Toward a Hydrogen-Based Transportation System

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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 requires radical changes in automotive engine/fuel technologies in directions that offer both the potential for achieving near-zero emissions of air pollutant and greenhouse gases and a diversification of the transport fuel system away from its present exclusive dependence on petroleum. This paper explores alternative technological options for achieving a transportation system in the long term with such characteristics. A number of engine/fuel options are considered, including variously fueled internal combustion engine/hybrid electric vehicles and fuel cell vehicles. The focus is on hydrogen used in fuel cell vehicles, an option that is found to have the lowest full fuel cycle environmental damage cost and potentially competitive lifecycle cost.

Approach

This paper summarizes the findings of a study (Ogden, Williams, and Larson, 2001) exploring alternative technological options for achieving a transportation system in the long term characterized by near-zero emissions of both air pollutants and greenhouse gases,[1] as well as a diversification of the supply system away from petroleum.

To compare alternative automotive engine/fuel options in evolving toward these goals, estimates were developed for automotive performance, full fuel cycle emissions and lifecycle costs (LCCs). The results of a base-case analysis for the engine/fuel options examined in this exercise are summarized in Table 1 and Figure 1.

Lifecycle Cost as a Yardstick

In the present study, the societal LCC is singled out as an important indicator for comparing alternative options. The estimated LCCs presented in Table 1 and Figure 1 include direct consumer costs for both the drivetrain and fuel. Also included are estimates of lifecycle environmental damage costs caused by air pollutant and greenhouse gas (GHG) emissions.

Cost estimates for alternative future drivetrains[2] are for mass production conditions[3] and do not take into account expenditures associated with launching new technologies in the market (expenditures for technology cost buy down). Details on assumed drive train costs are given in Table 2. The issue of buying down the costs of new technologies via mass production is addressed in a later section.

Likewise fuel cost estimates[4] in Table 1 (the present value of lifetime fuel costs for the vehicles) are based on conditions when alternative fuels are fully established in the market, projections of prices for conventional fuels in 2020, as well as engineering estimates of the fuel economies for

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[1] For the purposes of the present analysis, "near-zero" emissions is taken to mean that emissions are sufficiently low that fully internalized environmental damage costs associated with emissions are a small increment relative to direct economic costs for fuel.

[2] Vehicle mass produced drive train costs were based on estimates by Directed Technologies, Inc. (Lomax *et al.*, 1998; Thomas *et al.*, 1998a; Thomas *et al.*, 1998b; Thomas, 1999). These are broadly consistent with alternative fueled vehicle costs estimated in a recent study by researchers at MIT (Weiss *et al.*, 2000).

[3] The costs presented in Table 1 for internal combustion engine-based drive trains are "learned out" estimates, with little if any potential for further cost reductions as a result of increasing cumulative production—reflecting the relatively mature state of development of internal combustion engine technology. In contrast, the cost estimates for fuel cell-based drive trains are levelized (average) costs for the first large-scale (~ 300,000 per year) fuel cell drive train manufacturing facility—reflecting the embryonic state of development of fuel cell drive train technology.

[4] Delivered fuel prices do not include federal and state retail taxes, which, in the United States, averaged $0.42 per gallon for regular gasoline in 1999. Delivered costs for gasoline, Diesel, compressed natural gas, Fischer-Tropsch liquids, methanol and ethanol are estimates presented in a recent study by researchers at Argonne National Laboratory (Wang *et al.*, 1999.). Hydrogen production costs are based on estimates by Foster Wheeler (1996), and

alternative vehicles.[5]

Estimated costs presented in Table 1 for environmental damages were developed for this study based on: (*i*) estimated emissions [obtained using the Transportation Fuel Cycle Model (GREET) developed at Argonne National Laboratory[6]] of both air pollutants and GHGs from both vehicle operation and all activities upstream of the vehicle, (*ii*) estimates of damage costs per gram of emitted air pollutant [from studies carried out under the auspices of the European Commission's ExternE Programme,[7] adjusted for U.S. (lower) population densities], and (*iii*) the assumption that GHG emissions are valued at $100 per tonne of carbon (tC).

Air-Pollutant Damage Costs

The ExternE studies show that air pollution damage costs are dominated by adverse health impacts (mostly chronic mortality) associated with small particles in the air that are either emitted directly during fossil fuel combustion or are formed by reactions in the atmosphere from gaseous precursor emissions of SO_2 and NO_x. The ExternE air pollution damage cost estimates presented in Table 1 are median estimates of damages based on the "willingness to pay" to avoid air pollution health damages.[8] These are derived from damage cost estimates for Europe, adjusted for U.S. population densities.[9]

On the basis of the present scientific understanding, environmental damage cost estimates from air pollution are uncertain. Improved scientific understanding might lead to lower or higher cost estimates. A measure of the uncertainty for health damage costs is that, at one standard deviation from the median risk valuation, the damage cost is 0.25 times the median estimate on the low

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H_2 distribution and refueling station costs are from Ogden (1998)— see Table 1, note e, and Tables 3a, 3b. Fuel economies and delivered fuel costs ($/gge) in Table 1 are based on the lower heating values (LHV) of fuels. Delivered fuel costs in Table 3 (in $/GJ) are based on the higher heating value (HHV) of the fuel.

5 Vehicle fuel economies are based to a large extent on estimates generated from the GREET model (Wang, 1999) and simulations by Directed Technologies, Inc. (Thomas et al 1998b, Thomas 1999), except for the modifications indicated in note a of Table 1. Again, these estimates are broadly consistent with those of the MIT study (Weiss *et al*., 2000).

6 Wang and Huang (1999); Wang (1999).

7 Spadaro *et al.* (1998); Spadaro and Rabl (1998a); Rabl and Spadaro (2000).

8 The willingness to pay tends to increase with per capita income levels, so that air pollution damage costs rise in importance as societies become more affluent.

9 The ExternE studies were conducted for European conditions. Air pollution 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 pollution health damage costs are less. For this study, the ExternE damage costs were scaled to southern California population densities. The results presented here match fairly well with southern California air pollutant damage costs estimated by Delucchi and McCubbin using a different method (Delucchi 2000; McCubbin and Delucchi, 1999). The present study and Delucchi and McCubbin's study give ranges of estimated damage costs that overlap; the median damage costs estimated in the present study are within 40% of those estimated by Delucchi and McCubbin (see Appendix).

side and 4 times the median estimate on the high side. Uncertainties in estimating air pollution damage costs are discussed in detail in the Appendix.

For this study southern California was chosen as a site for estimating U.S. damage costs from automotive air pollutant emissions. Southern California is an area with severe air quality problems. And California has been a U.S. leader in implementing restrictive air pollution 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 about 20% of the U.S. light-duty vehicle market. Because these four states account for such a large share of the total market, because the trend is toward increasingly stringent standards nationwide, and because of the inefficiencies of having to develop different automotive technologies for different regions, air emission damage estimates for southern California were adopted as the U.S. norm for this study.

Environmental Damage Costs from Greenhouse Gas Emissions

Evaluating environmental damage costs of GHG emissions is inherently difficult. The approach taken here is to value GHG emissions at $100 per tonne of carbon (tC). This is the current cost of achieving deep reductions in CO_2 emissions at coal power plants with the least costly emissions-reduction technology, as estimated in the World Energy Assessment.[10] This abatement cost is a surrogate for a true damage cost, which is not well established for climate change. The rationale for choosing this valuation is that, if society were to decide to seek deep reductions in GHGs, it would try to allocate resources efficiently among different sectors, and, under this condition, priority would be given to technologies and strategies for achieving deep reductions in GHG emissions in the transport sector if the cost of achieving deep reductions in CO_2 emissions from transport were less than or equal to the costs for the least costly options outside the transport sector. A measure of the significance of carbon valuation at $100 per tC is that if there were a carbon tax of this magnitude in place, the pump price of gasoline would be $0.25 per gallon higher.

Lifecycle Cost Comparisons

Base Case Vehicle

In addressing the question: can alternative fueled cars compete? "Compared to what?" is an important consideration. Here the reference car is taken to be, not today's gasoline internal combustion engine vehicle (ICEV), but rather a future mid-sized internal combustion engine/hybrid electric vehicle (ICE/HEV) that is fully established in the market—offering double the fuel economy for an estimated "learned out" first cost increment of ~ $1,300 as compared to today’s gasoline ICEV (see Table 2). Such cars are expected to be competitive with gasoline ICEVs on a LCC basis, even without taking into account environmental benefits (see Table 1), because of their higher fuel economy and related savings in fuel costs.

[10] For a coal-integrated-gasifier combined-cycle (IGCC) power plant (Williams, 2000).

General Findings

Figure 1 shows the total LCC of transportation for a variety of alternative fueled vehicles. Figure 2 shows the environmental damage costs (including both air pollutant damage costs and greenhouse gas emission costs) for each vehicle/fuel option. Comparing the alternatives shows that:

- For today's gasoline ICEVs and also for advanced gasoline, Diesel, and compressed natural gas (CNG) ICE/HEVs that satisfy Tier II emissions standards, air pollutant damage costs are of the same order as greenhouse emissions costs and for each option the sum is comparable to or greater than the fuel cost.

- There would be significant reductions of environmental damage costs in shifting from today's gasoline ICEVs to more efficient, lower polluting ICE/HEVs. Lifetime environmental damage costs are estimated to be about $4000 for a conventional gasoline ICEV, about 1/2 this value for gasoline or Diesel ICEV/HEVs, and 1/3 this value for CNG ICE/HEVs.

- The hydrogen (H_2) fuel cell vehicle (FCV) stands out as offering the least environmental damage cost among all the advanced options. When fueled with H_2 derived from natural gas, damage costs are 1/8 as large as for today's gasoline ICEVs without CO_2 sequestration and 1/15 as large with CO_2 sequestration.

- Several advanced options [gasoline, Diesel, Fischer-Tropsch (F-T) liquids, and CNG ICE/HEVs, and H_2 FCVs] offer comparable total LCCs (including environmental damage costs) that are significantly lower than for today's gasoline ICEVs. Although the H_2 FCV has a higher first cost and lifecycle fuel cost than the gasoline, Diesel, and F-T liquids-fueled ICE/HEV options, its low environmental damage costs make it competitive on a LCC basis.

- Among the FCV options, the H_2 variant offers a significantly lower LCC (with or without taking into account environmental damage costs) than variants with onboard fuel processors based on gasoline or methanol as the energy carrier, largely because of the lower first cost of the H_2 FCV.

To examine the robustness of these findings, sensitivity studies were carried out (see Box 1).

Major Findings Relating to Vehicles Fueled with Hydrogen

The study found that, without taking into account environmental benefits, H_2 FCVs would not be competitive on a LCC basis with gasoline ICE/HEVs. However, in the base-case analysis, mass produced H_2 FCVs would be competitive if environmental benefits are taken into account (see Table 1) (at the estimated levelized mass production cost of FCV drive trains from the first large plant).

The outlook for the H_2 ICE/HEV is less promising, primarily because of the projected lower fuel economy (60% of the fuel economy of the H_2 FCV—see Table 1) and higher first cost (~ $1200 more than for the CNG ICE/HEV—largely because of the added cost for H_2 storage)—see Table 2). For the range of cases considered in the study (see Box 1), the CNG ICE/HEV and the H_2 FCV always have lower LCCs than the H_2 ICE/HEV.

