

Societal lifecycle costs of cars with alternative fuels/engines

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Abstract

Effectively addressing concerns about air pollution (especially health impacts of small-particle air pollution), climate change, and oil supply insecurity will probably require radical changes in automotive engine/fuel technologies in directions that offer both the potential for achieving near-zero emissions of air pollutants and greenhouse gases and a diversification of the transport fuel system away from its present exclusive dependence on petroleum.

The basis for comparing alternative automotive engine/fuel options in evolving toward these goals in the present analysis is the “societal lifecycle cost” of transportation, including the vehicle first cost (assuming large-scale mass production), fuel costs (assuming a fully developed fuel infrastructure), externality costs for oil supply security, and damage costs for emissions of air pollutants and greenhouse gases calculated over the full fuel cycle.

Several engine/fuel options are considered—including current gasoline internal combustion engines and a variety of advanced lightweight vehicles: internal combustion engine vehicles fueled with gasoline or hydrogen; internal combustion engine/hybrid electric vehicles fueled with gasoline, compressed natural gas, Diesel, Fischer–Tropsch liquids or hydrogen; and fuel cell vehicles fueled with gasoline, methanol or hydrogen (from natural gas, coal or wind power). To account for large uncertainties inherent in the analysis (for example in environmental damage costs, in oil supply security costs and in projected mass-produced costs of future vehicles), lifecycle costs are estimated for a range of possible future conditions.

Under base-case conditions, several advanced options have roughly comparable lifecycle costs that are lower than for today’s conventional gasoline internal combustion engine cars, when environmental and oil supply insecurity externalities are counted—including advanced gasoline internal combustion engine cars, internal combustion engine/hybrid electric cars fueled with gasoline, Diesel, Fischer–Tropsch liquids or compressed natural gas, and hydrogen fuel cell cars.

The hydrogen fuel cell car stands out as having the lowest externality costs of any option and, when mass produced and with high valuations of externalities, the least projected lifecycle cost. Particular attention is given to strategies that would enhance the prospects that the hydrogen fuel cell car would eventually become the Car of the Future, while pursuing innovations relating to options based on internal combustion engines that would both assist a transition to hydrogen fuel cell cars and provide significant reductions of externality costs in the near term.

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1. Introduction

Continued reliance on current transportation fuels and technologies poses serious oil supply insecurity, climate change, and urban air pollution risks. Globally, transportation consumes oil at a rate equivalent to $\frac{3}{4}$ of world oil imports and accounts for $\frac{1}{4}$ of greenhouse gas (GHG) emissions and a significant fraction of air-pollutant emissions. Even with continuing incremental progress in improving energy efficiency and reducing

emissions per vehicle, oil supply insecurity risks and emissions of GHGs and air pollutants are expected to grow over the next century under business-as-usual conditions because of rapidly growing demand for transportation fuels, especially in developing countries.

Effectively addressing environmental and oil supply insecurity concerns will probably require radical changes in automotive engine/fuel technologies in directions that offer the potential for achieving near-zero emissions of air pollutants and GHGs and a diversification of transportation fueling away from present exclusive dependence on petroleum.

To compare alternative automotive engine/fuel options in evolving toward these goals, estimates are

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developed for automotive performance and costs, fuel costs, full fuel cycle emissions, externality costs and system costs. The societal lifecycle cost (LCC) is singled out as an important indicator for comparing alternatives. The present study differs from earlier LCC studies [e.g., Weiss et al., 2000] in that valuations of air-pollutant and GHG emissions and oil supply insecurity risks as well as direct economic costs are included in LCCs. Options compared include current gasoline internal combustion engine vehicles (ICEVs) and a variety of lightweight, advanced vehicles: (i) ICEVs fueled with gasoline or hydrogen (H₂); (ii) internal combustion engine/hybrid electric vehicles (ICE/HEVs) fueled with gasoline, compressed natural gas (CNG), Diesel, Fischer–Tropsch (F–T) liquids or H₂; and (iii) fuel cell vehicles (FCVs) fueled with gasoline, methanol or H₂. For H₂, supplies considered include H₂ derived from natural gas and coal, without and with sequestration of the separated CO₂, and H₂ derived from windpower via electrolysis.

There are large uncertainties inherent in the analysis (for example, in air-pollutant damage costs, GHG costs, oil supply insecurity costs and projected mass-produced costs of future vehicles) that make precise comparisons of LCCs difficult. To shed light on these uncertainties, sensitivity studies were carried out to estimate LCCs for a range of possible future conditions, with a focus on variations in externality costs. In one set of sensitivity analyses, estimates are made of allowable drive-train cost increments for advanced options that would give rise to LCC parity with a reference car, for alternative valuations of externalities. In another set of sensitivity analyses, values of avoided CO₂ emissions are estimated that would bring about LCC parity between the reference car and the H₂ FCV (the advanced option offering the lowest externality costs) for alternative valuations of other externalities.

2. Estimation of societal lifecycle costs

The societal LCC is defined as: $LCC (\$/vehicle) = \text{vehicle first cost} + \text{the present value of lifetime costs for: (fuel + non-fuel operation and maintenance + full fuel cycle air-pollutant damages + full fuel cycle GHG emission damages + oil supply insecurity)}$. LCCs for the major options considered are presented in Table 1 and Fig. 1 for a base case than involves best estimates of direct economic costs and median valuations of externalities.

2.1. First costs and fuel economies of alternative vehicles

Alternative-fueled, mid-sized (4–5-passenger) automobiles are considered, each designed to have the same performance. Table 2 presents the estimated first costs

and fuel economies of the options studied. These estimates are broadly consistent with those of another recent study by MIT researchers (Weiss et al., 2000).

The vehicle first cost includes costs for the vehicle body plus the drive train (the engine, transmission, and fuel storage). It is assumed that an aluminum-intensive vehicle body or “glider” (e.g., the vehicle excluding drive-train components) is used for all vehicles except the current gasoline ICEV. Glider costs other than the additional cost for an aluminum-intensive body (see Table 2) are assumed to be the same for all vehicles and are not included in the cost comparisons.

Cost estimates for alternative future drive trains are for mass production conditions and do not take into account expenditures associated with launching new technologies in the market (expenditures for “technology cost buy down”). Issues relating to buying down costs of new technologies as they advance along their experience curves will be addressed in a companion paper (Ogden et al., 2003).

The automotive performance and cost estimates in Table 2 are based on engineering and cost models from several sources but mainly on a series of papers by analysts at Directed Technologies, Inc. (DTI). In these studies computer simulations were made of vehicles with alternative fuel/engine combinations—including conventional and lightweight gasoline ICEVs, ICE/HEVs fueled with Diesel, CNG and H₂, and FCVs fueled with gasoline, methanol and H₂ (Thomas et al., 1998a,b; Thomas, 1999; Lomax et al., 1998). Vehicle components were sized in DTI’s models to give identical performance for the vehicles compared, and the indicated fuel economies are for the US Environmental Protection Agency (EPA) urban/highway driving cycle. To calculate projected costs for these vehicles, DTI researchers estimated the mass-produced cost of both ICE/HEV and FCV components (see Box 1) as a function of engine size and annual production level (Lomax et al., 1998).

Four lightweight engine/fuel options that were not explicitly modeled in the DTI studies are also considered: advanced gasoline and H₂ ICEVs, spark-ignition direct-injection (SID) ICE/HEVs run on gasoline, and compression-ignition direct-injection (CID) ICE/HEVs run on FT50, a 50/50 mix of F–T liquids and Diesel fuel. For the gasoline and H₂ ICEVs, fuel economy and vehicle cost estimates from researchers at Ford Motor Company (Kenney, 2002) are assumed.¹

¹The Ford analysts did not provide a disaggregation of their estimated retail cost increment of \$2500 for the H₂ ICEV drive train (Table 2), which corresponds to a \$2136 manufacturing cost increment according to the methodology used in estimating other costs presented in Table 2. However, this might reasonably be divided into the incremental cost for H₂ storage [\$1611 for the 7.4 kg H₂ required for a 380-mile range (see Box 1) less \$125 for a gasoline tank] plus an incremental cost of \$650 for the H₂ ICE compared to a gasoline ICE of

For the gasoline ICE/HEV, the fuel economy is based on Kenney (2002), and the cost is estimated from component sizes and costs used in the DTI models for CNG and Diesel hybrids. Drive-train costs for FT50 CIDI ICE/HEVs are assumed to be the same as for these hybrids running on Diesel fuel.

The DTI studies estimate manufacturing costs of vehicle components including materials, labor, machine time (machine capital and O&M expenses), plus a 22% mark-up for engineering and R&D, and a 10% contingency. However, the retail cost (consumer's purchase price, exclusive of sales taxes) should be used in LCC calculations rather than the manufacturing cost. To estimate the retail cost several other costs should be added to the manufacturing costs, including: (i) assembly costs, (ii) division costs (e.g. the cost of operating an automotive manufacturers' division, and costs for non-manufacturing labor, engineering, testing, advertising, operation of buildings), (iii) corporate costs (e.g., the cost of operating the company at the corporate level, executives, capital, R&D, cost of money and profit), (iv) dealers' costs (dealer staff salaries, dealer advertising, cost of buildings and their O&M), and (v) shipping costs (which depend on vehicle weight). Based on such costs presented by Delucchi et al. (2000), the difference in retail price between two vehicles is estimated to be 1.17 times the difference in their manufacturing costs. This factor is used to convert the manufacturing costs in the DTI studies into retail costs.²

2.2. Fuel costs for alternative vehicles

The lifetime fuel cost presented in Table 1 is the present value of lifetime fuel expenditures calculated for the indicated fuel economy and levelized fuel price, assuming an 8% discount rate and a car driven 12,000 miles/year (19,300 km/year) for 10 years—so that the present value of fuel expenditures is 0.671 times the present value calculated for a 0% discount rate.

Delivered fuel prices in Table 1 do not include federal and state retail taxes that, in the United States, averaged \$0.42/gallon (\$0.11/l) for regular gasoline in 1999. Delivered costs for gasoline, Diesel, CNG and F-T

(footnote continued)

the same performance. Assuming the 2625lb H₂ ICEV has the same power-to-weight ratio as today's 100kW gasoline ICEV that weighs 3625lb, the engine capacity would be 72.4kW. Assuming a specific cost of \$19/kW or \$1376 for a gasoline engine of this size, the cost of the H₂ ICE would be \$2026 or \$28/kW, about 1.5 times the specific cost of a gasoline ICE (approximately the same as the ratio of the Diesel ICE cost to the gasoline ICE cost). The H₂ ICE is expected to be more costly than a gasoline ICE because: (i) the engine is larger, (ii) it operates at a higher compression ratio, and (iii) more costly valves and injectors are required.

²For comparison, a 10% mark-up is used by DTI (Thomas, 2000) and Ford (Muniz, 2002) in translating manufacturing cost differences into retail price differences.

liquids, are estimates presented in a recent study by researchers at Argonne National Laboratory (Wang et al., 1999). Costs for H₂ (see Table 3 for H₂ derived from fossil fuels and Table 1, note e, for electrolytic H₂ based on wind power) are from Williams (2002) for H₂ production and Ogden (1998, 2002) for H₂ distribution and refueling station costs. Fuel economies and delivered fuel costs in Tables 1 and 2 are expressed on a lower heating value (LHV) gasoline-equivalent basis.³

2.3. Non-fuel operation and maintenance expenses

Non-fuel operation and maintenance costs, assumed to be the same in all cases, are not included.

