5.6	5.1	5.0
	Vehicle test weight (kg)	1719	1576	1570
PHEV-40	Engine kW	99	93	91
	Motor kW	69	64	64
	Battery kWh	15.2	14.0	13.5
	Vehicle test weight (kg)	1802	1654	1644
FCHEV	Fuel cell efficiency %	60	62	65
	Fuel cell kW	104	95	92
	Motor kW	129	119	116
	Battery kWh	1.2	1.1	1.1
	Vehicle test weight (kg)	1875	1705	1683
	DOE mpg FUDS/FHWDS	62/59	73/68	82/77

Notes: The first three rows of each table show the road load characteristics: drag coefficient C_D*, frontal area* A_F *in meters squared, and tire rolling resistance* F_r*.*

Vehicle test weight = curb weight + 136 kg

FUDS = Federal Urban Driving Schedule (a driving cycle that simulates city driving) and FHWDS = Federal Highway Driving Schedule (a driving cycle that simulates highway driving); mpg ratings arrived at by the U.S. Department of Energy (DOE) are shown here.

The PHEV-20 has a small battery (25–33 kg, all-electric range or AER of 10–20 mi); the PHEV-40 has a large battery (55–80 kg, AER 40–60 mi); batteries are assumed to be discharged to a 30-percent state-of-charge. Battery kWh refers to the total energy stored in the battery.

Fuel Economy and Energy Savings Simulation Results

The simulation results are shown in the following tables for midsize passenger cars and small/compact size SUVs in 2015, 2030, and 2045, with the corresponding fuel savings (as a percentage) compared to 2007 vehicles for each case. Also shown when they are available are simulation results previously published by the DOE,[12] MIT,[13] and the NRC.[14] In all cases the fuel saving comparisons are made based on the simulation results. It is thus assumed that on a percentage basis, the fuel savings would be the same for actual on-road driving.

The results for vehicles using each type of advanced technology are discussed separately in the following sections.

FUEL ECONOMY SIMULATION RESULTS FOR VARIOUS DRIVING CYCLES

Midsize passenger cars

% Fuel Saved = $(1-(mpg)_0/mpg)) \times 100$, $(mpg)_0 = 34.5$, which is the average of the city and highway dynamometer fuel economy of the 2007 baseline vehicle.

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		
Battery Electric (BEV)		**FUDS Wh/mi/ range**	**FHWDS Wh/mi/ range**	**% Fuel Saved (1)**	**US06 Wh/mi/ range**	**Accel. 0–30/0–60 mph**
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.*

Small/compact SUVs

% Fuel Saved = (1-$(mpg)_0$/mpg)) x 100, $(mpg)_0$ = 30, which is the average of the city and highway dynamometer fuel economy of the 2007 baseline vehicle.

Year	Study By	FUDS mpg	FHWDS mpg	% Fuel Saved	US06 mpg	Accel. 0–30/0–60
Baseline 2007		25	34	0		
Adv. ICE						
2015	UCD	34	44.4	23	27.3	
	DOE	24	34			
2030	UCD	38.9	50.3	33	30.8	
	DOE	27*	38*	8		
2045	UCD	40.2	53	36	32.5	
	DOE	28*	39*	10		
HEV						
2015	UCD	52.7	44.7	39	29.7	
	DOE	54.6	46.4	41		
2030	UCD	58.7	51	45	34	
	DOE	61	51	46		
2045	UCD	61	54.1	48	34.9	
	DOE	63	54	49		
FCHEV						
2015	UCD	61	60	50	40.5	
	DOE	62	59	50		
2030	UCD	74.7	73	59	48.8	
	DOE	73	68	57		
2045	UCD	80.8	78.7	62	52.9	
	DOE	82	77	62		

* *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.*

Notes: FUDS mpg = Federal Urban Driving Schedule mpg; FHWDS mpg = Federal Highway Driving Schedule mpg; US06 mpg = US06 Driving Schedule mpg

Fuel consumption in L/100 km = 238/mpg

Conventional engine/transmission vehicles

The simulation results indicate that large improvements in the fuel economy of conventional midsize passenger cars and compact SUVs 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. For conventional compact SUVs, the projected improvements in fuel economy are 30 percent (2015) to 49 percent (2030) with fuel savings of

23 percent (2015) to 33 percent (2030). These improvements result from the combined effects of decreases in weight and drag coefficient and increases in engine efficiency. In the table below, it is shown that projected increases in engine efficiency have a considerably larger effect than reductions in weight and drag for both vehicle types.