The cost of H_2 delivered to motor vehicles is likely to be considerably higher than costs for various liquid energy carriers (e.g., from Table 1, the untaxed refueling station "pump prices" for H_2 from alternative primary energy sources range from $2.0 to $3.5 per gallon of gasoline equivalent, compared to $0.95 per gallon for gasoline). Thus the energy efficiency of the vehicle plays an important role in determining the cost competitiveness of H_2 vehicles—which suggests focusing on H_2 FCVs, which would typically have about three times the gasoline-equivalent fuel economy of gasoline ICEVs of comparable performance.[11] [This result is consistent with estimates in a recent report by researchers at MIT (Weiss *et al.*, 2000).]

The major uncertainty regarding the FCV option is whether costs in mass production will be low enough for the FCV to compete with both conventional ICEVs and ICE/HEVs. Today FCV drivetrain costs are high, ~$200,000 per car, and must be reduced to ~ $5,000 per car for the H_2 FCV to be competitive with the gasoline ICE/HEV. 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 costly[12] as to preclude the FCV's 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.

Major Findings Relating to Hydrogen as a Fuel for Motor Vehicles

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[11] If the shift from an internal combustion engine to a fuel cell were complemented by measures to improve energy efficiency by reducing aerodynamic drag and rolling resistance and by using light-weight materials to reduce vehicle weight, the fuel economy of a H_2 FCV could be increased to over 100 mpge without sacrificing performance or size [Ogden *et al.*,(1998); Ogden *et al.*(1999)]. Such opportunities for fuel economy improvement, along with drive-train improvements [focusing on compression-ignition direct-injection (CIDI) ICE/HEVs and FCVs] are being pursued in the United States under the Partnership for a New Generation of Vehicles (PNGV)—a government/industry-sponsored initiative to develop by 2004 production-ready prototypes of the “car of the future.” The PNGV goal is a car that would be at least three times as fuel efficient as today’s new cars (80 mpg) but would cost no more to own and operate than conventional cars and would meet all air-quality and safety requirements.

[12] The proton exchange membrane fuel cells favored for automotive applications require platinum-group catalysts, but costs are expected to be relatively modest if platinum catalyst loadings for the fuel cell can be reduced to levels already achieved in the laboratory. For the present analysis it is assumed that the platinum loading (anode plus cathode) is 0.25 mg per cm^2 or 0.4 grams per kilowatt, corresponding to a cost of ~ $400 per car. It remains to be demonstrated whether such loadings would provide satisfactory FC operation over the operating life of the car.

The major issues relating to the use of H_2 in motor vehicles are: What about onboard H_2 storage? Is H_2 safe? How would the H_2 be produced? Is H_2 affordable?

Box 1. Sensitivity of the Findings of the Lifecycle Cost Analysis to Uncertainties

The LCC calculations depend on inputs from several complex models, each with a host of assumptions. To examine the robustness of LCC findings, sensitivity studies were carried out varying key parameters:

Air pollution damage costs. Air pollution damage costs were varied over the range suggested by the ExternE study (from 0.25 to 4.0 times the scaled ExternE mean estimated damage costs). As expected, as pollutants are valued more, the LCC advantage of low polluting technologies such as FCVs becomes greater. Although H_2 FCVs have roughly the same LCCs as gasoline, CNG or Diesel ICE/HEVs at the median ExternE pollution damage values, the H_2 FCV would offer the least LCC by a decisive margin if air pollution damages were valued at 4 times the ExternE median estimates.

Mass produced costs of electric drive train components. For the base case analysis presented in Table 2, drive train costs are based on studies carried out by Directed Technologies, Inc. (DTI). Although costs for internal combustion engines, transmissions, controls and fuel storage systems can be estimated with confidence, the mass produced costs of electric drive train components (fuel cells, fuel processors, peak power batteries, and motor/controllers) are known with much less certainty. The costs for the latter components were varied from 0.5 to 2.0 times the DTI values to estimate the impact on the LCC. This sensitivity analysis showed that the LCC is quite sensitive to the assumed cost of electric drive train components. The relative ranking of vehicles on the basis of LCC can change as costs for these drive train components are varied. For example, if FCV drive trains end up costing twice as much as estimated by DTI, the LCC of the H_2 FCV would be higher than that for the gasoline ICE/HEV unless air pollution damage costs are at the high end of the range.

Cost of greenhouse gas emissions. The value of CO_2 emissions was varied from $50 to $200 per tonne of carbon. For greenhouse gas emissions valued at more than $60-$65/tC and air pollutant emissions valued at the ExternE mean estimates, the FCV operated on natural gas-derived H_2 would have a lower LCC than the gasoline ICE/HEV.

Population density: Air pollution damage 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 pollution damage costs would be higher. Although detailed calculations were not carried out to examine this effect, pollution damage costs could be expected to be roughly three times as high for typical European conditions as for the southern California base case (mean ExternE) values.

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 fuel processor costs presented in Table 2 for the base case are DTI’s “probable” estimates. If instead DTI's “best case” values were assumed, LCCs for the gasoline and methanol variants would be less, but the H_2 FCV variant would still offer the lowest first cost and LCC.

The only viable H_2 storage option at present[13] is compressed gaseous storage, which is bulky, because compressed gaseous H_2 storage systems typically have just 1/10 the volumetric energy storage density of gasoline. The storage challenge can be mitigated to a large degree by selecting energy-efficient H_2 FCV designs. For example, a PNGV-type (see footnote 11) H_2 FC car with a gasoline-equivalent fuel economy of 106 mpg would require a storage volume of about 42 gallons in order to achieve a range between refuelings of 350 miles[14]—a range that is likely to be acceptable to most people. Such a storage volume is large but not infeasible. Vehicles could be redesigned to accommodate such large tanks without compromising passenger or trunk space. The major uncertainty is whether storage of gaseous H_2 at high pressure (~ 350 bar) onboard vehicles is acceptable to consumers.

Box 2: Hydrogen Safety

Largely because of the Hindenburg fire, which was vividly captured on film, H_2 is widely perceived to be an unsafe fuel. Hydrogen burns or detonates over a wider range of concentrations in air than other fuels, and very little energy is required to ignite H_2 mixed with the minimum amount of air needed for complete combustion. Although H_2 is flammable in air over a wide range of mixtures, when it is used in unconfined spaces (as will be typical in transport applications), the lower limits for flammability and detonability matter most. In this regard, H_2 is comparable to or better than gasoline. Gasoline and natural gas can also be easily ignited with low-energy ignition sources such as electrostatic discharges—like those that result from a person walking across a rug. Moreover, in dilute mixtures with air, the ignition energy for H_2 is essentially the same as for methane. In another regard, H_2 has an advantage over gasoline: In case of a leak in an unconfined space, H_2 will disperse quickly in the air because of its buoyancy, whereas gasoline will puddle.

An important safety issue for H_2 is leaks—prevention, detection, and management—particularly in confined spaces. Areas where H_2 is stored and dispensed have to be well ventilated; because of H_2's buoyancy, this means providing vents at the highest points in ceilings. Considering all these issues, a major 1994 study of H_2 safety carried at the Sandia National Laboratory (Ringland, 1994) concluded that "H_2 can be handled safely, if its unique properties—sometimes better, sometimes worse, and sometimes just different from other fuels—are respected."

Concerns are often raised about H_2 safety. In this regard, H_2 is better than other fuels in some ways, worse in some ways, and in still other ways just different. However, H_2 can be used safely if procedures are followed that respect its physical and chemical properties (see Box 2). Such theoretical considerations are buttressed by extensive experience with residential town gas (up to

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[13] With advanced storage technologies (e.g., advanced carbon nanofibers), it might one day be feasible to reduce storage volumes and extend vehicle range significantly (Dresselhaus, Williams, and Ecklund, 1999).

[14] Ogden, *et al.* (1998 and 1999) designed a PNGV-type FCV that would have an estimated gasoline-equivalent fuel economy of 106 mpg, and for which it was assumed that that the H_2 is stored as a gas compressed to 345 bar (5000 psia) in cylinders with an aggregate storage capacity of 3.75 kg of H_2—an amount that would provide a range of 425 miles between refuelings. State-of-the-art system storage densities for canisters (carbon-fiber-wrapped tanks with aluminum liners) are 7.5% H_2 storage by weight, so that the loaded storage system weight is 50 kg. It is assumed that the H_2 is stored in 3 cylindrical canisters, each of which is 103.4 cm (40.7 inches) long and has an outside diameter of 28.3 cm (11.1 inches). The total storage system volume is thus 195 liters (51.5 gallons), and the volumetric storage density is 52 liters per kg or 195 liters (51.5 gallons) total. (Note that the interior volume required for 1 kg of H_2 at this pressure is 32 liters.) These cylinders might be stored in a compartment under the roof of the car, as demonstrated for the Daimler-Benz NECAR II fuel cell passenger van.

50 percent H_2), which was widely used in the United States until the 1940s and in Europe until the 1960s and is still used in China and South Africa.

The major options for providing the H_2 are to make it from a fossil fuel, from biomass, or from an electricity source via electrolysis. Because of the interest in providing H_2 with near-zero emissions of GHGs, a comparison will be made here of fossil-fuel-derived H_2 without and with geological sequestration of the separated CO_2, and the electrolytic option will focus on renewable electricity sources.

Even though H_2 would be more expensive than gasoline on a dollar per gallon of gasoline equivalent energy basis, the fuel cost per mile would be less with the least costly options for making and using H_2 with near-zero fuel cycle emissions (see Table 1).

Hydrogen from Fossil Fuels with Geological Sequestration of Carbon Dioxide

With commercially available technologies for making H_2 from a fossil fuel, the produced H_2 contains most of the chemical energy in the fossil fuel input, and a stream of relatively pure CO_2 that accounts for most of the carbon in the fossil fuel input can be recovered as a byproduct. If climate change were not a societal concern, this byproduct CO_2 would be vented to the atmosphere. But as a response to climate change concerns, this CO_2 could be sequestered in isolation from the atmosphere. Although there are many uncertainties that must be resolved, there is growing scientific confidence that the potential for securely sequestering CO_2 in various geological reservoirs (depleted oil and gas fields, deep beds of unminable coal, and deep saline formations) is large (Williams, 2000).

The least costly way to make H_2 with commercial technology is via the steam reforming of natural gas at large, centralized plants. Hydrogen is manufactured this way today[15] to serve chemical industrial needs (e.g., in the production of ammonia fertilizers) and oil refinery processing needs (e.g., for the manufacture of reformulated gasoline or the processing of heavy crude oils). The plant-gate cost for H_2 manufacture from natural gas costing \$3.4 per GJ[16] at such facilities is estimated to be about \$6.0 per GJ (see Table 3a). This wholesale production cost is equivalent to about \$0.86 per gallon of gasoline. [For comparison, the U.S. average wholesale (refinery gate) price of gasoline in 1997 was \$0.70 a gallon (EIA, 2000b).] Advanced H_2 production technologies—for example those based on the use of H_2 separation membrane reactors—could lead to lower costs and might make it possible to manufacture H_2 from coal via coal gasification at even lower cost than H_2 from natural gas (Williams, 1999).

With commercial technology, the production cost for natural gas-derived H_2 would increase about 27 percent if CO_2 accounting for 85 percent of the carbon content of the original natural gas were recovered, transported to, and injected into a remote geological storage reservoir for

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15 About 1 percent of U.S. primary energy consumption is for H_2 manufacture.