2.4. Externality valuations

In the economic valuations of damages from air-pollutant and GHG emissions and of oil supply insecurity, present values of estimated lifecycle external costs are calculated for a 3% discount rate (in accordance with guidelines established for the ExternE studies of the European Commission) and are thus 0.853 times the present values for a 0% discount rate.

2.4.1. Air-pollutant damage costs

Costs of air-pollutant damages were estimated based on: (i) estimated emissions (grams/mile) both from vehicle operations and all fuel supply activities upstream of the vehicle, and (ii) estimates of damage costs (\$/g) of emitted air pollutants.

Emissions estimates. Full fuel-cycle ("well-to-wheels") emissions calculations include not only emissions from vehicles but also from "upstream" operations, such as fuel extraction, production, refining, storage, distribution and dispensing.

A key reference for air-pollutant emissions estimates is the Transportation Fuel Cycle Model (GREET) developed at Argonne National Laboratory (Wang, 1999; Wang and Huang, 1999).

GREET model results are used for emissions of air pollutants "upstream" of vehicles—from fuel feedstock extraction (e.g., natural gas production or coal mining), most fuel production operations (e.g., oil refining and H₂ production from natural gas), and fuel transmission and refueling operations. GREET model estimates are also used for direct in-use emissions from current gasoline ICEVs and CNG ICE/HEVs.

However, air-pollutant emissions for coal-derived H₂ plants (see Table 1, note d) and wind-power-derived H₂ plants (see Table 1, note f) are from Williams (2002). Also, air-pollutant emissions for the cases involving H₂ production from fossil fuels with CO₂ sequestration (see

³Assuming the gasoline LHV = 115,000 BTU/gallon (121.9 MJ/gallon or 32.2 MJ/l).

Table 1
Projected base case societal lifecycle costs for automobiles with alternative fuel/engine options^a

Alternative fuel/engine options {gasoline-equivalent fuel economy (in mpg) and fuel price [in \$/gallon of gasoline equivalent (gge)]}	PV of lifetime AP and GHG damage costs for fuel cycle			PV of OSI costs	PV of AP + GHG + OSI costs	PV of lifetime fuel costs	Retail cost of drive- train (incl. fuel storage)	Cost of alum- inum- intensive frame	Total societal lifecycle costs				
	AP	GHG	Total Environ- mental costs						Without external costs	AP only	GHG only	AP + GHG	AP + GHG + OSI
Current gasoline SI ICEV (27 mpg, \$0.95/gal)	2640	1429	4069	2654	6723	2828	2837	0	5665	8305	7094	9734	12388
<i>Advanced lightweight ICEVs</i>													
Gasoline SI ICEV (45.6 mpg, \$0.95/gal)	1162	846	2008	1571	3579	1674	2837	936	5448	6609	6293	7455	9026
H ₂ (NG) SI ICEV (52.6 mpg, \$2.21/gge)	524	746	1270	0	1270	3381	2837 + 2500	936	9654	10,178	10,400	10,924	10,924
<i>Advanced lightweight ICE/HEVs</i>													
Gasoline SIDI ICE/HEV (58 mpg, \$0.95/gal)	1097	683	1780	1235	3015	1316	2837 + 1342	936	6432	7528	7114	8211	9446
CNG SI ICE/HEV (62 mpg, \$1.19/gge)	644	515	1160	0	1160	1552	2837 + 1556	936	6881	7525	7397	8041	8040
H ₂ (NG) SI ICE/HEV (63 mpg, \$2.21/gge)	458	623	1081	0	1081	2823	2837 + 2780	936	9376	9834	9999	10457	10457
Diesel CIDI ICE/HEV (67 mpg, \$0.83/gge)	1150	590	1740	1069	2809	996	2837 + 1863	936	6632	7782	7222	8372	9441
FT50 (NG) CIDI ICE/HEV (67 mpg, \$0.88/gge)	1122	596	1718	535	2253	1058	2837 + 1863	936	6694	7816	7290	8412	8947
<i>Lightweight fuel cell vehicles</i>													
Gasoline FCV (38 mpg, \$0.95/gal)	338	1019	1357	1886	3243	2009	2837 + 5097	936	10,879	11,217	11,898	12,236	14,122
Methanol (NG) FCV (56 mpg, \$1.56/gge)	248	668	916	0	916	2238	2837 + 3220	936	9231	9479	9899	10,147	10,147
H ₂ (NG) FCV (82 mpg, \$2.21/gge)	257	479	736	0	736	2169	2837 + 2459	936	8402	8659	8881	9138	9138

H ₂ (NG) FCV (82 mpg, \$2.46/gge) w/CO ₂ seq ^b	119	106	225	0	225	2411	2837 + 2459	936	8644	8763	8750	8869	8869
H ₂ (coal) FCV (82 mpg, \$2.24/gge) ^{c,d}	366	881	1247	0	1247	2200	2837 + 2459	936	8432	8798	8798	9679	9679
H ₂ (coal) FCV (82 mpg, \$2.48/gge) w/CO ₂ seq ^{b,c,d}	215	99	314	0	314	2435	2837 + 2459	936	8667	8882	8766	8981	8981
H ₂ (wind electrolytic) FC (82 mpg, \$3.46/gge) ^{e,f}	68	114	182	0	182	3394	2837 + 2459	936	9626	9694	9740	9808	9808

^a Table entries were developed for the present analysis except those for H₂ from coal and wind, which are from Williams (2002). Fuel economies and vehicle first costs are from Table 2. Lifetime air pollutant (AP) and greenhouse gas (GHG) emissions and associated lifetime damage costs, as well as oil supply insecurity (OSI) costs, were calculated as indicated in the main text—assuming: (i) median ExternE estimates (Spadaro et al., 1998; Spadaro and Rabl, 1998; Rabl and Spadaro, 2000) of specific damage costs (\$/kg of emissions) for AP emissions, adjusted for US population densities; (ii) a GHG emission value of \$120/t C; and (iii) an OSI cost of \$0.70/gallon of gasoline-equivalent fuel (see main text). Some details of the GHG and AP damage cost estimates are discussed in notes d and f, respectively. Fuel prices and lifetime fuel costs were calculated as discussed in the main text, except for the coal H₂ (note c) and the wind H₂ (note e) cases.

^b For the sequestration cases, it is assumed that electricity consumed at H₂ refueling stations (17.5 kWh_e/GJ H₂ for compression) is provided by the US average mix of electricity supplies for 2015 as projected in GREET but with coal electricity (54% of all electricity) provided by coal IGCC plants with sequestration—for which CO₂ emissions are 15.9 gr C/kWh [compared to 195.3 gr C/kWh for the same IGCC plant with CO₂ vented—see Table 4 in Williams (2002)] and for which SO₂, NO_x, and PM₁₀ emissions equal the measured emissions for the coal IGCC plant at Buggenum, The Netherlands Williams, (2000). Damage costs associated with electricity consumed at refueling stations is \$0.0016/kWh for GHGs and \$0.00386/kWh for APs (compared to \$0.0182/kWh for GHGs and \$0.0424/kWh for APs for the mix of power plants projected by GREET for 2015).

^c Costs for coal-derived H₂ are from Table 3.

^d Coal system AP and GHG emissions upstream of the coal conversion facility are from the GREET model (Wang, 1999; Wang and Huang, 1999): the discounted value of upstream emissions is \$0.092/GJ of coal for GHGs (64.6% CH₄, 35.2% CO₂, and 0.2% N₂O) and \$0.559/GJ of coal (43.7% NO_x, 25.2% SO_x, 28.6% PM₁₀, and 2.4% VOCs) for APs. The CO₂ emissions for the coal-to-H₂ plant are from Table 3, note b. The only AP emissions taken into account for the coal-to-H₂ plant are NO_x emissions (all other emissions are assumed to be negligible). For H₂ manufacture without CO₂ capture and sequestration [where the synthesis gas not converted to H₂ is burned to provide coproduct electricity in a steam turbine power plant [see Table 4 in Williams (2002)]], it is assumed that NO_x emissions are 43 ppmv (dry) at 3% O₂ (typical for natural gas steam-electric power plants) or 6.9 gr NO_x/GJ of coal, for which the discounted value of environmental damages is \$0.081/GJ of coal. For H₂ manufacture with CO₂ capture and sequestration [where the synthesis gas not converted to H₂ is burned in the gas turbine combustor of a combined cycle power plant to provide coproduct electricity—see Table 4 in Williams (2002)] it is assumed that NO_x emissions are 25 ppmv (dry) at 15% O₂ (typical for natural-fired gas turbines) or 4.7 gr NO_x/GJ of coal, for which the discounted damage value is \$0.056/GJ of coal.

^e The cost parameters for the wind system are based on Williams (2002). A future wind electric generation cost of 2.9 ¢/kWh is assumed—the cost projected for excellent (Class 6) wind resources in 2020 (EPRI/OUT, 1997). It is assumed that intermittent wind power at this cost is coupled to a compressed air energy storage (CAES) unit to provide baseload electricity, which is transported 300 km via a high-voltage transmission line at an estimated delivered cost of 4.0 ¢/kWh to an urban center where it is used to make H₂ electrolytically for transport applications using advanced electrolytic technology. For the electrolysis plant, the assumed capital cost and efficiency are \$300/kW and η = 83%, respectively (Ogden et al., 1998), and the byproduct O₂ is estimated to be worth \$1.7/GJ of H₂ (Williams, 2002). The resulting net plant-gate H₂ cost = \$15.0/GJ (89% of which is for the electricity “feedstock”). To this must be added \$9.0/GJ for ½ day of H₂ storage at the H₂ plant, H₂ distribution to refueling stations, plus the cost of refueling stations (see Table 3), bringing the delivered H₂ cost to \$24.0/GJ (HHV) or \$3.436/gallon of gasoline equivalent.

^f Emissions for the wind/CAES system arise from burning 0.32 GJ of natural gas in the CAES combustor per GJ of H₂ produced. Direct + upstream GHG damage costs = \$0.49/GJ of H₂ (4.82 kgC-equivalent/GJ of H₂). Upstream AP damage costs = \$0.294/GJ of natural gas (\$0.094/GJ H₂). The only AP emissions considered for the CAES plant are NO_x (other emissions are assumed negligible). Assuming NO_x emissions are 25 ppmv (dry) at 15% O₂ (typically realized for natural gas-fired gas turbines), NO_x emissions for the CAES plant are 38.4 g/GJ of natural gas, for which the discounted damage cost is \$0.53/GJ of natural gas (\$0.17/GJ H₂). Assuming all coal power in the GREET power mix for 2015 is replaced by wind/CAES power, GHG and AP damage costs for electricity consumed at refueling stations are \$0.046/GJ of H₂ (from emissions of 25.8 g C-equivalent/kWh of electricity) and \$0.059/GJ of H₂, respectively.