CHANGES IN FUEL ECONOMY FROM TECH IMPROVEMENTS, ICE VEHICLES

Midsize passenger cars

Technology	**2015**		**2030**	
	FUDS mpg	**FHWDS mpg**	**FUDS mpg**	**FHWDS mpg**
2007 engine (baseline)	27	42	28	43
Engine efficiency improvements, but no weight and CD reduction	39	56	42	61
All improvements	43	63	48	72

Small/compact SUVs

Technology	**2015**		**2030**	
	FUDS mpg	**FHWDS mpg**	**FUDS mpg**	**FHWDS mpg**
2007 engine (baseline)	22	31	24	32
Engine efficiency improvements, but no weight and CD reduction	30.1	37.4	34.7	43.2
All improvements	34.8	44	38.1	48.1

Hybrid vehicles (HEVs and PHEVs)

This category of advanced technology includes HEVs (gasoline fueled) and PHEVs (wall plug-in electricity and gasoline). Large improvements in the fuel economy of HEVs are projected for both midsize passenger cars and small/compact SUVs, resulting in fuel savings of 50–60 percent for the cars and 40–50 percent for the SUVs 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.

IMPROVEMENTS (AS RATIOS) IN THE FUEL ECONOMY OF HEVS COMPARED TO ADVANCED ICE VEHICLES

Technology	**2015**		**2030**	
	FUDS	**FHWDS**	**FUDS**	**FHWDS**
Midsize passenger car	1.65	1.15	1.79	1.21
Small/compactSUV	1.55	1.05	1.56	1.06

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. 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 for either vehicle will depend on its usage pattern (average miles driven per day and number of long trips taken).

Assuming for the PHEV-20 and PHEV-40 mid-size car that 20% and 65% of the total annual miles (city plus highway), respectively, are driven on electricity, one can calculate the wall-plug electricity and gasoline used and the total energy (gasoline plus energy needed to generate the electricity) savings. Assuming 15,000 annual miles, a battery charger efficiency of 90%, and a powerplant efficiency of 40%, one calculates the following results for the two PHEVs in 2030 compared to an advanced ICE vehicle. For the PHEV-20, one finds a gasoline saving of 40% and a total energy saving of 26% for the 40% efficient powerplant. The PHEV-20 would use 480 kWh of electricity from the wall-plug. The corresponding values for the PHEV-40 are 75% gasoline savings, 30% total energy savings, and 1538 kWh electricity used from the wall-plug. Note that the total energy savings (gasoline plus that to generate the electricity) are about the same for a 40% efficient powerplant. For a 50% efficient powerplant, the difference in total energy savings is larger being 29% for the PHEV-20 and 39% for the PHEV-40.

PHEV FUEL ECONOMY AND ELECTRICITY USAGE SIMULATION RESULTS

Midsize 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

Small/compact SUVs

Year	Driving Cycle	Electric Range mi	Charge-depleting mpg	Charge-depleting Wh/mi (at battery)	Charge-sustaining mpg
PHEV-20					
2015	FUDS	19	All-elec.	213	51.9
	FHWDS	16	All-elec.	257	45.4
	US06	12	379	384	30.6
2030	FUDS	19	All-elec.	192	57.9
	FHWDS	14	All-elec.	255	50.6
	US06	10	525	360	34
2045	FUDS	19	All-elec.	188	62.0
	FHWDS	16	All-elec.	226	53.8
	US06	10	576	348	36.3
PHEV-40					
2015	FUDS	49	All-elec.	218	54.6
	FHWDS	40	All-elec.	266	46.1
	US06	28	547	385	30.7
2030	FUDS	51	All-elec.	192	60.4
	FHWDS	41	All-elec.	239	51.4
	US06	28	781	351	33.9
2045	FUDS	50	All-elec.	188	62.6
	FHWDS	41	All-elec.	230	55.2
	US06	28	879	338	36.5

Notes: FUDS = Federal Urban Driving Schedule; FHWDS = Federal Highway Driving Schedule; US06 = US06 Driving Schedule; Wh/mi = watt hours per mile.

The PHEV-20 has a small battery (25–33 kg, all-electric range or AER of 10–20 mi); the PHEV-40 has a large battery (55–80 kg, AER 40–60 mi).

Electric vehicles (Fuel cell–powered and battery vehicles)

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 in our simulation 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 and by 40 percent (2015) to 53 percent (2030) for the compact SUV. This reduction in energy use of the fuel cell vehicles compared to the baseline gasoline vehicle is for tank-to-wheels (TtW). The energy use reduction from the hydrogen production plant-to-wheels (the so-called well-to-wheels reduction) would be less depending on the relative efficiencies of production and distribution of hydrogen and gasoline.

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 $(\text{gal/mi})_{\text{gas.equiv.}} = (\text{kWh/mi})/33.7$. 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%.

SUMMARY: FUEL SAVINGS FOR THE VARIOUS TECHNOLOGIES

The fuel savings results for the midsize passenger car and the compact SUV compared to the baseline 2007 conventional vehicle are summarized in the table below.