16 This is the average price projected by the U.S. Energy Information Administration for electric generators in the United States in 2020 (EIA, 2000a).

long-term storage (see Table 3a). The incremental fuel cost associated with sequestering the separated CO_2 would be about 12 percent for users of H_2 motor vehicles, because the delivered cost of H_2 would typically be more than double the manufacturing cost, when costs for H_2 refueling stations and H_2 distribution to these refueling stations are taken into account (see Table 3b).[17] Moreover, the incremental cost to consumers would be only 3 percent when expressed as a percentage of the total LCC for drive train plus fuel (neglecting environmental damage costs) for an H_2 FCV (see Table 1). Finally, the fuel cost per mile for a FCV operated on H_2 derived from natural gas with CO_2 sequestration would be less than 2/3 of the cost of gasoline (@ $0.95 per gallon) per mile for today's ICEV (see Table 1).

Another way to look at the economics of H_2 production from fossil fuels with sequestration of the separated CO_2 is to note that with present technology for making H_2 from natural gas, the cost of avoiding CO_2 emissions by CO_2 sequestration is ~ $100 per tC (see Table 3b). This is comparable to the least costly way of achieving deep reductions in CO_2 emissions from fossil energy systems in the power sector [as noted earlier, the avoided emissions cost is ~ $100 per tC for CO_2 removal from coal-integrated-gasifier combined-cycle power systems and sequestration (Williams, 2000)[18]]. Thus if H_2 FCVs can be made economically viable, a fossil energy decarbonization/CO_2 sequestration strategy for transportation would be an economically attractive option for achieving deep reductions in CO_2 emissions even with present H_2 production technology.

Aside from all the uncertainties regarding the prospects for H_2 vehicles, the major uncertainty regarding H_2 derived from fossil fuels with CO_2 sequestration is the extent to which CO_2 sequestration can be carried out at large scales.

The unresolved issues are not just technical—public acceptability issues are also paramount. Fuel decarbonization with CO_2 sequestration is unfamiliar to most people as a strategy for dealing with the climate change challenge. What will public attitudes be? The scientific community has major responsibilities to improve understanding of CO_2 storage security and of safety and environmental impacts of CO_2 sequestration, and to inform the public debates on such issues.

Hydrogen from Biomass

H_2 can be made from biomass via processes that begin with thermochemical gasification—in much the same way that H_2 would be made from coal. For the most promising gasifiers, the H_2 production cost would be about 1/3 more than for H_2 derived from natural gas with CO_2

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17 The costs for H_2 distribution to refueling stations and for the H_2 refueling stations in Table 3b are from Ogden (1998; 1999).

18 For comparison, the cost of CO_2 removal and sequestration at natural gas combined cycle power plants with current technology is in excess of $200 per tC [see Table 8.10 in Williams (2000)].

sequestration (Williams et al., 1995); the cost delivered to consumers at H_2 refueling stations would be about 1/6 more than for natural gas-derived H_2.

H_2 from biomass might be given focused attention if problems arise that limit the viability of large-scale sequestration associated with H_2 manufacture from fossil fuels, in light of the fact that near-zero CO_2 emissions can be realized without sequestration for biomass grown on a sustainable basis.

A major concern often raised about biofuels is that, because the overall efficiency of photosynthesis is low,[19] there would not be enough land to enable a major role for biofuels. A close look at the agricultural land situation in the context of making biomass-derived fuels for use in energy-efficient vehicles strongly indicates that this would not be the case.

Because of the rising trend in agricultural productivity, excess agricultural land resources in industrialized countries are currently large and may well be larger in the future. Using such excess agricultural lands for growing biomass for energy purposes would provide farmers with a new source of income and make it possible to greatly reduce if not eliminate agricultural subsidies (Williams, 1994). Moreover, excess agricultural land areas are likely to be adequate to provide a major fraction of transport energy needs if H_2 derived from biomass were used in energy-efficient vehicles.[20] Using excess agricultural lands for growing fast-growing trees or perennial grasses as energy crops would also typically be far less environmentally damaging than growing food crops. However, there is likely to be continuing debate about the desirability of converting excess agricultural lands to energy crop production; some will argue that it would be preferable to allow such lands to revert to wilderness and serve as wildlife habitat. Such debate should be framed in the context of the overall relative merits of biofuels vs. alternative options in the quest for near-zero emission vehicles and fuels.

H_2 from Renewable Electric Energy Sources

Technology for making H_2 from electricity via electrolysis is well established commercially and would lead to zero fuel cycle emissions if the electricity were provided by a zero-emitting power source—e.g., a renewable electricity source. In principle, most human energy needs could be met using H_2 derived from photovoltaic (Ogden and Williams, 1989) or other renewable electric

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[19] An optimistic but plausible average biomass yield for fast-growing trees or perennial grasses is about 15 dry tonnes of biomass per hectare per year, the energy content of which is about 0.5 percent of the amount of solar energy that falls on an "average" hectare of land in the United States in one year.

[20] Assuming an efficiency of 64% in converting biomass into H_2 (Williams *et al*., 1995) and a woody biomass productivity of 15 dry tonnes/hectare/year, about 20 million hectares of cropland would be required to support the projected demand for fuel by the entire 290 million light-duty vehicles expected to be on the road in the United States in 2020 if all such vehicles were PNGV-type H_2 FCVs with average gasoline-equivalent fuel economy of 106 mpg—see footnote 11). For comparison, 33 million hectares of U.S. cropland were idled in 1990 either to control erosion or keep food prices high. Moreover, the U.S. Department of Agriculture forecast in 1989 that by 2030 the US would have over 50 million hectares of excess food production capacity as a result of increasing crop yields, assuming a doubling by then of exports of corn, wheat, and soybeans (Williams, 1994).

sources (Ogden and Nitsch, 1993) without running up against land use or other physical resource limiting constraints. The major challenge relating to H_2 derived from renewable or any other electricity source is high cost.

Among renewable electricity sources, wind power is the closest to being competitive with conventional fossil electricity sources.[21] But at current wind power costs, the cost of H_2 delivered at refueling stations to consumers would be very costly: 4.5 times the retail price of gasoline and 1.9 times the cost of H_2 from natural gas with sequestration of the separated CO_2—see Figure 3.

Renewable power costs are expected to decline substantially. The outlook is especially auspicious for wind power, for which technological advances may well lead, over the next 30 years, to "baseload" wind power becoming competitive with baseload natural gas combined cycle power.[22] By 2030 FCVs powered by H_2 derived from wind power could plausibly be less costly to own and operate than today's gasoline ICEVs if air pollutant and climate change costs are internalized (see Table 1 and Figure 1). But the H_2 produced via electrolysis from such electricity and delivered to consumers would still be about 60 percent more costly than H_2 derived from natural gas with geological sequestration of the separated CO_2 (see Figure 3). Thus the rationale for choosing wind-electrolytic H_2 or any other renewable-electrolytic H_2 option over H_2 derived from natural gas (or an alternative fossil fuel) with CO_2 sequestration would have to be on the basis of shortcomings of large-scale CO_2 sequestration strategies that may not have been adequately quantified at present.

A Strategy for Pursuing Hydrogen Fuel Cell Vehicles as a Long-Term Option

The technology for manufacturing the H_2 FCV, the most environmentally attractive long-term option in Table 1, is technically proven; the major challenge is to reduce dramatically the costs of FCV drive trains to competitive levels. This might be achievable by exploiting opportunities for cost reduction via mass production, via experience (learning-by-doing), and via making continual marginal improvements in the technology.

Two formidable challenges to commercializing FCVs are the current high cost of such vehicles and the current lack of an infrastructure for supplying H_2 fuel to vehicles.

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21 In the late 1990s, unsubsidized wind power costs were 4.5 to 5.0 ¢ per kWh at the wind farm for good wind resources (e.g., average wind speeds of 6.4 to 7.0 m/s at 10 m) and 25 MW wind farms.

22 A 1997 study carried out for the Electric Power Research Institute and the U.S. Department of Energy projected that by 2030 the cost of windfarm electricity would decline at good wind sites to less than 2.5 ¢ per kWh [EPRI/OUT (1997); see also Table 5.1, p. 5-6, in PCAST Panel on International Cooperation on ERD[3] (1999)]. At this low cost it would often be worthwhile to convert this windpower into baseload electricity by coupling it to a compressed air energy storage system (Cavallo, 1995). Such baseload wind power could be delivered to urban centers at a delivered cost of less than 3.5 ¢ per kWh, which would be competitive with baseload electricity from natural gas combined cycle power plants.

The current initial high cost of H_2 FCVs is a hurdle that is common to all radically new technologies that target displacement of entrenched technology. To become competitive radically new technologies must be mass produced in highly automated factories, and cumulative production volumes must be built up to exploit cost-cutting opportunities as a result of both experience ("learning-by-doing"—as technologies evolve along their learning curves—see Figure 4), and continual marginal improvements in the basic technology that are made in light of growing experience.

Its simplicity and thus lower drivetrain costs, its higher efficiency, and its lower emissions characteristics imbue the H_2 FCV with a substantial LCC advantage over gasoline or methanol FCVs, once mass production level costs are reached (see Table 1). However, the H_2 FCV is typically not considered to be a serious candidate for launching FC automotive technology in the market: (*i*) because of the lack of a H_2 refueling infrastructure, (*ii*) because of the high cost of establishing such an infrastructure compared to a scenario where methanol FCVs are launched in the market by taking advantage of the present global excess capacity for methanol production, and (*iii*) because the only commercially viable H_2 storage technology for H_2 FCVs is compressed gaseous storage, which is bulky and thus "inconvenient."

For such reasons, many in the auto industry who are looking for ways to commercialize FCVs are targeting the introduction of FCVs that use onboard fuel processors with liquid fuels that are easier to store and handle than H_2—fully realizing that an eventual switch to H_2 will take place after FCV costs have reached market-clearing levels. Most of the automotive industrial effort is focused on developing FCVs with onboard gasoline or methanol fuel processors.

Gasoline as an Initial Fuel for Fuel Cell Vehicles

For FCV commercialization strategies based on gasoline and onboard fuel processing, the hope is that costs of FCVs could be bought down quickly to cost-competitive levels as a result of rapidly introducing large numbers of FCVs into the general automotive population without having to make changes in the refueling infrastructure. Once the cost of FCVs is reduced, there would be an economic pressure to move toward H_2, since the FCV drive-train cost and the LCC for transportation services would be less with H_2 than with gasoline (see Table 1).

The key technology needed to make this strategy viable is the gasoline fuel processor. Since the mid-1990s, gasoline reforming has received considerable R&D attention from fuel cell developers, the U.S.Department of Energy, automakers, and oil companies, but gasoline reforming is proving to be a difficult technical challenge**.** Most automakers now envision that successful development of gasoline processors will require 5-10 years.

As long as the main competition for the gasoline FCV was the conventional gasoline ICEV, an economic argument could be made in its favor: its higher first cost (~ $5100 more, as estimated in Table 1) could perhaps be more than offset by the fuel savings associated with nearly a doubling of fuel economy plus the environmental benefits that it would offer (see Table 1).

But this outlook has changed markedly with the emergence on the market of the gasoline ICE/HEV, which presents strong competition for the gasoline FCV. The advanced gasoline

ICE/HEV offers fuel economy similar to that for the gasoline FCV, comparable “well to wheels” carbon emissions, and significantly better economics, although the gasoline FCV has the advantage of lower tailpipe air pollutant emissions. It is uncertain whether the gasoline FCV would be able to capture sufficient market share to buy down FCV costs in a head-to-head competition with the advanced gasoline ICE/HEV, which is likely to have a significantly lower LCC, even when environmental damage costs are included (see Table 1).