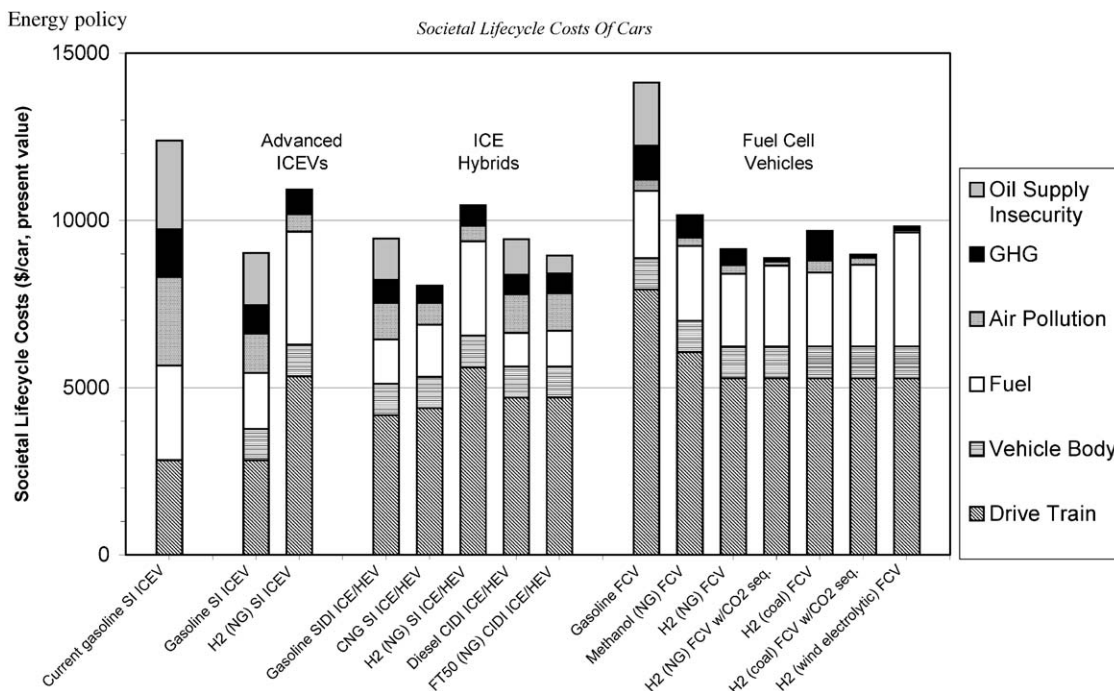


Fig. 1. Societal lifecycle costs for alternative fuel/engine options for cars—base case analysis (from Table 1).

Table 3) were developed to be consistent with the GREET framework but modified by the assumption that for these cases all coal power plants in the electricity supply mix providing electricity for H₂ refueling stations are coal integrated gasifier combined cycle (IGCC) plants for which CO₂ is recovered and sequestered (see Table 1, note b). Moreover, it is assumed that advanced spark-ignited gasoline ICEVs and ICE/HEVs satisfy Tier II, bin 3, standards and that compression-ignition engines using Diesel or F–T liquids satisfy Tier II, bin 4, standards of the US Clean Air Act Amendments of 1990.⁴ Vehicle emissions from H₂ ICEVs and H₂ ICE/

⁴Under the US Clean Air Act Amendments of 1990, vehicles must satisfy increasingly strict air-pollutant emission standards. So-called Tier I standards are currently in effect. Beginning in 2004, “Tier II” standards developed by the US Environmental Protection Agency will be phased in for cars and light trucks and will be fully implemented by 2007 (100% of new light-duty vehicles must satisfy the standard). A series of five emissions “bins” are specified, allowing some vehicles to emit more than others, as long as the pollutant emission standard is met on average. A recent assessment (Wang, 1999) suggests that advanced gasoline cars (ICEVs or ICE/HEVs) could meet Tier II, bin 3 standards and Diesel cars Tier II, bin 4 standards:

Pollutant emissions (g/m)	Tier I	Tier II, bin 3	Tier II, bin 4
VOC	0.25	0.04	0.055
CO	3.4	2.1	2.1
NO _x	0.4	0.04	0.07
PM ₁₀	0.08	0.01	0.01

HEVs and from all FCVs are from Thomas et al. (1998b).

Specific air-pollutant damage costs. Valuations of specific environmental damage costs (\$/g) are based on studies carried out under the auspices of the European Commission’s ExternE Programme (Spadaro et al., 1998; Spadaro and Rabl, 1998; Rabl and Spadaro, 2000), adjusted for US (lower) population densities.

The ExternE studies show that air-pollutant damage costs are dominated by human health effects (mostly chronic mortality) associated with small particles in the air that are either emitted directly in fossil fuel combustion or are formed by reactions in the atmosphere from gaseous precursor emissions of SO₂ and NO_x. The ExternE air-pollutant damage cost estimates are based on considerations of both direct medical costs and on the “willingness to pay” to avoid air-pollutant health damages.

For this study southern California was chosen as a site for estimating damage costs from automotive air-pollutant emissions in the United States. Southern California is an area with severe air-quality problems. And California has been a US leader in implementing strict air-pollutant control strategies—including zero emission vehicle (ZEV) mandates. New York, Massachusetts and Vermont have tended to adopt California regulatory rules relating to emissions. Collectively, these four states account for a large fraction (about 20%) of the US light-duty vehicle market. Because of the inefficiencies of having to develop different automotive

Table 2
 Projected fuel economy and drive train costs (\$/car) for mass-produced alternative vehicles^a

	Fuel economy (mpgge)	Fuel cell system	Fuel processor	ICE & auxiliaries	Transmission	Fuel tank system	Motor/controller (incl. generator for ICE/HEVs)	Peak battery system	Controls	Total drive-train mfg. cost	Retail drive-train cost ^b	Aluminum-intensive frame, retail cost ^c
Current gasoline SI ICEV (100 kW) ^d	27	0	0	1600	700	125	0	0	0	2425	2837	0
Gasoline SI ICEV, weight reduction	45.6	0	0	1600	700	125	0	0	0	2425	2837	936
Moderate engine improvements ^{c,d}												
H ₂ SI ICEV ^{f,g}	52.6										2837+2500	936
Gasoline Series SIDI ICE/HEV ^{f,g} (Thermostat) (46.3 kW ICE; 94.5 kW battery)	41			954	200	125	1612	1574	150	4615	2837+2562	936
Gasoline Series SIDI ICE/HEV ^{f,g} (load follow) (43.2 kW ICE; 38.1 kW battery)	46	0	0	939	200	125	1528	695	150	3636	2837+1417	936
Gasoline Parallel SIDI ICE/HEV^{f,g} (33.5 kW ICE; 35.5 kW battery)	58	0	0	890	700	125	1053	654	150	3572	2837+1342	936
Natural gas series SI ICE/HEV ^{f,h} (Thermostat) (45.2 kW ICE; 92.1 kW battery)	46	0	0	950	200	386	1587	1537	150	4810	2837+2790	936
Natural gas series SI ICE/HEV ^{f,h} (load follow) (42.3 kW ICE; 37.2 kW battery) ^{f,h}	50	0	0	935	200	369	1567	680	150	3901	2837+1727	936
Natural gas parallel SI ICE/HEV^{f,h} (32.9 kW ICE; 34.6 kW battery)	62	0	0	887	700	334	1043	642	150	3756	2837+1556	936
H ₂ series SI ICE/HEV ^{f,h} (Thermostat) (46.6 kW ICE; 94.7 kW battery)	47	0	0	959	200	1741	1637	1517	150	6204	2837+4421	936
H ₂ Series SI ICE/HEV ^{f,h} (Load Follow) (43.3 kW ICE; 38.8 kW battery)	51	0	0	942	200	1616	1549	669	150	5125	2837+3159	936
H₂ Parallel SI ICE/HEV^{f,h} (33.7 kW ICE; 35.8 kW battery)	63	0	0	893	700	1356	1067	629	150	4801	2837+2780	936
Series CIDI ICE/HEV ^{f,h} (Thermostat) (46.5 kW ICE; 94.5 kW battery)	48	0	0	1432	200	125	1612	1574	150	5093	2837+3121	936
Series CIDI ICE/HEV ^{f,h} (Load Follow) (43.5 kW ICE; 38.1 kW battery)	53	0	0	1408	200	125	1528	695	150	4106	2837+1967	936
Parallel CIDI ICE/HEV^{f,h} (33.5 kW ICE; 35.5 kW battery)	67	0	0	1334	700	125	1053	654	150	4017	2837+1863	936

(continued on next page)

Table 2 (continued)

	Fuel economy (mpgge)	Fuel cell system	Fuel processor	ICE & auxiliaries	Transmission	Fuel tank system	Motor/controller (incl. generator for ICE/HEVs)	Peak battery system	Controls	Total drive-train mfg. cost	Retail drive-train cost ^b	Aluminum-intensive frame, retail cost ^c
Gasoline FCV (probable)^{f,h} (57.6 kW FC, 45.7 kW battery)	38	2410	2129	0	200	128	966	798	150	6781	2837 + 5097	936
Gasoline FCV c,d (best) (48.8 kW FC, 43.1 kW battery)	50									5125	2837 + 3159	936
Methanol FCV (probable)^{f,h} (45.9 kW FC, 43.9 kW battery)	56	2006	950	0	200	157	943	771	150	5177	2837 + 3220	936
Methanol FCV ^{f,h} (best) (44.4 kW FC, 43.2 kW battery)	61									4521	2837 + 2453	936
H ₂ Fuel cell vehicle w/Peaking Battery ^{c,f,h} (38.1 kW FC; 40.3 kW battery)	81	1670	0	0	200	1073	906	728	150	4727	2837 + 2693	936
H₂ Fuel Cell Vehicle w/o Peaking Battery^{f,h} (74.1 kW FC)	82	2180	0	0	200	1096	901	0	150	4527	2837 + 2459	936

^a For cases where alternative options are available for a particular vehicle type, the option in bold was selected for more extensive analysis. All vehicles except the current gasoline ICEV have aluminum-intensive frames.

^b The retail cost is estimated to be 1.17 times the manufacturing cost.

^c For the advanced gasoline and H₂ ICEVs, added drive-train costs are from estimates by engineers at Ford Motor Company (Muniz, 2002). No extra drive-train costs are added for the “moderate improvements” package incorporated in the 45.6 mpg gasoline ICEV. For H₂ ICEV, the added retail costs for the drive-train and fuel storage are estimated to be \$2500.

^d Fuel economies are based on simulations by engineers at Ford Motor Company (Kenney, 2002).

^e The added manufacturing cost for the aluminum-intensive frame is assumed to be \$800 (Kenney, 2002; Muniz, 2002; Weiss et al. 2000; DeCicco et al., 2001). The added retail cost is found by multiplying by a factor of 1.17, to give $800 \times 1.17 = \$936$.

^f Fuel economies are based on simulations by engineers at Directed Technologies, Inc. (Thomas et al., 1998b; Thomas, 1999).