Technology	**Percentage fuel savings, 2015–2045**	
	Midsize passenger car	**Compact SUV**
Advanced ICE vehicle	33–45 (tank)	23–36 (tank)
HEV	53–61 (tank)	39–48 (tank)
PHEV-20	62% (wall-plug, tank))	—
PHEV-40	75% (wall-plug, tank))	—
FCHEV	60–72 (tank)	50–62 (tank)
BEV	79% (wall-plug) 45% (powerplant)	–

As expected, the magnitude of the fuel/energy savings is greatest for the fuel cell technology. However, the differences between the fuel savings achieved by the different technologies are not as large as we might have expected. Fuel cell vehicles achieve only about twice the fuel savings of the improved conventional engine/transmission power trains and only about 15 percent better savings compared to the HEV (charge-sustaining) power trains. This does not include a consideration of the differences in the efficiencies of producing gasoline from petroleum and hydrogen from natural gas or coal, however. The battery-powered vehicle (BEV) has a high energy savings (79%) from the wall-plug, but only modest savings (40%) when the power generation losses at the powerplant are included.

In terms of saving petroleum, the BEV and PHEV offer the greatest opportunity for fuel savings, especially the 40–50 mile PHEV design. It is difficult to quantify the savings of the PHEV because they depend on the usage pattern of the vehicle and the energy source used to generate the electricity. In any case, gasoline-only fuel economy of the PHEV will be significantly greater than for the HEV.

Comparisons of the simulation results from the various studies

The UC Davis simulation results are close to the DOE results except for advanced conventional vehicles (as noted previously the DOE projections are known to be low). However, the UC Davis and MIT fuel economy projections for the midsize passenger car for 2030 are in good agreement for both the advanced ICE and HEV technologies. In addition, the percentage fuel savings projected by the NRC for the advanced ICE vehicle in the near term is close to that projected in the UC Davis simulation (29 percent compared to 33 percent in 2015). In the case of the HEV technology, the NRC projects a fuel saving of 44 percent and UC Davis projects 53 percent in 2015. For the HEV and FCHEV technologies, the DOE and UC Davis results are in good agreement over the complete time period of the simulations, with the agreement being closest in the 2030–2045 time periods. It should be noted that the vehicle characteristics used in the UC Davis simulations were selected to match those used in the DOE study. Hence the agreement between the two studies indicates consistency in the modeling approaches in the two studies for the HEV and FCHEV technologies.

Cost Projections

The second part of our advanced vehicle study involved projecting costs for each of the power train combinations simulated. We did this using a spreadsheet cost model[15] that permits the quick analysis of the economics of hybrid vehicle designs for vehicles of various sizes operated in North America, Europe, and Japan. We analyzed the economics as a function of fuel price, usage pattern (driving cycle and miles/year), and discount rate.

Methodology and cost inputs

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 the earlier “Summary of Inputs Used in the Vehicle Simulations” tables. In all cases, the values for 2030 were used in the cost projections. The input values for the fuel economy projections were taken from the earlier

"Fuel Economy Simulation Results for Various Driving Cycles" tables. 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, we estimated a range of values for the unit costs of those components. There is a smaller uncertainty about the costs of advanced conventional engine components, so we used single unit cost values for those components. The values we used were based on information in Kromer and Heywood (2007) and Lipman and Delucchi (2003).[16] In all cases, we assumed that the vehicles and driveline components are manufactured in large volume for a mass market.

The inputs to the spreadsheet were selected to model the specific vehicle designs analyzed in this study. 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). We assumed that 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, we used 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 the NRC's 2010 "Assessment of Fuel Economy Technologies for Light-duty Vehicles" report. 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.

Discussion of the cost projection results

We show the results of the economic analysis of the various advanced vehicle cases for a midsize passenger car in 2030. 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 an advanced engine 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 2010 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.

The break-even gasoline prices do not include the effect of possible battery replacement. We assumed 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. 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.

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/kgH_2 range should make fuel cell vehicles cost competitive with HEVs and ICE vehicles using advanced engines.

We have also analysed the economics of battery-powered vehicles with a range of 100 miles 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 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 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.

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

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-40 has a large battery (55–80 kg, AER 40–60 mi).