Methanol as an Initial Fuel for Fuel Cell Cars

Several automakers are planning to offer first generation FCVs with methanol reformers.

Methanol has a number of attractive features as an initial fuel for FCVs. Like gasoline, but unlike H_2, methanol is a liquid fuel that can be easily distributed and stored. Methanol is much easier to reform than gasoline, and unlike the gasoline fuel processor, methanol fuel processor technology has already been demonstrated in working vehicles. Moreover, the base-case cost analysis presented in Table 1 indicates that, although the methanol FCV might cost less than the gasoline FCV, it would not be competitive with the gasoline ICE/HEV. Reductions in environmental damage costs would not offset the extra first cost of the vehicle (see Table 1).

There is currently excess methanol production capacity worldwide, so that refueling infrastructure costs would be lower than for H_2 until demand levels become sufficiently large that new methanol production capacity would be needed.

Demand for methanol by FCVs might never reach levels such that new methanol plants would have to be built, however, because once FCVs are established in the market H_2 FCVs would be cheaper to own and operate, creating market pressure to introduce H_2 as the preferred energy carrier (see Table 1).

This suggests that the main reason for considering methanol is as a convenient way for launching FCVs in the market and buying down the cost of these cars to market-clearing levels by quickly building up cumulative production volumes. If methanol is considered only as a temporary energy carrier along a path to H_2, the main consideration is how the expenditures required to buy down FCV costs would compare with such expenditures for alternative options for launching FCVs in the market—an issue discussed below.

Hydrogen as an Initial Fuel for Fuel Cell Vehicles

In what follows the prospects for using centrally refueled fleets for launching H_2 FCVs in the market is explored, and the conventional wisdom that a liquid fuel is needed for commercializing FC vehicle technology is challenged.

The option of launching FCV technology in the market using H_2 in centrally refueled fleet vehicles (including government or corporate car or truck fleets and urban transit bus fleets) is worthy of close attention for several reasons:

- For centrally refueled fleets, only a limited fuel supply infrastructure is needed. Hydrogen could be delivered via truck or pipeline or produced onsite via small scale steam reforming or electrolysis using commercially available technology. Concentrating initially on fleet markets would defer the challenge of a lack of H_2 infrastructure until FCV costs are bought down to market-clearing levels—a decisive advantage in that the attractive costs of H_2 FCVs after buy down would provide substantial market pull for subsequent H_2 infrastructure development.

- A high level of technical competence could be assured for the personnel operating the refueling station. Trained personnel would be able to gather experience in a more controlled environment than that of public refueling stations.

- Current compressed gaseous H_2 storage technology provides a fully adequate range for centrally refueled fleet vehicles, which can be conveniently refueled more frequently than non-fleet vehicles.

- The initial experience with dedicated fleets would provide invaluable demonstration of the unique features of the H_2 FCV and would provide a substantial base of experience that could facilitate consumer acceptance of compressed gaseous H_2 storage if fleet experience with storage is favorable.

In addition, as will be shown: (*i*) markets for centrally refueled fleet vehicles are sufficiently large, even considering such markets only in the United States, for buying down quickly the costs of FCVs to market clearing levels; and (*ii*) buy-down costs are likely to be substantially less for this strategy than for either gasoline or methanol strategies for launching FCVs in the market.

What is the Least-Costly Fuels Strategy for Commercializing Fuel Cell Vehicles?

To identify the least-costly fuels strategy for commercializing FC vehicles, a "learning curve analysis" was developed for H_2, methanol, and gasoline FCVs—assuming that drivetrain costs for FCVs (in $ per kW) decline at a fixed rate (X percent cost reduction for each cumulative doubling of production[23]) as they advance along their learning curves (see Figure 4).
A learning curve analysis can be helpful in understanding the evolution of costs for technologies that are amenable to the economies of mass production—as long as costs predicted by the learning curve remain well above the costs of the materials involved plus irreducible (minimum) fabrication costs. As noted above, materials costs are not likely to be limiting if platinum catalyst loadings near those demonstrated in the laboratory prove to be adequate for the expected life of a FCV; moreover, FCV drive train manufacture involves no exceptionally difficult fabrication

[23] It was assumed for all fueling options that FCV drivetrain costs decline 17% for each cumulative doubling of production [corresponding to a "progress ratio" of 83% (= 100% - 17%)]. This rate of cost decline provides a good fit of data regarding both costs for present drive trains that are produced on a "one-off" basis and costs in factory mass production at a scale of 300,000 vehicles per year, as estimated by Directed Technologies, Inc., for the Ford Motor Company.

Cost reductions of the order of 20% for each cumulative doubling of production are typical of many industrial products amenable to the economies of mass production (see, for example, Figure 4).

processes. Nevertheless, learning curve cost projections do not constitute proof of future cost trends and thus should always be used cautiously in conjunction with other evidence relating to prospective costs.

The learning curve analysis for FCVs is carried out under the following plausible scenario for FCV manufacture by a single firm (see Figure 5):

- *For the first 5 years*, 10 FCVs are produced annually "by hand" for small fleet demonstrations, during which time the FCV design for factory manufacture is developed;

- *For the next 5 years*, 10,000 FCVs are produced annually in a pilot manufacturing facility, during which time the manufacturing process is tested and refined;

- *For the following 15 years*, 300,000 FCVs are produced annually in a commercial factory.

It is assumed that a FCV is cost-competitive when its total LCC ($ per car) is identical to that for its major competitor. The major competitor is assumed to be, not the average gasoline ICEV on the market today, but rather a gasoline ICE/HEV—which stands a good chance of becoming the dominant next-generation car technology in terms of performance and cost.

The objective of the analysis is to estimate, for each FCV technology, the total number of cars that must be produced and the cumulative LCC expenditures in excess of the market clearing cost (the LCC at which the FCV is competitive with the gasoline ICE/HEV) required to reach this market-clearing cost level. These cumulative expenditures for the incremental cost are called here the "buy-down cost," as illustrated in Figure 6.

It should be noted that the point where LCC parity with the gasoline ICE/HEV hybrid is reached does not necessarily represent the asymptotic cost for the FCV drive train. The drive train cost might well continue to decline along the learning curve as cumulative drive train production increases further, if the predicted cost is still well above the irreducible materials plus fabrication cost limits. The potential for net LCC savings for all units produced after LCC parity has been realized is of course a major incentive for investing in the buy-down process. But, of course, learning curve analysis cannot guarantee such eventual savings and unforeseen difficulties might prevent even LCC parity from being realized—in other words, significant financial risks are involved in the buy-down process, so that a rough understanding of the prospective magnitudes of the financial resources at risk in buy down is crucial for those planning to participate in the buy-down process.

The base-case analysis is for the cost parameters presented in Table 1 for alternative cars, except that the ICE/HEV drive train cost is assumed to be "learned out" (so that there is no further opportunity for cost reduction), whereas the drive train costs presented for FCVs are estimated levelized costs (costs averaged over the expected 15-year factory life) for manufacturing FCV drive trains in the first large (300,000 vehicles per year) plant. Thus, at startup of the manufacturing plant, costs would be higher and at plant closing costs would be lower than the levelized costs presented in Table 1. The base-case analysis presents expenditures for buy down for the case where LCCs include both air pollutant and GHG emission damage costs, as presented in Table 1.

Figure 7 shows the evolution of the drive train cost for each type of FCV as it evolves along its learning curve, with indicators showing the buy-down cost, the total number of vehicles required to reach LCC parity with the gasoline ICE/HEV, and the FCV drive train cost at the LCC-parity point. The learning curve projects for each case that the cost will fall to 2/3 of the levelized cost by the end of the 15-year life of the first large factory. Although costs a these levels are still well above inherent materials costs, it is quite uncertain on the basis of present knowledge whether it is feasible to reduce costs this much.

It is notable that for the base case, the H_2 FCV reaches breakeven with the gasoline ICE/HEV after 1.2 million vehicles have been produced, at a cost approximately equal to the levelized drive train cost estimated by DTI for a manufacturing plant producing 300,000 drive trains per year. The methanol FCV requires a drive train cost below the levelized cost to achieve LCC parity with the gasoline ICE/HEV, after 3.0 million vehicles have been produced. The gasoline FCV does not achieve LCC parity even at the end of the 15-year life of the factory, at which time 4.5 million vehicles would have been produced.

The base-case analysis shows that the estimated buy-down cost is by far the lowest for H_2 FCVs ($1.6 billion); buy down for methanol FCVs costs more than twice as much ($4.1 billion). For the gasoline FCV case, where LCC parity with the gasoline ICE/HEV is not achieved during the operating life of the factory, the cumulative LCC difference is almost ten times that for the H_2 FCV case at the end of the plant life. The ordering of buy-down costs among these alternative technologies does not change under alternative cost assumptions considered in a sensitivity analysis (Box 1).

The time required to reach LCC cost parity is shown in Figure 8a for H_2, methanol and gasoline FCVs for the base case with both air pollutant and GHG damage costs included in LCCs. In this figure the cumulative LCC cost difference between the FCV and the gasoline ICE/HEV is plotted versus time for each FCV type. The maximum point on each curve represents the time at which LCC parity is reached, and the cumulative incremental LCC difference at that point is the buy down cost.

In Figure 8b, buy-down costs for H_2, methanol, and gasoline FCVs are compared, assuming no environmental costs are included. The trends are similar, with H_2 offering the lowest cost route to LCC competitiveness. However, the buy-down cost for H_2 FCVs is almost three times as large as for the case with environmental costs included.

In summary, the H_2 FCV offers, by a wide margin, the least costly and quickest route for bringing FCVs to LCC cost parity with gasoline ICE/HEVs.

Buying Down the Cost of Fuel Cells with Fleet Markets

In order to exploit the FCV buy-down cost advantage offered by H_2 fueling, readily accessible markets must be large enough to support the H_2 FCV sales required for buy down. Are centrally refueled fleet markets (for which the H_2 infrastructure challenge is tractable) large enough to support cost buy-down initiatives for H_2 FCVs?

Fleet Vehicle Markets

In recent years, several studies have evaluated U.S. vehicle fleets as a potential market for alternative fueled vehicles (Miaou *et al.*, 1992; Motta *et al.*, 1996; Nesbitt and Sperling, 1998). Based on these studies, it is estimated that in the United States alone almost 900,000 new vehicles are sold each year into centrally refueled fleets. These include about 300,000 passenger cars, 540,000 light trucks, and 28,000 buses (including 5,000 transit buses but excluding school buses). These vehicles are typically kept for 100,000 miles or 5-7 years. (Fleets of rental cars are excluded from this estimate as they are not centrally refueled, and the vehicles are typically resold after about a year.) Extrapolating from the U.S. situation, the annual turnover of fleet vehicles in OECD countries other than the United States might be an additional 2.5 million.

Thus, centrally refueled fleets represent large enough markets to accomplish buy down for H_2 FC vehicles, and buy down with H_2 fueling could probably be accomplished early in the next decade.

This approach to commercialization would also make it possible to launch H_2 FCVs in the market without having to wait for development of advanced H_2 storage technologies that some automakers think are needed to realize wide consumer acceptance of H_2 FCVs—because available compressed gaseous storage technologies would be fully adequate for serving centrally refueled fleet markets.