^g Cost estimate for the gasoline SIDI ICE/HEV by the authors—based on DTI estimates of component costs for Diesel hybrids, except that the Diesel engine is replaced by a four-cylinder gasoline engine having the same power output. DTI analysts estimate that the manufacturing cost of a four-cylinder gasoline engine is $\$720 + 5.14P$, where P is output power in kW (Thomas et al., 1998b).

^h All vehicle component sizes and manufacturing costs are from Thomas et al. (1998b) and Thomas (1999).

Box 1

Projected manufacturing cost for mass-produced fuel cell vehicle drivetrains

The most detailed estimates in the public domain of costs for mass-produced cars powered by proton exchange membrane (PEM) fuel cells are those developed in studies by DTI for the Ford Motor Company (Lomax et al., 1998; Thomas et al., 1998a, b; Thomas, 1999).^a DTI analysts surveyed costs arising with alternative mass production methods, for a factory producing 300,000 fuel cell systems per year and operated for 15 years (Lomax et al., 1998). Their estimates of the levelized mass-produced costs for drive trains for H₂, methanol and gasoline fuel cell cars are presented in Table 2.

Automobiles using PEM fuel cells require H₂ fuel. Either H₂ would be the energy carrier and stored in cylinders as a compressed gas onboard the car or it would be produced onboard in a fuel processor from a more easily stored liquid energy carrier (e.g., methanol or gasoline) into an H₂-rich gas that can be used by the fuel cell. The alternative FCVs displayed in Table 2 have different weights and different-sized engines but the same power-to-weight ratios, so that the vehicles have essentially the same performance.

The projected specific cost SC_{fc_{sys}} (\$/kW) of a complete fuel cell system for DTI's least costly automotive fuel cell system design under mass production conditions (Thomas, 1999; Thomas et al., 1998b) is:

$$SC_{fc_{sys}} = SC_{fc_{st}} + SC_{fc_{aux}}$$

$$SC_{fc_{st}} = \text{specific cost of fuel stack} = \$357/P_N + (3.46 + 29.66 \times L_{Pt})/P_d, \text{ and}$$

$$SC_{fc_{aux}} = \text{specific cost of fuel cell system auxiliaries}^b = \$775/P_N + 3.27, \text{ so that}$$

$$SC_{fc_{sys}} = \$1132/P_N + 3.27 + (3.46 + 29.66 \times L_{Pt})/P_d, \text{ where:}$$

P_N = net peak power output of the fuel cell stack in kW,

L_{Pt} = platinum loading (anode + cathode) in mg/cm², and

P_d = cell peak power density in W/cm².

Assuming projected values of $L_{Pt} = 0.25$ mg/cm² and $P_d = 1.00$ W/cm² for fuel cells with neat H₂, and $L_{Pt} = 0.52$ mg/cm² and $P_d = 0.80$ W/cm² for fuel cells with reformat (probable case, Table 2), $SC_{fc_{sys}} = \$1132/P_N + 14.15$ with neat H₂ and $SC_{fc_{sys}} = \$1132/P_N + 23.60$ with reformat.

Thus the specific cost is \$19, \$29, and \$48/kW for power plant capacities of 250 kW (fuel cell bus, neat H₂), 74 kW (fuel cell car, neat H₂—Table 2), and 46 kW (fuel cell car, methanol—Table 2), respectively.

In addition, electric motors and controllers are estimated to cost \$10–\$20/kW and peak power batteries \$15–18/kW (depending on vehicle type).

For a H₂ FCV there is an extra capital cost for the cylinders in which gaseous H₂ is stored at pressures up to 5000 psia (345 bar). DTI analysts estimate this cost as a function of H₂_{stored} (kg of H₂ that can be stored at rated storage capacity) to be $C_{H_2stor} = \$121 + 201 \times H_{2stor}$. For a range of 380 miles (611 km) and a FCV with an 82 mpg gasoline-equivalent (2.87 l/100 km) fuel economy (Table 1), a storage capacity of 4.7 kg would be required (assuming that 99% of the stored H₂ could be used between refuelings). Thus storage would cost about \$1100 or \$15/kW for a 74 kW FC car using neat H₂.

For methanol and gasoline FCVs, an onboard fuel processor is needed to convert the liquid fuel to a H₂-rich gas that the fuel cell can use. The cost of onboard fuel processors is estimated to be \$10–20/kW for methanol steam reformers and \$20–40/kW for gasoline partial oxidation fuel processors.

^aFor other estimates of PEM fuel cell costs see Lipman and Sperling (1999), Rogner (1998), and Teagan et al. (1998).

^bAuxiliaries include air compressors, heat exchangers, humidification systems, safety devices and control systems.

technologies for different regions, air-pollutant damage estimates for southern California were adopted as the US norm for this study.⁵

The base-case air-pollutant damage costs presented in Table 1 and Fig. 1 are median damage estimates. The uncertainty in these estimates is reflected by valuations at one standard deviation from the median that are 0.25 and 4.0 times the estimated median cost estimates (Rabl and Spadaro, 2000).

⁵The ExternE studies were conducted for European conditions. Air-pollutant health damage costs depend on the population density, which is generally higher in European cities than in the United States. At lower population densities, air-pollutant health damage costs are less. For this study, the ExternE damage costs are scaled to Southern California population densities. Considering the uncertainties, the results of the present study for direct emissions from vehicles are in reasonable agreement with damage costs for Southern California estimated by Delucchi and McCubbin, using a different method (Delucchi, 2000; McCubbin and Delucchi, 1999). For damages associated with direct emissions from a typical new car in the Los Angeles area McCubbin and Delucchi estimate a lifecycle damage cost of \$1280, compared to \$2120 for the present study. (Note that the damage costs shown in Table 1 include costs for emissions upstream of the car as well as for direct emissions.)

2.4.2. Damage costs from greenhouse gas emissions

Emissions estimates. Direct CO₂ emissions from vehicles are calculated by the authors for the indicated fuels and fuel economies for vehicles. Most upstream GHG emissions are estimated using the GREET model. Exceptions are direct CO₂ emissions from natural gas-, coal-, and wind-derived H₂ production facilities. For natural gas-derived H₂, emissions are from Foster Wheeler (1996), as developed in Williams (2002). For coal- and wind-derived H₂, emissions (see Table 1, notes d and f) are from Williams (2002).

Specific damage costs. Specific climate-change damage costs (\$/t C as CO₂-equivalent) as a result of anthropogenic GHG emissions are highly uncertain. The ExternE studies of the European Commission suggest that at the 95% confidence level the value of carbon lies in the range \$14–\$510/t C and in an “illustrative restricted range” of \$66–\$170/t C if only discount rates in the range of 1–3% are considered (EC, 1997).

For the base-case analysis a valuation of \$120/t C is assumed for CO₂ and the CO₂-equivalent of other GHGs, at the middle of the illustrative restricted range considered in the ExternE studies. This valuation is

Table 3
Costs of fossil-fuel-derived H₂ using commercial technology

	H ₂ from natural gas via steam reforming ^a		H ₂ from coal via O ₂ -blown gasification ^b	
	CO ₂ vented	CO ₂ captured/sequestered	CO ₂ vented	CO ₂ captured/sequestered
Production cost for H ₂ ^c (\$/GJ, HHV)				
Capital (except for CO ₂ disposal)	1.56	2.56	4.09	4.69
O&M (except for CO ₂ disposal)	0.24	0.39	0.94	1.08
Fuel input ^d	4.53	4.71	1.42	1.43
Credit for byproduct electricity ^e	—	—	−0.76	−0.46
CO ₂ disposal ^f	—	0.38	—	0.62
Subtotal	6.33	8.04	5.69	7.36
Cost of H ₂ delivered to consumers at refueling stations ^g (\$/GJ, HHV)				
Production cost	6.33	8.04	5.69	7.36
Additional cost for compressing H ₂ , 60–68 bar, at NG H ₂ plants	0.02	0.02	—	—
Buffer H ₂ storage at central plant (for ½ day output)	1.63	1.63	1.63	1.63
100 km H ₂ transmission pipeline (H ₂ plant to city gate)	—	—	0.35	0.35
H ₂ recompression at city gate	—	—	0.55	0.55
H ₂ distribution system (city gate to refueling stations)	1.29	1.29	1.29	1.29
Refueling station	6.06	6.06	6.06	6.06
Total delivered cost (\$/GJ, HHV)	15.33	17.04	15.57	17.24
Delivered H ₂ cost in \$/gallon, gasoline equivalent (LHV)	2.21	2.46	2.24	2.48

^a Based on Foster Wheeler (1996), a study prepared for Statoil and the IEA GHG Programme for H₂ at 60 bar, except that: the FW results are presented here with all energy quantities expressed on a HHV basis; the annual capital charge rate and system capacity factor are assumed to be, respectively, 15%/year and 80% (as in the coal case). The CO₂ emission rate is 17.56 kg C (2.74 kg C)/GJ H₂ for CO₂ venting (CO₂ capture/sequestration). For the CO₂ capture/sequestration case 85% of the carbon in the feedstock is recovered as CO₂ and compressed to 112 bar; the CO₂ disposal rate is 57 kg CO₂/GJ H₂.

^b For H₂ produced at 67–68 bar from high-sulfur coal using a 70 bar Texaco O₂-blown gasifier with quench (Williams, 2002); a glycol solvent is used to recover H₂S, which is converted to S. The CO₂ emission rate is 36.33 kg C (2.62 kg C)/GJ H₂ with CO₂ venting (CO₂ capture/sequestration). For the CO₂ capture/sequestration case 92.7% of the carbon in the feedstock is recovered as CO₂ and compressed to 150 bar; the CO₂ disposal rate is 124 kg CO₂/GJ H₂.

^c For H₂ produced at a scale of 1 GW_{th} (HHV basis), so that 25.2 million GJ of H₂ is produced annually.

^d The natural gas (coal) price is assumed to be \$3.67/GJ (\$0.92/GJ), the average price projected for US electric generators in 2020 (EIA, 2001).

^e Electricity is produced as a byproduct at 15.29 (9.15) kWh/GJ of H₂ from coal for the CO₂ venting (capture/sequestration) case; its value is assumed to be 5.0 ¢/kWh—the cost of making electricity in a natural gas combined cycle at 2020 US gas prices and including the cost of a \$120/t C carbon tax (Williams, 2002).

^f Estimated cost for transporting CO₂ 100 km and aquifer sequestration 2 km below ground: \$6.64 (\$5.02)/t CO₂ for natural gas (coal) (Ogden, 2002).

^g H₂ infrastructure (post-production) costs are from Ogden (2002); for a city-gate natural gas H₂ plant but a coal H₂ plant 100 km from the city gate.

consistent with the estimated cost of achieving deep reductions in GHG emissions via the least-costly approaches for decarbonizing fossil fuels.^{6,7} A measure

⁶ Society should be willing to pay for avoiding environmental damages no more than the cost of the least-costly mitigation technologies and strategies.