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/gal1
HEV	71.1	1000	70	70	.62	$3204	$2.61/gal1
		800	70	56		$3003	$2.45/gal1
		600	70	42		$2802	$2.29/gal1
PHEV-20	75.34	800	100	80	.65	$6409	$5.03/gal1
							$3.64/gal2
		600	100	60		$5605	$4.40/gal1
							$3.19/gal2
		400	100	40		$4801	$3.77/gal1
							$2.73/gal2
PHEV-40	1275	700	150	105	.79	$10,228	$6.58/gal1
							$4.77/gal2
		500	150	75		$8218	$5.29/gal1
							$3.83/gal2
		300	150	45		$6208	$3.99/gal1
							$2.89/gal2
FCHEV	89.8						
$75/kW FC		800	70	56	.70	$7549	$5.47/gal1
							$3.31/gal3
$50/kW FC		800	70	56		$5549	$4.02/gal1
							$2.43/gal3
$30/kW FC		800	70	56		$3949	$2.86/gal1
							$1.73/gal3
Battery electric BEV	Equiv. 176						
Range 100 mi.		$700	170	119	.77 wallplug	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)

2030 BREAKEVEN FUEL PRICE $/GAL GASOLINE EQUIV.

Vehicle design	**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 $/kWh**	**w/o disc**	**with disc**	**w/o disc**	**with disc**	**w/o disc**	**with disc**
700	2.94	4.76	4.32	7.00	7.54	12.22
500	2.42	3.92	3.27	5.30	5.71	9.25
300	1.89	3.06	2.22	3.60	3.88	6.29
Fuel cell HEV*** **5 yr at 4% disc** **fuel cell cost**	**w/o disc**	**with disc**	**w/o disc**	**with disc**	**w/o disc**	**with disc**
75	5.07	5.68	6.48	7.26	9.62	10.77
50	4.16	4.66	4.88	5.47	7.25	8.12
30	3.44	3.85	3.61	4.04	5.36	6.00
10 yr at 10% disc **fuel cell cost$/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* H_2

Summary and Conclusions

- To determine how much of a reduction in fuel consumption we can expect from new vehicle technologies, we ran simulations for a midsize passenger car and a small/compact SUV for 2015, 2030, and 2045. We compared fuel economy (mpg) and fractional energy saved by advanced, higher-efficiency engines, hybrid-electric vehicles (HEVs and PHEVs), and electric-drive vehicles (BEVs and FCVs) in relation to a conventional vehicle marketed in 2007.

- According to our simulation results, large improvements in the fuel economy of conventional midsize passenger cars (50–70 percent) and compact SUVs (30–49 percent) relative to 2007 models can be expected in the next ten to twenty years even without large changes in the basic power train technology. These improvements will result from the combined effects of decreases in weight, vehicle drag, and tire rolling resistance and increases in engine efficiency.

- We found that gasoline/energy savings of about 40 percent can be expected due to vehicle and engine improvements and up to 60% when the powertrain is hybridized. A fuel/gasoline savings of nearly 80 percent is projected for a PHEV with a large battery (40- to 50-mile all-electric range). The corresponding total energy saving is about 40% for a 50% efficient electricity powerplant. The fuel cell vehicle has a projected energy savings (tank-to-wheels) of 72 percent in 2030 and an equivalent fuel economy of more than 100 mpg.

- For 2030 BEV, the gasoline energy equivalent saved is 79% from the wall-plug and 57% at a 50% 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%.

- Although we did expect that the magnitude of the fuel/energy savings would be greatest for the fuel cell technology, the differences between the fuel savings achieved by the different technologies are not as large as we might have expected. FCVs achieve only about twice the fuel economy of the improved conventional engine/transmission power trains and only about 15 percent better savings compared to the HEV (charge-sustaining) power trains. This does not include a consideration of the differences in the efficiencies of producing gasoline from petroleum and hydrogen from natural gas or coal, however. The BEV has a high energy savings (79 percent) from the wall plug, but more modest savings (40–55 percent) when the power generation losses at the power plant are considered.

- In terms of saving petroleum, the BEV and the PHEV offer the greatest opportunity for fuel/gasoline savings, especially the 40–50 mile PHEV design. It is difficult to quantify the real-world savings because they depend on the detailed usage pattern of the vehicle and the energy source used to generate the electricity. In any case, the gasoline-only fuel economy of the PHEV will be significantly greater than for the HEV.

- Our cost studies indicate that both the advanced ICEV and HEVs using advanced high-efficiency engines would be cost competitive with the baseline vehicle in 2015 to 2030, with a break-even gasoline price of $2.50–$3.50/gal calculated for a five-year performance period (12,000 mi/yr) and a 4-percent discount rate.

- The PHEV with the small battery (all-electric range of about 20 miles) becomes competitive with the HEV when the retail battery cost is $400/kWh and the performance period is ten years. The PHEV with the large battery (all-electric range of about 50 miles) becomes cost competitive at a battery cost of $300/kWh. The cycle life of the batteries was assumed to be ten years. The FCV becomes cost competitive with the HEV when the retail fuel cell cost is $30–$50/kW and the price of hydrogen is about $3/kg. BEVs are not cost competitive with advanced ICEVs and HEVs even at a battery cost of $300/kWh.

Notes

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