Moreover, the times required for FCV technology cost buy down and for "turning over" the car fleet are likely to set the pace for H_2 FCV adoption rather than the time required for building new H_2 infrastructure.

These findings call into question the wisdom of strategies currently being pursued by most automakers, which are aimed at commercializing FCVs using either methanol or gasoline as the initial fuel. Redirecting commercialization efforts from these methanol and gasoline fueling strategies to H_2 fueling strategies for centrally refueled fleets would make it possible to buy down FCV technology costs to competitive levels more quickly and with fewer financial resources.

Toward Learned-Out Costs for Hydrogen Fuel Cell Vehicles

The H_2 FCV might continue to advance along its learning curve after cost parity with the gasoline ICE/HEV is reached, as the cumulative production of the first large drivetrain factory increases.

The learning curve analysis projects for H_2 FCVs that the point of cost parity with the gasoline ICE/HEV without taking into account environmental damage costs due to greenhouse gas emissions would be reached after 1.7 million H_2 FCVs have been produced—during the 6^{th} year of operation of the first large FCV drive train factory (before 2017). If this learning curve projection is borne out, subsequently, H_2 FCVs could be sold in markets where limited incentives are provided to car buyers to buy clean cars.

Fueling Strategies for Centrally Refueled Fleets

It is fairly straightforward to sketch how a H_2 infrastructure for centrally refueled fleets could be built. Hydrogen could be delivered by truck or small pipeline to a limited number of sites or produced onsite via small scale reforming or electrolysis. [Options for H_2 supply have been considered in Ogden (1999) and Thomas, *et al.* (1998).] A strategy for moving beyond initial fleet markets into general automotive markets is discussed below.

Widespread Deployment Strategy for Cost Competitive Hydrogen Fuel Cell Vehicles

It is far easier to pursue widespread deployment strategies with FCVs that are already cost competitive than pursuing cost buydown and widespread deployment simultaneously. Once FCV costs are bought down using fleets, the major challenges regarding widespread deployment are: (*i*) to have an infrastructure in place for distributed refueling stations by the time FCVs are launched in mass markets, and (*ii*) to do so in a manner that leads to full capacity utilization as quickly as possible

It appears to be possible to do this with appropriate supportive public policies. A key element of the needed widespread deployment policy might be *an aggressive* zero emission vehicle (ZEV) mandate (e.g. 50% or so) implemented when H_2 FCVs become cost-competitive.

To serve the general public, H_2 must be widely available. Eventually, it is envisioned that the infrastructure would consist of large-scale "city-gate" H_2 production facilities plus local pipeline networks for distributing H_2 to refueling stations. However, pipeline systems are costly, and only make economic sense when a geographically concentrated demand for H_2 fuel exists. How long would it take to build up a sufficiently concentrated demand for H_2 pipelines to become cost effective?

Urban areas in the United States with air-quality problems are likely to be targeted as early mass markets for FCVs. Consider, as an illustrative example, the Los Angeles Basin, where half the population of 13.6 million people lives in areas where the population density exceeds 2000 people/km^2 and the light-duty vehicle population density is 1500 cars/km^2 (three cars for every four people).[24]

Ogden (1999) estimated that a vehicle population density of 200 H_2 FCVs per km^2 would be sufficient to justify building a local pipeline system to provide transportation fuel. For Los Angeles this is equivalent to 13% [100*(200/1500)] of the total fleet. Thus, assuming for the moment that a 50% ZEV mandate is put into effect (i.e., 50% of new cars sold must be ZEVs),

24 An average urban population density of 2000 people/km^2 is not especially high. In downtown areas of Los Angeles, as much as 25% of the population live in areas where the population density exceeds 4000/km^2. Also, population densities are higher than 2000/km^2 in some Eastern U.S. and European urban areas.

the time to reach a H_2 demand concentrated enough to justify building a H_2 pipeline system in the Los Angeles Basin is about 4 years.[25]

Of course, the H_2 production and distribution system would be underutilized for a few years until demand catches up, so that a government incentive to H_2 suppliers might be needed to help compensate for capacity underutilization in the early years and thereby enhance the prospects that the infrastructure will be in place when needed—i.e., when an aggressive (~ 50%) ZEV mandate is enacted. However, it is estimated that this underutilization of capital would add only about 5% to the delivered H_2 cost. Moreover, if H_2 FCV cost buy down is successful, there would also be strong market pull to build H_2 infrastructure for stationary combined heat and power (CHP) applications of fuel cells, because CHP systems will often be cost competitive at installed costs (in $ per kW) that are an order of magnitude higher than the cost levels needed to enable H_2 FCVs to compete. Thus the incentive required to motivate H_2 fuel suppliers to put into place in time the needed infrastructure is not likely to be especially large if H_2 FCVs are cost competitive. This suggests that in densely populated urban areas the fuel producer, knowing that demand would rise rapidly to meet supply, would be motivated to build H_2 production and distribution capacity, if a strong ZEV mandate were in place, perhaps supplemented by a modest H_2 supplier incentive.

If H_2 FCV demand rises more slowly or where population densities are relatively low, the economic penalties of underutilization of infrastructure capacity and the barriers to widespread deployment would be greater. Such considerations underscore the importance of an aggressive ZEV mandate or similarly effective enabling policy and a focus on markets in high population density regions in the early years of widespread deployment.

With this focus, the challenge of supplying fuel for passenger cars on long trips might be handled reasonably well with a chain of H_2 refueling stations (e.g., replenished initially with trucked-in liquid H_2) located along superhighways. In any case, long-distance driving accounts for a small fraction of miles traveled by passenger cars.

An Optimistic Scenario for Hydrogen Fuel Cell Vehicles Worldwide

The process of planning a transition to a H_2-based transportation system would be assisted by an understanding of how fast H_2 FCVs might potentially penetrate the market. To this end an optimistic scenario for the growth of the population of H_2 FCVs is constructed. This scenario is presented in the context of a World Energy Council (WEC, 1995) projection of the global automotive population[26] and a modeling of total new car sales based on this WEC projection. The assumptions underlying the optimistic FCV scenario are the following:

[25] Assuming that the number of new cars each year is about 7% of the total fleet.

[26] In the WEC "Market Rules" scenario, the number of passenger cars at the global level increases from 470 million in 1990 to 1,160 million in 2020. In the present study, this WEC projection is extrapolated to a global passenger car population of 1,350 million in 2025.

- Air pollution, global warming and energy supply insecurity become issues of increasing concern around the world during the next 25 years.

- Over the next decade, governments in a small number of countries respond to these concerns by enacting both measures aimed at internalizing environmental damage costs in consumer vehicle/fuel purchase decisions and technology-forcing measures [e.g., modest (up to 10%) ZEV mandates] to encourage vehicle manufacturers to accelerate H_2 FCV commercialization.

- Vehicle manufacturers respond to such initiatives by quickly making and deploying enough H_2 FCVs to buy down costs to market-clearing levels.

- As FCV prices approach cost-competitive levels, governments in these same countries enact a new set of technology-forcing policies: aggressive (~ 50%) ZEV mandates and perhaps also modest H_2 supplier incentives to encourage accelerated widespread deployment in densely populated urban areas of cost-competitive H_2 FCVs.

- Fuel producers respond to such initiatives by rapidly ramping up H_2 fuel infrastructure development for cars, so that by the time FCVs are cost-competitive, the needed infrastructures are in place.

- After H_2 FCVs become cost competitive, a rapidly growing number of countries introduce both measures aimed at internalizing environmental damage costs in consumer purchase decisions and aggressive (~ 50%) ZEV mandates—incentives that induce both accelerated expansion of H_2 FCV manufacturing and sales and accelerated H_2 infrastructure building.

- H_2 FCV prices continue to fall with cumulative FCV production, eventually reaching levels where FCVs are cost-competitive even without taking credit for environmental benefits—at which point many more countries adopt measures to encourage H_2 FCV technology/H_2 infrastructure deployment, which accelerate worldwide.

The scenario based on these assumptions begins with the production activities of a single H_2 FCV manufacturer, as outlined above:

- *2000-2004*: 10 FCVs are produced annually "by hand" for small fleet demonstrations.

- *2005-2009*: 10,000 FCVs are produced annually in a pilot manufacturing facility.

- *2010*: 300,000 FCVs are produced annually in the first commercial factory.

- *After 2014*: When LCC parity[27] has been reached with the gasoline ICE/HEV, both measures internalizing environmental damage costs and aggressive (~ 50%) ZEV

[27] Assuming lifecycle costs include air pollutant and GHG damage costs.

mandates are enacted in growing numbers of regions around the world, and the H_2 FCV becomes the technology of choice for meeting these mandates.

- *2015-2019*: Three new factories, each producing 300,000 H_2 FCV drive trains per year, go into operation each year to meet the growing demand for ZEVs, and sales into markets served by distributed refueling stations begins.

- *By 2020*: H_2 FCVs become cost-competitive without taking into account the environmental benefits they offer.

- *2020-2025*: The number of new H_2 FCV drivetrain factories going on line increases to ten per year, with new sales targeted for countries with policies that do not yet internalize environmental damage costs.

Under this optimistic scenario, percentages of H_2 FCVs in the overall global car population are 0.7% in 2015, 3.3% in 2020, and 9.7% in 2025, when there would be 130 million FCVs on the road worldwide.

This scenario exercise shows that, even under optimistic circumstances, the H_2 FCV will not be able to "solve" the environmental and energy insecurity problems posed by today's ICEVs during the first quarter of this century.

But the gasoline ICE/HEV now coming onto the market offers *significant* benefits that *are* realizable in mass markets in this period—lower direct economics costs, a 50% reduction in air pollutant damage costs, and a factor of two reduction in GHG emissions, along with a major reduction in energy insecurity risk, as a result of the doubling of the fuel economy compared to conventional ICE cars (see Table 1). As discussed in the larger study from which this paper is derived (Ogden, Williams, and Larson, 2001), alternative interim fuel/engine strategies based on the ICE (such as ICE/HEVs fueled with either compressed natural gas or ethanol derived from woody biomass) come up short in comparison to gasoline ICE/HEVs—largely because they pose significant risks that the interim investments needed for fuel infrastructure development might end up being stranded assets on a path to zero emissions for transportation. The larger study concludes that the gasoline ICE/HEV appears to be the interim fuel/engine technology combination of choice on the path to a H_2-based transportation system, both because of the significant near-term environmental and energy security benefits it offers and because its successful commercialization would help pave the way to H_2 FCVs because of the experience it would provide with electric drives.

This scenario exercise also shows that, by 2025, the H_2 FCV could be poised *to solve* the environmental and energy security problems posed by the gasoline ICEV sometime during the second quarter of this century. Under this scenario, annual worldwide sales of H_2 FCV sales grow from 3 million in 2015 (3.3% of car sales worldwide) to 9.6 million in 2020 (9.3% of worldwide sales) to 25 million in 2025 (20% of worldwide sales). Continuing on this track, the H_2 FCV could come to dominate automotive sales throughout much of the second quarter of this century.

And finally, this exercise shows that without an aggressive effort to launch H_2 transportation technologies in the market in the near term (e.g., with implementation rates comparable to those for this optimistic scenario), bolstered by appropriate public policies, solving, during the second quarter of this century, the environmental and energy security problems posed by present transportation technologies will not be possible.