⁷ To put into perspective the \$120/t C valuation of climate-change damages, consider the following estimates of mitigation costs for current technology from Williams (2002). For H₂ produced from natural gas via commercial steam reforming technology it is estimated that if CO₂ emissions were valued at \$115/t C the producer would have the incentive to capture and sequester CO₂. The corresponding CO₂ values required to induce CO₂ removal and sequestration are estimated to be about \$90/t C for a coal IGCC power plant and about \$50/t C for making H₂ from coal. For all these cases it is assumed that the CO₂ is recovered at the energy conversion facility and transported 100 km to a site where the CO₂ is disposed of in an aquifer 2 km below ground.

of the significance of carbon valuation at \$120/t C is that if there were a carbon tax of this magnitude in place, the pump price of gasoline would be \$0.30/gallon higher.

2.4.3. Oil supply insecurity costs

Concern about oil supply insecurity in light of growing dependence on oil from the politically volatile Persian Gulf,⁸ the primary driver of energy policy-making in the 1970s, has again come into focus as a result of the 11 September 2001 events. The valuation of

⁸ For example, the Energy Information Administration (EIA, 2002a) projects (Reference Case) that Persian Gulf oil production will increase from 21.2 million barrels/day in 2000 to 39.6 million barrels/day in 2020, and that Persian Gulf production as a share of world consumption will increase from 28.1% to 33.4% in this period.

the risk of being dependent on this insecure source of oil is difficult, but a conservative estimate for the United States is likely to be the cost of maintaining a military capability for safeguarding access to Persian Gulf oil, some \$20–\$60 billion/year (O’Hanlon, 2000). The cost of this “insurance policy” aimed at preventing disruption of oil flowing from the Gulf can be converted into a marginal external cost of \$0.35–\$1.05/gallon of gasoline-equivalent (\$15–\$44/barrel) assigned to all oil consumed in the United States—or \$0.70/gallon as a mean estimate selected for the base-case analysis—a value calculated by dividing the total cost of maintaining this military activity by 20% of Persian Gulf exports to reflect the fact that the United States accounts for 20% of gross oil imports at the global level.⁹

3. Lifecycle cost comparison for alternative fuel/engine options

3.1. Choosing a reference vehicle

In addressing the question: Can advanced vehicles with alternative fuels/engines compete? Compared to what? is an important consideration. Even though the gasoline ICE represents mature technology, the potential for ICE innovation is not exhausted. Here it is assumed that the lightweight 45.6 mpg (5.161/100 km) gasoline ICEV modeled by engineers at Ford Motor Company (Kenney, 2002) will be the “car to beat”—i.e., the reference car against which other advanced options will be compared. Although this car is estimated to cost \$900+ more than today’s 27 mpg gasoline ICEV, its LCC would be less—even without taking credit for more than \$3,000 in reduced external costs (see Table 1).

3.2. Findings for the base case

A striking feature of the base-case analysis presented in Table 1 and Fig. 1 is that externalities account for

⁹If the expenditures on military activity were instead divided by actual US oil imports from the Persian Gulf (0.9 billion barrels in 1999), the estimated marginal cost of oil insecurity would be 50% higher. However, the actual US oil imports from the Persian Gulf is probably an inappropriate measure of the volume of imports at risk. Even if U.S. oil imports from the Persian Gulf could be reduced to zero in favor of more imports from other regions and other oil importers were thereby forced to become more dependent on Persian Gulf oil, US oil security would not become significantly enhanced thereby, because oil supplies are fungible. Accordingly, it is assumed here that these military expenditures are instead charged against 20% of Persian Gulf exports (1.35 billion barrels in 1999), corresponding to the US share of total gross global oil imports in 1999. [In 1999, gross oil imports amounted to about 54 million barrels/day at the global level (EIA, 2002b), of which the United States accounted for about 11 million barrels/day.]

over half of the LCC for today’s typical new cars and about 40% of the LCC for the reference car. Moreover, all three major components of the external cost are critical. Even though a seemingly high value (\$120/t C) is placed on GHG emissions (the reduction of which is usually regarded as the most daunting externality challenge) for the base case and even though enormous progress has been made in reducing air-pollutant emissions, more than $\frac{3}{4}$ of the total externality cost for both today’s typical new car and for the reference car (which is assumed to meet stringent Tier II air pollution standards) are associated with air pollution and oil supply insecurity.

Notably, with the exception of the advanced gasoline ICEV (the reference car), all advanced options have higher LCCs than the current gasoline ICEV when externalities are not internalized, but all advanced options other than the gasoline FCV are less costly than today’s cars when externalities are internalized at median valuations of these costs. Thus, the analysis indicates that the goal of reducing externalities should be the main driver for technological innovation in car engines and fuels.

The least-costly option under base-case conditions, with an externality cost and a total LCC about 50% and 90%, respectively, of these costs for the reference car, is the CNG ICE/HEV. However, there is little enthusiasm among auto manufacturers, transport fuel suppliers, and most analysts for CNG cars. A shift to CNG cars would require a costly fuel infrastructure change for an option for which the long-term sustainability prospects are highly uncertain both because of natural gas supply considerations (discussed below) and the prospect that a near-term shift to a CNG infrastructure might have to be followed later by a shift to a H₂ infrastructure to support FCVs, because of the attractions of the H₂ FCV in mitigating externalities that are growing concerns (as discussed in the next section).

Consider the situation in the United States, where domestic natural gas production peaked in 1971, and a major shift to CNG cars would probably require the US becoming a major LNG importer. For the period 1994–2001, US natural gas production was nearly level, varying by $\pm 2\%$ from an average value that was 87% of 1971 production. However, the most recent reference energy forecast of the US Energy Information Administration bullishly bucks the historical trend and projects that domestic gas production will increase about 50% by 2020, along with a comparable increase in natural gas imports, which would account for about $\frac{1}{6}$ of total natural gas supplies at that time (EIA, 2001). But the same forecast estimates that 90% of incremental supplies would be absorbed by residential, commercial, industrial, and power generation markets—which have well-established infrastructures—and that only 1% of incremental supplies would go to transportation. The

demand for extra gas is expected to be especially strong for power generation, where the natural gas combined cycle is the option of choice for new power plants if gas is readily available. The EIA's even more bullish "rapid technological progress" scenario does not change this outlook much, with essentially all the 4% increase by 2020 in gas supplies relative to the reference scenario absorbed by the same well-established markets.

If there were a major shift to CNG ICE/HEVs in the United States, most of the required gas would have to come from LNG imports because of supply constraints on additional pipeline gas from Canada or Mexico.¹⁰ Although there is probably ample natural gas available to support a major expansion of worldwide LNG trade for decades, there will be rapidly growing competition for this natural gas in the longer term, especially from developing countries, which might raise CNG prices over the longer term to levels much less attractive than assumed in the construction of Table 1. Moreover and perhaps more important, the needed new LNG port facilities would often be difficult to site, as a result of safety and terrorist concerns.

Several advanced options presented in Table 1 have nearly identical LCCs: the reference car, the FT50 CIDI ICE/HEV, and the FCVs operated on fossil fuel-derived H₂ with sequestration of the separated CO₂, followed closely by the gasoline SIDI ICE/HEV, the Diesel CIDI ICE/HEV, and the FCV operated on natural gas-derived H₂ with venting of the separated CO₂.

The ICEV and ICE/HEV operated on natural gas-derived H₂ with CO₂ vented have externality costs that are only $\frac{1}{3}$ of those for the reference car and LCCs that are less than for today's gasoline ICEV—but their LCCs are 14–21% higher than for the reference car or for the FCV also operated on H₂ derived from natural gas with CO₂ vented. H₂ ICEVs and H₂ ICE/HEVs do not fare especially well under base-case conditions because: (i) their fuel economies are much less than for FCVs, (ii) at the pump, H₂ is 2.3 times as costly as gasoline, so that fuel costs are \$1150–\$1700 more than for the reference car (Table 1), and (iii) H₂ storage cylinders cost \$300–\$500 more than for the more fuel-efficient H₂ FCVs.

Hydrogen FCVs have the lowest air-pollutant and GHG damage costs of all the options presented in Table 1: for FCVs powered by H₂ derived from fossil fuels with sequestration of the separated CO₂, environmental costs are only 11–16% of those for the reference car, and oil supply insecurity costs are zero (see Table 1). Notably, the LCCs for the natural gas- and coal-derived

H₂ cases with CO₂ separation and sequestration costs taken into account are only about 3% more than for the corresponding cases with CO₂ vented, when externalities are not valued. Moreover, among the FCV options, the variants that use fossil fuel-derived H₂ offer a significantly lower LCC (with or without internalization of externalities) than variants with onboard fuel processors based on gasoline or methanol as the energy carrier, largely because of the lower first cost of the H₂ FCV. It appears that gasoline FCVs might have an especially hard time competing with advanced gasoline ICEVs or ICE/hybrids, even with externality costs included. The FCV option based on H₂ derived electrolytically from wind electricity has a LCC that is \$800–\$1,000 more than for the FCV options based on H₂ derived from fossil fuels with CO₂ sequestration because of the 40% higher cost for this electrolytic H₂.

If H₂ vehicles are successfully launched in the market before 2020, it is highly likely that these vehicles would be fueled initially mainly with H₂ derived from natural gas—not at central conversion facilities (as envisioned in Table 3) but rather at refueling stations. For the case where the CO₂ coproduct of H₂ manufacture is vented, natural-gas-based H₂ costs to consumers would be about the same for both such decentralized production options and for the central-station H₂ production option described in Table 3, because the economies of scale gained by centralized H₂ production would be offset by the absence of costs for H₂ distribution in the case where H₂ is produced at refueling stations (Ogden, 1999). Although CO₂ recovery and sequestration is prohibitively expensive when H₂ is produced at the small scales of refueling stations (Ogden, 2002), this is not a significant concern in the early years of a H₂ economy when H₂-fueled vehicles would represent a minor fraction of the total vehicle fleet, so that CO₂ sequestration would not be a high priority. Moreover, even with CO₂ vented, a FCV fueled with natural gas-derived H₂ would emit much less fuel-cycle-wide GHGs than the reference car (see Table 1).

3.3. Sensitivity analyses

Estimates of LCCs presented in Table 1 and Fig. 1 depend on inputs from several complex models each with a host of assumptions, many of which have considerable uncertainties. To examine the robustness of the base-case findings, sensitivity studies were carried out varying key parameters with large uncertainties.

3.3.1. Technical performance and cost of onboard fuel processors

One of the key components in the FCV fueled with gasoline or methanol is the onboard fuel processor. The base-case fuel processor costs presented in Table 1 are for DTI's "probable" estimates. If instead DTI's "best

¹⁰Suppose, hypothetically, that all US light-duty vehicles were converted to 63mpgge CNG ICE/HEVs at projected use levels for 2020 (EIA, 2001). The required additional natural gas in 2020 would amount to almost 8 EJ/year—nearly 40% of US natural gas production or more than 1.7 times natural gas consumption for power generation in 2000. Most would have to come from LNG imports, at a level more than 70 times LNG imports in 2000.

case” values were assumed (see Table 2), LCCs for the gasoline and methanol variants would be less, but LCCs would still be lower for the FCV variants powered with H₂ from fossil fuels with CO₂ sequestration.