Public Policy for Bringing about a Transition to Near-Zero Emissions

Developments in recent years suggest strongly that a long-term goal of zero or near-zero emissions for transportation might be within reach, with an appropriately focused technological innovation effort for the transport sector. Government has major roles in encouraging such innovation, because the private sector tends to invest in the innovative process at less than socially optimal levels. Private firms cannot appropriate the full benefits of such investments (free-rider problem); and, especially important in relation to the quest for near zero-emissions in transportation, private firms may not invest adequately in innovation needed to reduce costs not reflected in market prices (such as environmental costs). At the same time, the private sector, not the government, should be the primary agent for such innovation to facilitate technology transfer from the laboratory to the market. The government's role should be restricted to establishing zero or near-zero emissions as a broad long-term societal goal for transportation and to providing effective incentives that represent efficient use of public-sector resources in support of the innovation process.

The United States has had a decade of experience with the quest for zero emissions in transportation, in the form of the ZEV mandates in California and the other states that have followed California's lead. Under these mandates, about 80,000 new ZEV passenger cars and light trucks must be sold each year in California, New York, Massachusetts and Vermont, beginning in 2003 (assuming that 4% of new car sales must be ZEVs). The quest has proved to be more difficult than was originally envisioned, in that the mandates have not launched their original target, the battery-powered electric vehicle, as a viable commercial product suitable for displacing the ICEV except in niche markets. But the ZEV mandates have been enormously helpful in advancing electric-drive technology, in catalyzing industrial interest in FCV technology, and, more generally, in persuading an increasing number of private- and public-sector leaders that the seemingly elusive goal of zero emissions for transportation might indeed be within grasp in the form of the FCV.

Prioritization of engine/fuel developmental activity to be consistent with a transition over the longer term to zero or near-zero emitting technologies is desirable, in order to allocate more efficiently scarce private and public resources that might be utilized to bring low-polluting vehicles and fuels into wide use. At the same time, there is much uncertainty regarding technological outcomes, so that a portfolio approach to technology development policy is warranted.

Policy initiatives are needed for the entire chain of innovation activities. Public sector support is warranted not only to promote widespread dissemination of newly commercial clean technologies, but also to encourage early deployment for commercially ready clean technologies for which costs are still high, and to encourage research, development, and demonstration for advanced concepts that offer promise in relation to goals for transportation. And perhaps most importantly, political leadership is needed to establish as a societal goal the realization over the longer term of a transportation system characterized by zero or near-zero emissions.

Widespread Dissemination

Once candidate alternative technologies for achieving near-zero emissions are established in the market, the major challenge for policy is to level the playing field among the options, which requires means of internalizing environmental (and other) damage costs in consumer decisionmaking. There are several alternative options for accomplishing this "leveling of the playing field"—including regulation, fuel taxes, taxes on vehicles, feebates, and feebate/clean technology mandate combinations—each of which will be considered in turn.

Regulation. Technology-forcing regulation represents one approach for promoting the dissemination of clean engines and fuels. Perhaps the most familiar technology-focusing regulation relating to clean engines and fuels at the state level in the United States is the ZEV mandate. Heretofore the ZEV mandate has been used as an instrument to promote early deployment (technology cost buydown—see below) of ZEVs; in this application, the mandate must be restricted to a small (but growing) percentage new vehicle purchases.

But the ZEV mandate might also be used to promote widespread deployment of zero-emitting technologies once their costs have been bought down to market clearing levels (i.e., LCC parity with environmental damage costs internalized). As noted earlier, after H_2 FCV costs have been bought down, very rapid market growth in high population density regions is needed to facilitate H_2 refueling infrastructure development. Rapid market growth might be most easily accomplished with aggressive (~ 50%) ZEV mandates for such regions.

Fuel taxes. Many economists argue that the most efficient way to cope with externalities is to internalize them in market prices—e.g., by taxing emissions at the damage cost rates and making the emissions tax a part of the fuel price.

The revenues raised by such taxes would be a significant fraction of total tax revenues of a country. For example, U.S. federal revenues from a $100 per tC carbon tax would, in 2000, amount to about $160 billion, about 8 percent of total expected federal tax revenues for that year. The adoption of such taxes would probably be via tax shifts—e.g., shifts to taxes on emissions ("bad things") and away from taxes on labor and capital ("good things"). Because the "bad things" do not represent a stable tax base (i.e., emission tax revenues would fall to near zero as emission rates fall to near zero as a consequence of technological advance), emission taxes would probably be implemented in ways that offset revenue requirements from traditional tax sources, rather than by replacing existing revenue-raising tax structures entirely. Such tax shifts would have to be crafted carefully to avoid significant economic disruptions. Moreover, any shift would generate both winners and losers and so would be politically contentious, and it might take a long time to reach political consensus.

Vehicle taxes. Risks of economic disruption and political challenges might be reduced while still leveling the playing field if, instead of taxing fuels generally, lifecycle emissions costs were charged against new car owners at the time of new car purchase. If emissions costs were manifest as taxes on all new light-duty vehicle purchases at the rates indicated in Table 1 for our base-case analysis, the initial average tax would be about $4000 per car (about 20% of the average new car price in 1997), assuming that the average car today is a 22 mpg gasoline ICEV; and the total tax levy on the 15 million new light-duty vehicles sold each year would initially be about $60 billion per year. This is still sufficiently large that it would require a major tax shift that would take considerable time to put into place, both to achieve political consensus regarding the desirability of the tax and subsequently to work out the details of its implementation.

Feebates. A near-term approach that could avoid entirely the complications of a tax shift and might be considered as a first step along a path toward a tax shift over the longer term would be a revenue-neutral system of "feebates" that would tax polluting vehicles and use the tax revenues to provide tax incentives for the purchase of vehicles characterized by low emissions.

To see how a feebate system might work, suppose that 15 million light-duty vehicles are sold each year in the United States—14 million of which are conventional 22.4 mpg gasoline ICEVs and 1 million of which are 46.9 mpg gasoline ICE/HEVs (see Table 1). Suppose further that conventional gasoline ICEVs are taxed to the extent needed to provide incentives for the ICE/HEVs that reflect the environmental benefits they offer compared to conventional gasoline ICEVs (see Table 1). The incentive offered for purchase of a gasoline ICE/HEV would be:

$$\$3998 - \$1899 \sim \$2099,$$

while the tax on each new conventional gasoline ICEV required to pay for this incentive would be:

$$(1 \text{ million cars})*(\$3998-\$1899)/(14 \text{ million cars}) \sim \$150 \text{ per car}.$$

Although this emissions fee on conventional ICEVs would represent only about 4 percent of the estimated environmental damage cost of the conventional cars and thus would not provide the "correct" incentive to would-be car purchasers not to purchase a conventional car, the feebate would give an appropriate market signal to the purchaser of the ICE/HEV, and politically it would be far easier to it adopt this feebate scheme than one that would tax all new vehicles at the full environmental damage cost rates.

With this scheme, the tax on conventional cars would be low at first (because there would be few low-polluting cars on the market) but would rise over time as the number of alternative vehicles grows. One might consider evolving from a feebate system to a more economically efficient tax-shift arrangement by the time the tax on conventional cars under a feebate scheme approaches the full environmental damage cost (in this instance, ~ $4000 per car).

A feebate system or a feebate scheme that evolves over time into a tax shift scheme would be relatively economically efficient, it would satisfy the policy criterion that a portfolio of clean technology options be supported by appropriate incentives, and it would be "fair" toward all clean technologies that are fully established in the market: it would "level the playing field" for them.

Feebate/zero emission vehicle mandate combinations. Regulatory and price incentive schemes are not necessarily mutually exclusive options and might be considered instead as complementary measures. For example, a mandate requiring that some percentage of new car purchases be ZEVs coupled to a feebate scheme that would make such vehicles more affordable to consumers would provide a much more powerful incentive to vehicle manufacturers to produce such vehicles than would either of these measures alone.

Early Deployment

A feebate policy that provides incentives to clean vehicle/fuel technologies equal to the environmental benefits they offer, by itself would not be fair to radically new technologies such as H_2 FCVs that would initially be far more costly than various ICE/HEV hybrids, which involve relatively modest departures from existing ICEV technologies.

For a radically new technology one might argue that private firms should be willing to forward price the product initially in order to capture market share later. Indeed, it is very likely that there would be some degree of forward pricing of clean vehicles when they first come onto the market. However, a private firm will not forward price to the extent that is optimal from a societal point of view, because of the great difficulty it would have in preventing competitors from reaping some of the benefits of its investments in technology cost buy down. The improvements that lead to lower cost cannot easily be kept secret, so that some of the benefits of investment in technology cost buy down would be appropriated by competitors. In addition, private firms may be reluctant to forward price both because they do not have enough information to determine with confidence: (*i*) how far costs will fall as a result of mass production in factories, cumulative experience ("learning by doing"), and continual marginal technological improvement; and (*ii*) what values society will put on the environmental benefits offered by the technology.

Such considerations indicate that for radical new (and thus initially very costly) technologies that offer potentially large societal benefits, some degree of public-sector support for technology cost buydown is warranted (Duke and Kammen, 1999; PCAST ICERD[3] Panel, 1999).

The H_2 FCV appears to be a technology that would qualify for such technology cost buy-down support. The technical analysis presented in this paper indicates that: (*i*) even with environmental damage costs fully internalized, the cost of buy down for H_2 FCVs would be of the order of $2 billion and would require a market large enough to absorb more than 1 million vehicles, (*ii*) it would be desirable to focus the buy-down effort on centrally refueled fleets in order avoid the formidable problems of H_2 fuel infrastructure development during the buy-down process.

Particular attention might be given to a "policy package" that couples a small but growing ZEV mandate to financial incentives for deploying ZEVs in centrally refueled fleet markets. Notably, as indicated in Figure 9,[28] the ZEV market in states that have ZEV mandates is comparable to the projected markets for centrally refueled fleets of autos and light trucks in these states, so that a policy coupling ZEV mandates and fleet incentives for ZEVs appears to be promising.

Policies are already in place aimed at using fleets to help launch clean engines and fuels in the market. The Energy Policy Act of 1992 (EPAct) requires that alternative fuels be phased in for use in certain centrally refuelable fleets of more than 25 vehicles. About 1 million new vehicles per year are subject to these rules; about half of these are cars, and half are trucks. And, under the Clean Air Act Amendments of 1990, a number of state-based initiatives are in place to encourage use of lower polluting alternative fueled fleets, such as the "Clean Cities" program. A problem with the existing fleet market incentives is that they are diffuse ("letting a thousand flowers bloom") and generally not focused on radical innovations (although "extra credits" are sometimes given for ZEV vehicles) with appropriate financial incentives.

Key to success is likely to be the "appropriate financial incentive." The appropriate amount of public-sector support for clean technology cost buy down is not easily determined, but some general guidelines seem clear. First, there should always be a substantial contribution to the total buy-down cost from the private firms involved, demonstrating their conviction that eventually there will be a viable commercial product (otherwise the risk would be too great that the public-sector investment would be wasted on a technology that never makes it into the market). Second, the required public-sector investments should be "affordable" (i.e., relatively modest). Third, the public-sector support should be temporary, with a declining level of subsidy over time that is specified in advance. And fourth, for a given technology, the buy-down support policy should be reviewed periodically during the buy-down process, to ascertain whether sufficient progress is being made to warrant continued support or if instead the appearance of seemingly insurmountable hurdles on the path to a commercial product indicates that support should be discontinued.