3.3.2. Societal LCCs for alternative valuations of externality costs

Externality valuations are especially uncertain. Consider, as an example, air-pollutant damage costs. These costs are mainly due to health effects, which increase with population density for given income levels. In regions such as Europe, where income levels are comparable to those in southern California but population densities are higher, estimates of air-pollutant damage costs would be higher. Although detailed calculations were not carried out to examine this effect, median air-pollutant damage costs based on ExternE studies would be roughly three times as high for typical European conditions as for the base-case analysis presented in Table 1 (for southern California). If the air-pollutant damage costs in Table 1 were tripled, FCVs powered by H₂ derived from fossil fuels with CO₂ sequestration and the CNG ICE/HEV would be the least-costly options, with about the same LCCs at 15–19% less than for the reference car.

Fig. 2 presents the total societal LCC for low, median, and high externality valuations for the major options

studied. The low (high) valuations assess air-pollutant damage costs at 0.25 (4.0) times the median costs, GHG damages at \$60/t C (\$180/t C) of CO₂ or CO₂-equivalent, and oil-supply insecurity at \$0.35/gallon (\$1.05/gallon) of gasoline-equivalent.

Varying the valuation of external costs has a powerful impact on LCC of the various hydrocarbon fueled engine options—e.g., for the reference car, the ratio of the externality cost to the direct economic cost (the costs for the drive train, vehicle weight reduction, and fuel) ranges from 0.27 for low estimates of externality costs, to 0.64 for the base case, to 1.45 for high estimates of externality costs. But for all the values of externalities considered, externality costs are tiny for FCVs powered with H₂, so that the relative attractiveness of these options increases as externality valuations increase (see Fig. 2).

In contrast to the base-case analysis, which indicates that many advanced options have roughly comparable LCCs, the sensitivity analysis shows that: (i) for low valuations of externality costs, the reference car is the least-costly option—with a LCC that is 5% less than for the CNG ICE/HEV and 21% less than for the FCVs powered by H₂ derived from fossil fuels with CO₂ sequestration, and (ii) for high valuations of externality costs, the less-polluting, more energy-secure options fare best—e.g., the FCV powered by H₂ derived from fossil

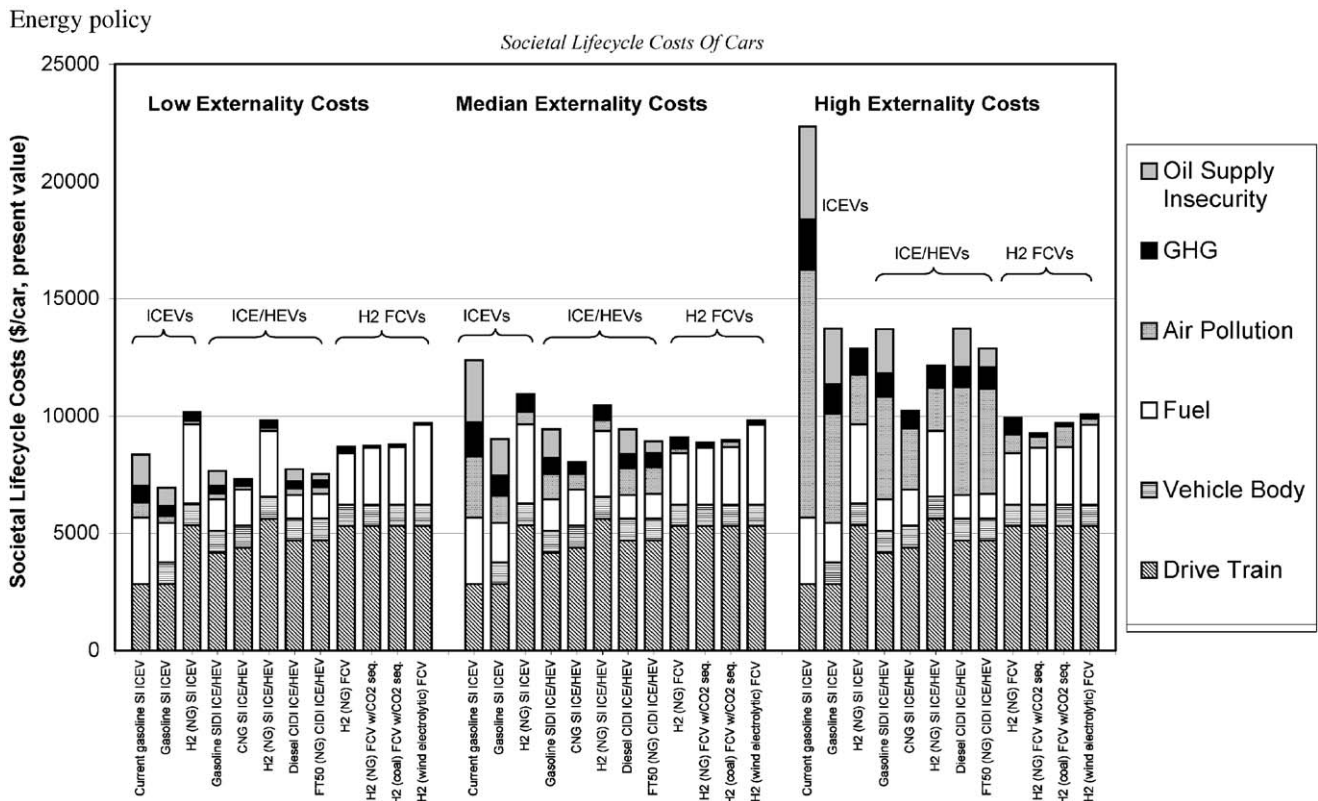


Fig. 2. Lifecycle costs for cars with alternative fuel/engine options and low, median, and high estimates of externality costs.

fuels with CO₂ sequestration is the least costly option— with a LCC that is 5–11% less than for the CNG ICE/ HEV and 28–32% less than for the reference car. Another striking feature of the high-externality-cost analysis is that both the H₂ ICEV and the H₂ ICE/HEV have LCCs that are lower than for the reference car, though still higher than for the H₂ FCV options.

One should expect that externality valuations will change over time both as a result of improved scientific understanding and as a result of shifting societal values. Although externality valuations might decline over time, the long-term trend in the making of energy policy has been toward ever tighter controls on emissions that are thought to entail environmental damages. This trend may well continue both as a result of improved scientific evidence of damages [e.g., Pope et al. (1995) in the case of health damage caused by small-particle air pollutants, and O’Neill and Oppenheimer (2002) in the case of climate-change damages], and the increasing importance of environmental issues in the public mind as incomes rise (Williams, 2000). Moreover, as already noted, energy supply insecurity concerns, which were paramount in energy policymaking in the 1970s, have once more become a prominent concern.

3.3.3. Allowed incremental drive train costs for alternative valuations of externalities

Cost estimates for the drive trains of advanced vehicle options are also quite uncertain—especially for FCVs,

which are the furthest from being commercial products among the options considered. For median estimates of externality costs, the H₂ FCV would not be able to compete on a societal LCC basis if drive train costs turn out to be much higher than the costs indicated in Table 1 and Fig. 1.

One way to understand better the drive-train cost challenge for all the advanced options considered is to quantify for each the increment in retail drive-train cost above the cost of the drive train for the reference car that would enable that option to compete with the reference car on a societal LCC basis, for alternative valuations of externality costs. Such “breakeven” incremental drive-train costs are shown in Fig. 3 for low, median, and high estimates of externality costs. Also shown for each advanced option (from Table 1) is the estimated increment in drive-train cost relative to the reference car under mass production conditions.

This analysis shows that with the low valuation of externalities, most advanced options would not be able to compete with the reference car unless the drive-train cost no more, or in some cases less than, the drive train for the reference car. However, for the high valuation of externalities the non-oil-based options offering low emissions could be competitive even if drive trains cost much more than estimated in Table 1. In particular, FCVs fueled with H₂ could still compete with the reference car if the drive train cost up to about three times the cost of the reference car drive-train (see Fig. 3).

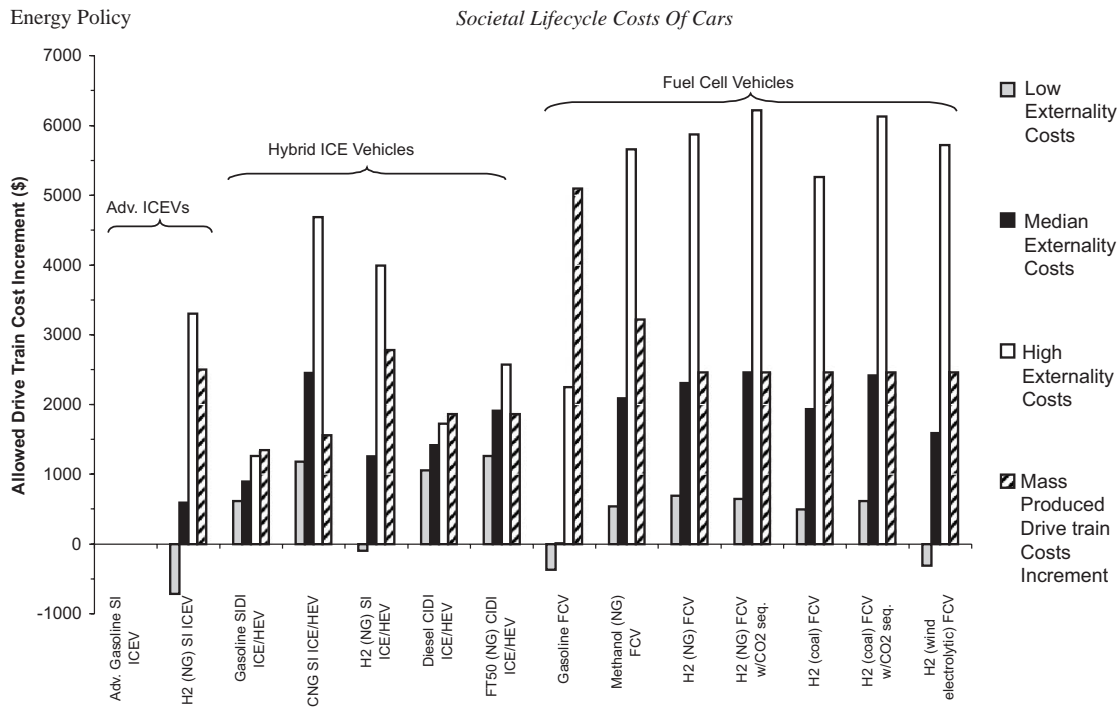


Fig. 3. Drive train cost increment relative to the reference vehicle for advanced fuel/engine combinations that would lead to LCC parity with the reference vehicle, for low, median, and high estimates of the externality costs—with a comparison to the estimated cost increment for the drive train under mass production conditions (from Table 2).