A financial incentive for technology cost buy down that would satisfy these criteria is a variant of the feebate discussed above for environmental damage benefits. Suppose, for example, that when a radical new clean automotive technology is first introduced into the market (before mass produced cost levels are realized), the total incentive provided by government is some time-varying multiple $X(t) > 1$ of the environmental damage benefit offered relative to the typical new car on the market, with the multiplier of the damage cost declining to $X(t) \longrightarrow X(T) = 1.0$ after a period of T (a few) years, as the technology becomes established in the market.

Public-sector expenditures needed to buy down hydrogen fuel cell vehicle costs. How much would buy down cost the government in helping launch in the market H_2 FCVs, which will initially be the most costly of all the advanced technologies considered in this study? To address this question assume that at the time the H_2 FCV is launched in the market, the technology being displaced is the gasoline ICE/HEV (rather than today's gasoline ICEV). Assume also that the feebate scheme described in the previous section for providing environmental incentives is in effect.

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[28] Figure 9 shows projections of centrally refueled fleet and ZEV markets for California, New York, Massachusetts, plus Vermont. The projected ZEV market is based on the assumption that 10% of new cars and light trucks must be ZEVs.

For the base-case analysis, it was estimated that some 1.2 million H_2 FCVs would have to be sold before the H_2 FCV would be competitive under these conditions, and that the total buy down cost would be $1.56 billion—about $1300 per car on average. If the private firms involved were to forward price these cars to the extent of half the total buy-down cost, the government's contribution would be $0.78 billion or $650 per H_2 FCV, on average, during the buy-down period, so that the total buy-down incentive provided by government in this period (environmental feebate + buy-down incentive) would average about $2050 per car, and the average value of X(t) during the buy-down period would be about 1.5.[29]

The buy-down subsidy might be paid directly out of general tax revenues, or an earmarked buy-down tax might be levied on conventional cars. Assuming total annual light-duty vehicle sales amount to 15 million vehicles per year, this buy-down tax would average about $6 per new car[30]—which is quite modest in relation to the cost of environmental feebates to purchasers of conventional cars.

A shortcoming of the buy-down cost calculation presented above is that it is for one H_2 FCV manufacturer. Government would probably never subsidize just one manufacturer but would insist that there be competition. Because there would probably be some spillover of technological knowledge among producers, the incentive required to support N producers would probably be less than N times the incentive required to support one producer. Thus if N = 3, the buy-down tax on conventional vehicles would be less than $20 per new car—which would probably still satisfy the affordability criterion.

Of course, in this base-case calculation, buy down is accomplished in a relatively short period, and the actual buy-down cost might turn out to be more. However, government liability for providing buy-down incentives would be limited by the initial value it specifies for X(0), by the

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29 In this instance, the environmental damage feebate would be (see Table 1):

feebate = damage cost (gasoline ICE/HEV) – damage cost (H_2 FCV) =

$1899-$501 = $1398 per car.

Added to the buy-down incentive described in the text above, the total is about $650 + $1398 = $2048 per car. Thus, the average X(t) during buy-down is given by:

X(t) = (environmental feebate + buy down incentive)/environmental feebate = $2048/1398 = 1.46

30 The buy-down tax rate is calculated as follows. The total number of H_2 FCVs that must be produced to reach market clearing levels in competition with gasoline ICE/HEVs is estimated to be 1.244 million, and the estimated buy-down cost is $1560 million, of which $500 million occurs during the operation of the pilot FCV manufacturing plant that produces 10,000 vehicles per year over a 5 year period, and the rest of which occurs during 4.0 years of operation of the full-scale commercial FC vehicle manufacturing plant that produces 300,000 vehicles per year. Assuming that the tax covers half the buy-down cost and that total vehicle production is 15 million vehicles per year, made up only of gasoline ICE/HEVs and H_2 FCVs, the average buy-down tax penalty on the purchase of gasoline ICE/HEVs during this 9.0 year buy-down period is:

($1560 million)/[(9.0 y)*(15 million/y) - 1.244 million]/2 = $5.8 per car.

term T it specifies during which X must decline to X(T) = 1.0, and by the results of periodic reviews it conducts of buy-down progress for specific technologies to determine whether continued subsidy is warranted.

Buying down the costs of hydrogen fuel cell vehicles in centrally refueled fleets. The next 10-15 years might be targeted as the period in which technology costs are bought down for H_2 FCVs, via their expanded deployment in centrally refueled fleet markets, as discussed above.

Research, Development, and Demonstration

In parallel with activities aimed at widespread dissemination of commercial clean vehicle/fuel technologies and at accelerated technology cost buy down for radical near-commercial technologies, considerable investment in research, development, and demonstration is needed to increase prospects of realizing the near-zero emissions goal for transportation (PCAST Energy R&D Panel, 1997).

High priority should be given to advanced onboard H_2 storage technologies for cars, to advanced technologies for making H_2 from a wide range of feedstocks (including natural gas, petroleum residuals, heavy oils, coal, biomass, muncipal solid wastes, and renewable electric sources), and to options for reducing the costs of CO_2 separation in H_2 manufacture and to increasing the capacity for its secure disposal in geological formations. And high priority should be given to critical study of the security, safety, and environmental impacts of alternative strategies that offer promise in realizing the long-term goal of near-zero emissions for transportation—but especially of strategies for geological sequestration of CO_2 and large-scale production of biomass for H_2 production in the quest for near-zero emissions.

Implications for Developing Countries

And finally, in the pursuit of a near-zero emissions transportation system, attention should be given to applications of promising engine/fuel technology combinations for developing countries. Many developing country cities today have severe air-quality problems that would be greatly exacerbated under business-as-usual conditions for future transportation, in light of the expected explosive growth in the demand for transportation services there.

If industrialized countries could successfully develop and bring to market near-zero emissions technology for transportation over the next 10-15 years, and if policies were enacted to promote the transfer of such technology to developing countries, those countries would have the opportunity to “leapfrog” then to state-of-the-art super-clean transportation technologies. Developing countries could avoid retracing the evolutionary path of the already industrialized countries, where, over the last 30 years, environmental goals in transportation have been met largely by the costly means of continually ratcheting up in the regulatory process levels of mandatory controls on end-of-pipe pollutant emissions.

But providing the near-zero emission transportation technology needed by developing countries 15+ years from now would require extensive collaborative international research, development, and demonstration activities in the interim, to shape such technology to the conditions and needs of developing countries (PCAST Panel on International Cooperation in ERD[3], 1999). Whereas the automobile is the focus of clean vehicle/fuel development in the industrialized countries, the dominant modes of transportation in developing countries are instead small passenger vehicles (e.g., two- and three-wheeled vehicles), buses, trucks, and locomotives—the mix of which varies markedly from region to region. All of these, as well as cars, would have to become foci of serious international collaborative developmental efforts [e.g., via international industrial joint ventures and new public-/private-sector partnerships (including international partnerships involving participants from both industrialized and developing countries, as well as from international agencies such as the World Bank and the Global Environment Facility)] during the next 10-15 years in order to provide a basis for technologies characterized by near-zero emissions subsequently playing major roles in the transport sectors of developing countries.

Conclusion

This study has shown that there are plausible futures for transportation based on advanced technologies, notably H_2 FCV-based futures, that could provide transportation services at direct economic costs that are not much higher than at present but that offer the potential for near-zero emissions of both air pollutants and greenhouse gases, while simultaneously making it possible to diversify transportation energy away from the present near-exclusive dependence on oil.

The analysis highlighted the critical importance of environmental concerns as a driver for radical technological innovation in automotive technology—showing that the most likely future in which the H_2 FCV emerges as a major option is in response to strong policy measures (e.g., ZEV mandates plus environmental damage cost feebates) that would steer the course of motor vehicle technological innovation toward technologies characterized by near-zero emissions.

The analysis focused on the automobile. However, many of the most promising technological options considered—including H_2 and FCVs—are also relevant for developing countries, both for passenger transportation (dominated today by small vehicles, buses, and trains) and for freight transportation [dominated today by transport vehicles (e.g., Diesel-powered trucks) that generate large and human-health-damaging amounts of air pollutant emissions].

Thus the technological options considered here have potentially wide-ranging applications. But new public-/private-sector partnerships, including international partnerships involving participants from both industrialized and developing countries, as well as from international agencies such as the World Bank and the Global Environment Facility, are needed to make the goal of near-zero emissions a realistic option.

A set of policies for converting these options into realizable transportation system futures has been suggested in this study. Implementation of these or similar policies could put the world's transportation system on a path that could make the goal of near-zero emissions realizable during the second quarter of this century.

Acknowledgments

For helpful comments on earlier drafts of this paper, the authors thank Andrew Armstrong (BP), Roger Cracknell (Shell Hydrogen), Mark Delucchi (University of California, Davis), David Hart (Imperial College), Thomas Kreutz (Princeton University), Ari Rabl (Ecole des Mines), Jeff Rinker (BP), Marc Ross (University of Michigan), Ron Sims (Ford Motor Company), Robert Socolow (Princeton University), Sandy Thomas (Directed Technologies, Inc.) and Michael Wang (Argonne National Laboratory). For research support the authors thank the W. Alton Jones Foundation, the Geraldine R. Dodge Foundation, the Energy Foundation, the David and Lucile Packard Foundation, and the United States Department of Energy Hydrogen R&D Program.

TABLES

Table 1. Lifecycle Costs for Alternative Fuel/Engine Combinations for Cars (*$ per car*)

Alternative Fuel/Engine Technological Options[a] [*gasoline equivalent fuel economy (in mpg) and fuel price (in $/gallon of gasoline equivalent)*]	**Lifetime environmental damage costs for fuel cycle**[a,b]			**Present value of lifetime fuel costs**[c]	**Retail Cost of drivetrain**[d] **(***including fuel storage***)**	**Total lifecycle costs**			
	Air pollution = ExternE Median Value	GHG emissions	Total			Without environmental damage costs	With environmental damage costs		
							Pollution Only	GHG Only	Pollution & GHG
Current gasoline SI ICEV (22.4 mpg, $0.95/gal)	2563	1435	3998	3408	2837	6245	8808	7680	10243
Advanced ICE/Hybrid Electric Vehicles									
Gasoline SIDI ICE/HEV (46.9 mpg, $0.95/gal)	1196	704	1899	1627	2837 + 1342	5807	7002	6510	7706
CNG SI ICE/HEV (48.6 mpg, $1.19/gge)	685	547	1232	1986	2837 + 1556	6380	7065	6927	7612
H_2 (NG) SI ICE/HEV (50 mpg, $1.96/gge)	461	484	945	3163	2837 + 2780	8780	9241	9264	9725
H_2 (NG) ICE/HEV (50 mpg, $2.19/gge) w/ CO_2 Seq.	461	114	575	3532	2837 + 2780	9149	9610	9263	9724
Diesel CIDI ICE/HEV (56.8 mpg, $0.83/gge)	1078	581	1659	1174	2837 + 1863	5873	6952	6454	7533
FT50 (NG) CIDI ICE/HEV (56.8 mpg, $0.88/gge)	905	586	1491	1369	2837 + 1863	6070	6975	6656	7561
Fuel Cell Vehicles									
Gasoline FCV (38 mpg, $0.95/gal)	242	849	1091	2009	2837 + 5097	9943	10185	10792	11033
Methanol (NG) FCV (56 mpg, $1.56/gge)	171	557	728	2238	2837 + 3220	8295	8466	8852	9023
H_2 (NG) FCV (82 mpg, $1.96/gge)	206	295	501	1928	2837 + 2459	7225	7431	7520	7726
H_2 (NG) FCV (82 mpg, $2.19/gge) w/$CO_2$ Seq.	206	69	276	2153	2837 + 2459	7450	7656	7519	7726
H_2 (wind electrolytic) FC (82 mpg, $3.46/gge)[e]	0	0	0	3180	2837 + 2459	8477	8477	8477	8477