3.3.4. Breakeven carbon valuation needed to make H₂ FCVs competitive

It is widely believed that the main reason for pursuing H₂ as a fuel for transportation is as a strategy for climate-change mitigation. So much progress has been made in reducing air-pollutant emissions from hydrocarbon-fueled ICEVs that many think the “the air pollution problem has been solved.” This judgment may have represented well the state of scientific understanding of air-pollutant damages before recognition of the plausibly high costs implicit in chronic mortality impacts of small-particle air pollution (Pope et al., 1995). However, this is no longer the case, as is indicated by the present analysis, which is based on studies representing some of the best state-of-the-art judgments of these costs, however uncertain (Rabl and Spadaro, 2000). Moreover, although oil-supply insecurity is widely regarded as an important concern relating to transportation, this concern is rarely quantified in terms of societal costs in ways that facilitate a comparison with climate concerns, which the present analysis has attempted to do. Indeed, the present analysis indicates that both air-pollutant damages and oil-supply insecurity risks are concerns of economic importance that are comparable to the climate-change risk—even if carbon is assigned the relatively high value (\$120/t C) assumed for the base-case analysis.

To help clarify the importance of these other externalities in relation to the carbon problem, estimates have been made of the value of carbon required to achieve LCC parity between H₂ FCVs and the reference car: (i) without taking into account other externalities, (ii) with only air-pollutant damage costs taken into account, and, finally, (iii) with both air-pollutant damage costs and oil-supply insecurity costs taken into account—in all cases assuming base-case values for both direct economic costs and median estimates of the other externality costs. This exercise helps clarify the value of pursuing H₂ fueling strategies for automobiles in relation other technological options for decarbonizing the energy system.

If no other externalities are considered, the breakeven value of carbon (the cost of avoiding CO₂ emissions) is \$520/t C for FCVs fueled with H₂ from fossil fuels with CO₂ sequestration and \$685/t C for wind H₂. If only air-pollutant damages are taken into account, the breakeven value of carbon is \$355–\$380/t C for FCVs fueled with H₂ from fossil fuels with CO₂ sequestration and \$520/t C for wind H₂. But if both air-pollutant damages and oil-supply insecurity costs are taken into account, the break-even value of carbon is \$100–\$130/t C (essentially the base case valuation for climate damages) for FCVs fueled with H₂ from fossil fuels with CO₂ sequestration and \$260/t C for wind H₂.

This exercise suggests that if air-pollutant damage costs and oil-insecurity-costs are neglected, it would be

difficult to justify H₂ strategies of any kind for transportation because of the high costs of avoiding CO₂ emissions. However, if these other externalities are taken into account, it is noteworthy that the cost of avoiding CO₂ emissions by shifting to FCVs powered by H₂ derived from fossil fuels with CO₂ sequestration [and thereby reducing GHG emissions about 90% relative to the reference car (see Table 1)] is comparable to the cost (~\$100/t C) of CO₂ emissions avoided by CO₂ recovery and disposal for a coal integrated gasifier combined cycle (IGCC) power plant—the least-costly technology for decarbonizing coal power plants (Williams, 2000, 2002). Although decarbonization of coal IGCC plants would probably be pursued before H₂ is produced for FCVs in a climate change-constrained energy economy, this exercise shows that the marginal cost of decarbonization would change very little if and when fossil fuel decarbonization activity is expanded to include H₂ production for FCVs. This finding considered together with the large and growing role of the light-duty vehicle (LDV) in contributing to CO₂ emissions¹¹ suggests the desirability from a climate-change perspective of putting the automobile on a path of technological change that might ultimately result in major roles for the H₂ FCV. Because both the coal IGCC option and the H₂-from-coal option involve making H₂ from coal via gasification¹² and disposal of the CO₂ separated out in the process, many advances made in the near term with decarbonized coal IGCC technology could subsequently be adapted to the production of H₂ for FCVs.

Electrolytic H₂ might play a role as an interim supply strategy for helping launch H₂ vehicles in the market where low-cost off-peak power sources are available (Ogden, 1998). The amount of hydrogen that could be produced from off-peak power is small compared to demands for automotive fuels (Williams 2002). More extensive use of electrolytic hydrogen might be made in the longer term, but this option is unlikely to be economically competitive unless the CO₂ sequestration option turns out not to be viable (Williams, 2002).

4. Formulating a strategy toward the car of the future

The societal LCC analysis presented here can provide helpful insights regarding the outcome of the ongoing race to the Car of the Future, in which the world's major car companies are competing. Just as the gasoline ICEV emerged early in the last century from among the many competing options (including battery-powered electric cars and steam-powered cars) as the winner of the race

¹¹ In 2000, LDVs and coal power plants accounted for 18% and 32% of US CO₂ emissions, respectively (EIA, 2001).

¹² High-purity H₂ for FCV applications and low-purity H₂ for decarbonized coal IGCC plants.

to become the Car of the 20th Century, it is likely that over the next couple of decades one major option will emerge as the clear favorite for the 21st century.

4.1. If only externalities matter

If the outcome of the race to the Car of the Future were determined solely by consideration of externalities associated with air-pollutant and GHG emissions and with oil supply insecurity, the H₂ FCV would be the clear winner, because its externality costs are far lower than for other advanced automotive options.

4.2. If only societal lifecycle costs matter

But the outcome of this car technology race depends more on relative societal LCCs and the valuations that society assigns to these externalities, via appropriate regulations or taxation, rather than the relative externalities considered in isolation of other costs. Consider the H₂ FCV with projected vehicle costs under mass production conditions. At low externality valuations the H₂ FCV cannot compete. For a median valuation of externalities (the base case) the FCV fueled by fossil-fuel-derived H₂ with CO₂ sequestration would be able to break even on a LCC basis with both the reference improved gasoline ICEV and various other ICE/HEVs. And at high valuations of externalities the H₂ FCV is highly favored on a societal LCC basis.

4.3. If infrastructure changes are also taken into account

A comparison of societal LCCs by itself does not provide a sufficient basis for charting a course to the car of the future. Consideration of required fuel infrastructure changes is also important. It is desirable to minimize the number of infrastructure changes that have to be made over time.

Considering the major findings of the societal LCC analysis in the context of the secular trend toward tighter environmental constraints on energy systems and revived concerns about oil supply insecurity suggests a strategy of limiting to *one* the number of capital-intensive infrastructure changes for automobiles—an *eventual* shift to H₂ FCVs for transportation, while pursuing *near-term* fuel economy improvements and emissions reductions using various advanced liquid hydrocarbon-fueled ICEVs and ICE/HEVs.

The main reason for minimizing the number of infrastructure changes is the huge cost involved for assets that may have to be retired in a few decades if there is an eventual shift to H₂. But there are other considerations as well, as illustrated by the methanol FCV and CNG ICE/HEV options.

Some automakers are considering offering the first generation of FCVs with methanol reformers. Methanol

has some attractive features as an initial fuel for FCVs. Like gasoline, but unlike H₂, methanol is a liquid fuel that can be easily distributed and stored. Methanol is much easier to reform than gasoline, and methanol fuel processor technology can be deployed in the near term. But the methanol FCV era based on this strategy would be short-lived, with H₂ displacing methanol as soon as it becomes available in light of the significantly lower LCC of the H₂ FCV (see Table 1). Moreover, methanol toxicity (a fatal dose is 2–7% methanol in a liter of water, which would defy detection by taste) could turn out to be a potentially troublesome liability issue for the transport fuel industry, which has already been burned by its experience with methanol-derived methyl tertiary butyl ether (MTBE).¹³

The CNG ICE/HEV offers the potential of a substantially lower LCC than the methanol FCV (Table 1), but, as noted, a major shift to CNG vehicles may well involve in some regions such as the United States large new LNG port facilities that would be difficult to site.

In contrast to the situation for CNG vehicles, major infrastructure concerns relating to the long-term outlook for natural gas supplies do not arise with either the FT50 CIDI ICE/HEV option or the various H₂ options based on natural gas.

The FT50 option would also be based mainly on natural gas-based imports—but as F–T liquids rather than LNG. Whereas LNG imports require large investments in new tanker and port facilities and would involve LNG port siting difficulties, F–T liquids can be imported using existing liquid hydrocarbon fuel infrastructures, without significant modifications.¹⁴

Likewise, launching FCVs in the market with H₂ derived from natural gas should not pose significant risks arising from uncertainties relating to long-term prospects for natural gas supplies. By 2020, the long-term outlook for natural gas should be greatly clarified relative to the present outlook. If, in a climate-constrained world, it turns out natural gas is abundant, natural gas would subsequently remain in the market as

¹³Regulatory efforts are underway in various US public agencies aimed at banning MTBE as an oxygenate additive to gasoline as a result of trace quantities of bitter-tasting MTBE showing up in ground-water supplies—after the fuels industry made huge investments in manufacturing and infrastructure development for MTBE as a gasoline additive to satisfy the air-pollutant regulatory requirement for oxygenates in gasoline.

¹⁴Suppose, hypothetically, that all US LDVs were converted to 67 mpgge FT50 CIDI ICE/HEVs at 2020 projected demand levels: (i) oil requirements for LDVs would be reduced to 3.5 EJ/year from 22.5 EJ/year [for vehicles operating at a projected average fuel economy of 21 mpg in 2020 (EAI, 2001)], (ii) total US oil import requirements for 2020 would be reduced in half, (iii) F–T liquids imports would grow to 3.5 EJ/year, compared to 6.0 EJ/year of natural gas imports projected for 2020 (EIA, 2001), and (iv) the externality cost per car would be less than 2/3 of that for the reference car (see Table 1).

a major competitor with coal and other prospective primary energy sources in the making of H₂, but as concerns grow about climate change, production would shift to centralized facilities where CO₂ separation and sequestration could be carried out cost-effectively. But if the long-term outlook for natural gas turns out to be not so auspicious, the history of transportation energy written in the distant future would show that the role of natural gas in transportation was mainly to facilitate a transition to H₂ that in the longer term was based mainly on H₂ made from coal and other primary energy resources.

4.4. Near-term strategies on a path to hydrogen fuel cell cars

The present analysis points to the H₂ FCV as a leading candidate option for becoming the Car of the Future, a finding that is consistent with ongoing industrial activities—e.g., this option is the focus of developmental efforts in the United States under the FreedomCAR initiative¹⁵ and on the part of various auto manufacturers in other countries.

But even if the H₂ FCV turns out to be the Car of the Future, it would be a mistake to focus automotive innovation activities *exclusively* on this option, because: (i) even under optimistic assumptions about the pace of introducing this technology it would be decades before it could account for a major fraction of the automotive fleet (Ogden et al., 2003), (ii) major automotive innovations are needed in the near term to reduce the high externality costs that characterize present technology (Table 1), and (iii) there are several promising advanced options based on the liquid hydrocarbon-fueled ICEVs and ICE/HEVs that offer significant reductions in externality costs and could be commercialized well before H₂ FCVs.

The prospect that in the very near term (~ 2005) a mid-sized gasoline ICEV (the reference car) could be commercialized that requires 40% less fuel and has half the externality cost of a typical new car, as well as a lower LCC even without considering externalities (Table 1), suggests the importance of finding appropriate public policies (e.g., in the United States, a new tighter corporate average fuel economy standard or an alternative policy more palatable to the auto industry for promoting higher automotive fuel economy) that could

accelerate the deployment of such technology, which involves only modest technological innovation.¹⁶

Introducing hydrocarbon-fueled ICE/HEVs could reduce externality costs further [by 15–35% relative to the reference car (Table 1)], but shifts to such vehicles would entail increased LCCs relative to the reference car unless externalities are internalized (via appropriate taxes or equivalent regulations). But such options could still be introduced well before H₂ FCVs. Indeed, two Japanese automakers had already introduced gasoline ICE/HEVs in Japanese and US markets at the time of this writing, and considerable developmental efforts are underway to develop Diesel ICE/HEVs. In addition to the reduced externality benefits offered by ICE/HEVs, the widespread deployment of such vehicles in the near term could also facilitate a transition to FCVs because of the extensive experience they would provide with electric drive trains.

The base-case analysis indicates that the H₂-fueled ICEV and ICE/HEVs would cost \$1450–\$1900 more than the reference car even with a full accounting for externality costs (Table 1 and Fig. 2). This finding, which reflects the high estimated cost of H₂ delivered to consumers, the high cost of H₂ storage, and the lower fuel economies of these cars compared to H₂ FCVs, suggests that these ICE-based options would not be major contenders for the transition to H₂ FCVs. But five considerations suggest that these options should not be so readily dismissed. Firstly, if externalities are internalized, these options are likely to be less costly on a LCC basis than typical new cars (Table 1). Second, at high valuations of external costs, these options are among the least costly of all advanced options other than H₂ FCVs (Fig. 2). Third, H₂ for internal combustion engine use can be less pure than for FCV use, which implies a lower fuel cost (Kreutz et al., 2002). Fourth, the H₂ ICEV and ICE/HEV options listed in Table 1 do not exhaust the technological opportunities: much higher fuel economies could be realized over the longer term with more advanced technologies (Kenney, 2002), though at higher incremental drive-train costs; such options might be needed in the longer term, if it turns out that there are (presently unforeseen) formidable obstacles to FCV commercialization. And finally, early experience with H₂-fueled ICEVs or ICE/HEVs (e.g., in fleet demonstrations) could provide valuable experience with H₂ fueling strategies for cars, while waiting for H₂ FCVs to become economically viable—just as ICE/HEVs more generally could provide valuable experience with electric drive trains as H₂ FCVs are being developed.

¹⁵In January 2002 FreedomCAR (CAR = Cooperative Automotive Research) was launched as a major new partnership between the US Department of Energy and Detroit automakers (General Motors, Ford, DaimlerChrysler) under the auspices of USCAR (US Council of Automotive Research). FreedomCAR is aimed at developing for the long term the H₂ FCV as the major fuel/engine option for cars and trucks.

¹⁶Even though the reference car would be cost-effective to consumers, there is no evidence that US automakers have plans to develop such a fuel-efficient car, so that a new public policy is needed to provide the incentive to commercialize the technology.

4.5. Uncertainties relating to the hydrogen fuel cell car's becoming the car of the future

The present analysis points to the H₂ FCV as the plausible Car of the Future, because of its promise in addressing the major environmental and oil supply insecurity risks and the prospect that it might well be competitive if policies are enacted to internalize these externalities.

However, costs might turn out to be less favorable than projected in this LCC analysis. Today FCV drive train costs are ~\$200,000/car and must be reduced to ~\$5,000/car (\$70/kW) for the H₂ FCV to break even with the reference car (Table 1). Clearly a great deal of uncertainty is inherent in any attempt to determine whether the needed 40-fold reduction in cost is achievable. Yet there is a fierce race underway among automakers worldwide to try to make FCVs competitive. One reason for the confidence of enthusiasts that it might be possible to make FCVs competitive is that they have far fewer moving parts and far milder operating conditions than do ICEVs—many are betting that simplicity implies lower cost. Moreover, FCV manufacture involves no materials or difficult fabrication procedures that are so costly¹⁷ as to preclude the FCV from becoming cost-competitive under mass production conditions. And of course the 40-fold cost reduction target compares apples and oranges—a mass-produced conventional car and a FCV that is literally *manufactured*—i.e., “made by hand,” like a race car.

But there are also uncertainties that could lead to economic conditions that are more favorable than those indicated in the LCC analysis. One conservative assumption underlying the present analysis is that in the time frame of interest H₂ will be stored onboard vehicles as a compressed gas—the most cost-effective storage option based on current technology. But over the course of the next couple of decades there might be a breakthrough in H₂ storage technology (e.g., relating to carbon nanostructures that would permit H₂ storage at relatively high densities and modest pressures compared to compressed gaseous storage) that could significantly improve the outlook for H₂ cars. Such a breakthrough might make it possible to reduce not only the cost of H₂ storage onboard vehicles but also the cost of H₂ delivered to consumers. About 35% of the cost of H₂ from fossil fuels delivered to consumers, assuming current technology with CO₂ sequestered, is for H₂

refueling stations (see Table 3).¹⁸ This component of total cost is high largely because of the underlying assumption that H₂ is provided as a compressed gas. Advanced H₂ storage technologies might make it feasible to reduce such refueling station costs.

Another conservative assumption underlying the present analysis is that the H₂ FCV would be a car that might offer the same amenities as today's gasoline ICEV and would be manufactured much as the ICEV is manufactured today. But some have argued that FCVs optimized to exploit the advantages inherent in fuel cell technology might offer greater consumer benefits and might even cost less to manufacture than the ICEVs they would replace—as is illustrated by possibilities suggested by the General Motors AUTOnomy concept vehicle, which was introduced at the North American International Auto Show in January 2002, and its follow-up Hy-Wire prototype car, introduced at the Paris Motor Show in September 2002 (Burns et al., 2002).

These advanced vehicles combine fuel cell and “drive-by-wire” technologies in a radical redesign of the entire car that might offer new private consumer benefits as well as the public environmental and oil supply security benefits that have been the focus of the present analysis. In these cars steering, braking, and other vehicle systems are controlled electronically rather than mechanically. Because computers and software control operations, upgrades could be downloaded to improve vehicle performance or tailor handling to suit particular consumer preferences. All of the car's control and propulsion systems (including H₂ storage canisters) are contained in a flat 28-cm thick “skateboard-like” chassis at the bottom of the car, which has a single “docking port” that provides all the electrical connections between the chassis below and body above. The car has a flat floor and spacious interior (no ICE up front or steering column/wheel or foot pedals taking up interior space), allowing driver and other occupants wide flexibility as to where to sit. Such vehicles offer maneuverability and safety benefits as a result of a low center of gravity; future plans are to exploit some of the interior spaciousness by adding “crush boxes” of impact-absorbing materials that would further enhance safety. Interchangeable bodies might be offered for the same chassis, which might outlive the car bodies served.

The basis for the speculation that FCVs might be cheaper to manufacture is based on the vision that substantial scale economies might be realized by mass-producing the compact “skateboard” chassis in truly

¹⁷If the platinum loading targeted in Box 1 (0.25 mg/cm² at 1 W/cm² of specific power for the fuel cell) can be realized for H₂ FCVs, the required platinum cost (\$7.4/kW or \$550/car) would not be prohibitive. It remains to be demonstrated whether such loadings, which have been demonstrated in the laboratory, would provide satisfactory fuel cell operation over the operating life of a car.

¹⁸Notably, the cost of making H₂, including the cost of CO₂ sequestration (see Table 3) is modest—about \$1.1/gallon of gasoline equivalent, not much higher than the average refinery gate cost of crude-oil-derived gasoline in 2000 (\$1.06/gallon), when the US refiner acquisition cost for crude oil averaged \$28/barrel.

huge centralized facilities (much larger than what is involved with ICEV manufacture) and shipping these compact chassis to many traditionally sized auto factories around the world that would specialize in making car bodies tailored to the needs of the local economy and where the chassis would be attached to the car bodies. Such possibilities were not taken into account in the present analysis, because without a base of experience upon which to draw, quantitative estimates of such potential benefits are not feasible at this time. Notably though, if the incremental drive train cost for the H₂ FCV were zero, the LCC for the H₂ FCV would be the same as for the reference car when CT = \$120/t C, if no credit is taken for air-pollutant damage or oil supply insecurity mitigation benefits.

5. Conclusions

In this study the societal LCC was chosen as an important indicator for comparing alternative advanced automotive engine/fuel options. A major finding is that most advanced options would not be competitive on a LCC cost basis without internalizing externalities associated with air-pollutant and GHG damages and oil supply insecurity risks. But when such externalities are internalized, most advanced options offer lower LCCs than typical new cars, for which externalities account for about half of the LCC under base-case conditions.

The H₂ FCV stands out with externality costs that are, by a wide margin, the lowest for all options considered. Under mass production conditions and with median valuations of externalities, the FCV powered by H₂ derived from fossil fuels with sequestration of the separated CO₂ would be one of the most competitive options, while at high valuations of externalities, it would be the least-costly option. This suggests that the H₂ FCV is a strong candidate for becoming the Car of the Future, considering the secular trend toward tighter environmental constraints on energy systems and revived concerns about oil supply insecurity. This singling out of the H₂ FCV is consistent with the intense efforts underway on the part of automakers around the world aimed at commercializing the H₂ FCV.

Despite the attractiveness of the H₂ FCV, there are significant barriers to its widespread use in automotive markets—the most important being the current high cost of fuel cells and lack of a H₂ fuel infrastructure. Even if such barriers can be overcome, decades would be required before this embryonic technology could make major contributions in reducing the major externalities that characterize today's cars. Thus it would be a mistake to focus all technological innovation efforts aimed at addressing these externalities on this single long-term option.

This study also found that various advanced, more fuel-efficient liquid hydrocarbon-fueled ICEVs and ICE/HEVs offer significant reductions in externalities. Moreover, the uncertainties relating to commercial prospects are much less for these technologies that involve incremental changes relative to today's cars than for H₂ FCVs. In light of the fact that such options could be commercialized much more quickly than H₂ FCVs, policies ought to be enacted that facilitate early commercialization of promising options in these categories while simultaneously encouraging accelerated development of the H₂ FCV.

In charting a course to the Car of the Future, societal LCC comparisons should be complemented by considerations of fuel infrastructure requirements. Because fuel infrastructure changes are costly, the number of major changes made over time should be minimized. The bifurcated strategy advanced here—of focusing on the H₂ FCV for the long term and advanced liquid hydrocarbon-fueled ICEVs and ICE/HEVs for the near term—would reduce the number of such infrastructure changes to *one* (an eventual shift to H₂).

It would be desirable to shape automotive innovation policies to include near-term options that facilitate long-term goals. Emphasizing ICE/HEVs in the near term would be helpful by providing valuable experience with electric drive trains needed for FCVs. Likewise, emphasizing fuel-efficient H₂ ICEVs and ICE/HEVs (e.g., in fleet demonstrations) could both provide near-term experience with H₂ fueling infrastructures and make available backup technologies, should H₂ FCV developmental efforts falter.

This societal LCC exercise indicates that advanced technologies bolstered by appropriate public policies can make possible major reductions in externalities for cars relative to today's new cars—and reductions to near-zero if H₂ FCVs can be successfully developed. Despite the uncertainties relating to the latter, one can be bullish in light of the enormous progress made over the last decade and the intense efforts underway among the world's automakers aimed at bringing this technology to market during the next 10–15 years.

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