[a] Automotive fuel economy and fuel cycle emissions estimates are based on Argonne National Laboratory's GREET1.5 Transportation Fuel-Cycle Model for current internal combustion engine vehicles (ICEVs), advanced internal combustion engine/hybrid electric vehicles (ICE/HEVs), and fuel cell vehicles (FCVs), except for the following, which were developed to be consistent with the GREET framework: (*i*) a case has been added involving H_2 ICE/HEVs based on estimates developed at Directed Technologies, Inc; (*ii*) cases have been added involving geological sequestration of the CO_2 byproduct of H_2 manufacture (the amount of CO_2 sequestered amounts to 85% of the CO_2 that would otherwise be released to the atmosphere at the plant where H_2 is made from natural gas—see Table 3) for both ICE/HEVs and FCVs fueled with H_2 derived from natural gas; (*iii*) a FCV option has been added involving use of electrolytic H_2 derived from wind power at projected wind power costs for 2030 (see note e); (i*v*) the fuel economy of the CNG ICE/HEV was adjusted upward from the GREET estimate of 40.8 mpg to 48.6 mpg in light of detailed vehicle modeling results by DTI (Thomas *et al.*, 1998b) and MIT (Weiss *et al.*, 2000), (*v*) estimates of FCV fuel economies are taken from DTI (Thomas *et al.*, 1999) rather than GREET. For each case where the fuel economy differs from the GREET value, GREET upstream emissions are scaled by the ratio of the GREET fuel economy to the new fuel economy.

[b] Pollution damage costs ($ per kg) are median estimates of damage costs based on ExternE studies, adjusted for US population densities. GHG emissions are assigned a value of $100 per tC; this represents the cost penalty, with the least costly current technology, for reducing CO_2 emissions to near-zero via decarbonization/CO_2 sequestration at coal-fired power plants.

Notes to Table 1, cont.

[c] It is assumed that cars are driven 12,000 miles per year for 10 years. The present value of lifecycle environmental damages is calculated for a 3 percent discount rate [in accordance with guidelines established for the ExternE studies (Spadaro and Rabl, 1998b)], whereas the present value of the lifecycle fuel cost for the car is evaluated for an 8% discount rate (appropriate for valuation of private consumer costs), so that the present value of the fuel cost is 0.671 times the present value evaluated for zero discount rate.

[d] See Table 2 for details regarding projected manufacturing costs and retail costs for drive trains.

[e] The windpower busbar cost for Class 6 winds (6.4 to 7.0 m/s average wind speed at 10 m) projected for the United States in 2020 by the EPRI and the U.S. DOE (EPRI/OUT, 1997) is 2.4¢ per kWh (down from a cost of 4.9¢ per kWh in the US in 1997 for this wind class)—see Table 5.1, page 5-6, in the 1999 report of the PCAST Panel on International Cooperation in ERD^3 (PCAST $ICERD^3$ Panel, 1999). It is assumed that this wind power in combination with compressed air energy storage technology is converted to baseload electricity (Cavallo, 1995) and transmitted at a delivered cost of 3.4 ¢ per kWh[31] to a city-gate plant, where H_2 would be made electrolytically from this electricity. From a study by Foster Wheeler (1996) [except that the FW results are presented here with all energy quantities expressed on a HHV basis (whereas the original FW report presented energy quantities on a LHV basis)], the cost C_{EH} ($ per GJ, HHV) of electrolytic H_2 produced from electricity at a price P_E (in $ per kWh) is given by $C_{EH} = \$3.52 + P_E/(\eta*0.0036$ GJ per kWh), where $\eta= 0.739$ = efficiency of converting electricity into H_2 (95.7% of electricity input is for the electrolysis plant, 4.2% is for compressing the H_2 to 60 bar, and 0.01% is for pumping the cooling water supply). Thus for $P_E = \$0.034$/kWh, $C_{EH} = \$16.30$/GJ. Assume, as in the case of H_2 derived from natural gas (see Table 3b) that the delivered H_2 price is $7.63/GJ more, or $23.93/GJ total, which is $3.46 per gallon of gasoline equivalent.

[31] For comparison, the busbar electricity cost would be 3.4 ¢/kWh for a combined cycle power plant burning natural gas (Williams, 2000) at the projected average U.S. natural gas price of $3.40/GJ for electric generators in 2020 (EIA, 2000a).

Table 2. Drive Train Costs (*$ per car*) for Alternative Vehicles[a]

	Manufacturing Cost of Components								Aggregate Costs	
	Fuel Cell System	Fuel Pro-cessor	ICE & Auxiliaries	Trans-mission	Fuel Tank System	Motor/Controller (includes generator for ICE/HEVs)	Peak Battery System	Controls	Total Drive Train Mfg. Cost	Retail Drive Train Cost[f]
Conventional Gasoline ICEV (100 kW)[b]	0	0	1600	700	125	0	0	0	2425	2837
Gasoline SIDI Hybrid [b,c]										
Series Hybrid (Thermostat)	0	0	954	200	125	1612	1574	150	4615	2837 + 2562
Series Hybrid (Load Follow)	0	0	939	200	125	1528	695	150	3636	2837 + 1417
Parallel Hybrid	**0**	**0**	**890**	**700**	**125**	**1053**	**654**	**150**	**3572**	**2837 + 1342**
Natural Gas ICE/HEV[b,d]										
Series Hybrid (Thermostat)	0	0	950	200	386	1587	1537	150	4810	2837 + 2790
Series Hybrid (Load Follow)	0	0	935	200	369	1567	680	150	3901	2837 + 1727
Parallel Hybrid	**0**	**0**	**887**	**700**	**334**	**1043**	**642**	**150**	**3756**	**2837 + 1557**
H_2 ICE/HEV[b,d]										
Series Hybrid (Thermostat)	0	0	959	200	1741	1637	1517	150	6204	2837 + 4421
Series Hybrid (Load Follow)	0	0	942	200	1616	1549	669	150	5125	2837 + 3159
Parallel Hybrid	**0**	**0**	**893**	**700**	**1363**	**1067**	**629**	**150**	**4801**	**2837 + 2780**
CIDI ICE/HEV[b,d]										
Series Hybrid (Thermostat)	0	0	1432	200	125	1612	1574	150	5093	2837 + 3121
Series Hybrid (Load Follow)	0	0	1408	200	125	1528	695	150	4106	2837 + 1967
Parallel Hybrid	**0**	**0**	**1334**	**700**	**125**	**1053**	**654**	**150**	**4017**	**2837 + 1862**
Gasoline FCV (probable)[b, e]	2410	2129	0	200	128	966	798	150	6781	2837 + 5097
Methanol FCV (probable)[b,,e]	2006	950	0	200	157	943	771	150	5177	2837 + 3220
H_2 Fuel Cell Vehicle w/Peaking Battery[b,e]	1670	0	0	200	1073	906	728	150	4727	2837 + 2693
Purebred H_2 Fuel Cell Vehicle[b,e]	**2180**	**0**	**0**	**200**	**1096**	**901**	**0**	**150**	**4527**	**2837 + 2459**

[a] For cases where alternative options are available for a particular vehicle type, the option in bold was selected for more extensive analysis.

[b] With the exception of the gasoline SIDI Hybrid (see note c below), all vehicle component manufacturing costs are from (Thomas *et al.*, 1998b; Thomas, 1999). Costs are for an aluminum intensive vehicle "glider" (AIV).

[c] Our estimate for the gasoline SIDI hybrid is based on DTI estimates of component costs for Diesel hybrids, except that the Diesel engine is replaced by a 4-cylinder gasoline engine having the same power output. DTI analysts suggest that the manufacturing cost of 4-cylinder gasoline engines is $720 + 5.14*P, where P is output power in kW (Thomas *et al.*, 1998b).

[d] For ICE/HEVs, the best DTI case (parallel hybrid) is chosen for more extensive analysis. Cost values for the fuel tank are from Table 5, p. 16 in Thomas (1999). The other component costs are from Thomas, *et al.* (1998b).

[e] For fuel cell vehicles all component costs are from Thomas (1999). Levelized FCV costs are for a manufacturing plant producing 300,000 drive trains per year for 15 years.

[f] The retail cost is estimated to be 1.17 x the manufacturing cost.

Table 3a. Production of 60 Bar H_2 from Natural Gas, at 1000 MW_t of H_2 Output Capacity[a]

	Without CO_2 Sequestration	With CO_2 Sequestration[b]
H_2 Output/NG Input (%)	81	78
CO_2 Emission Rate (kg C/GJ H_2)	17.56	2.74
CO_2 Sequestration Rate (t CO_2 /h)	-	204
Capital Investment w/o CO_2 Disposal ($ million)	262	429
Capital for CO_2 Pipeline ($million)	-	36
Lifecycle Cost ($/GJ)		
Capital (except CO_2 Pipeline)	1.56	2.56
Capital for CO_2 Pipeline	-	0.21
O&M (except for CO_2 Disposal)	0.24	0.39
O&M for CO_2 Disposal	-	0.07
NG input[c]	4.20	4.36
Total	6.00	7.59

Table 3b: Delivered Cost of H_2 from Natural Gas (*$/GJ*)

Production Cost	6.00	7.59
Central H_2 plant compression from 870 psia (60 bar) to 1000 psia for storage or pipeline transmission ($/GJ)[d]	0.03	0.03
Central H_2 plant buffer storage cost ($/GJ), storage capacity = 1/2 day's output of H_2 plant[d]	0.41	0.41
H_2 pipeline distribution system[d]	1.58	1.58
Refueling station[,d,e]	5.61	5.61
Total cost of delivered H_2	$13.6/GJ (HHV basis) ($1.96/gallon of gasoline equivalent on a LHV basis)	$15.2/GJ (HHV basis) ($2.19/gallon of gasoline equivalent on a LHV basis)
Cost of CO_2 Pipeline and CO_2 Disposal[f]		$5.0/t CO_2
Cost of Avoided CO_2 Emissions	-	$107/tC

[a] From a study (Foster Wheeler, 1996) prepared for Statoil and the IEA GHG Programme except that: the Foster Wheeler (FW) results are presented here with all energy quantities expressed on a HHV basis (whereas the original FW report presented energy quantities on a LHV basis); the annual capital charge rate and system capacity factor are assumed to be 15% and 80%, respectively (compared to 12.4% and 90% in the original FW study), so that the annual H_2 production rate is 25.2 million GJ/year. For these systems all energy requirements for H_2 production are provided from natural gas.

[b] 85% of the CO_2 in the feedstock is recovered, compressed to 112 bar, and transported by pipeline to a disposal site in a depleted natural gas field 105 km from the H_2 production plant site.

[c] For a natural gas price of $3.4/GJ, the average natural gas price projected for U.S. electric generators in 2020 by the U.S. Energy Information Administration (EIA, 2000a).

[d] Based on Ogden (1999) high auto density case (1600 cars per square mile)—equivalent to half the cars I in the Los Angeles area being H_2 FCVs..

[e] For a refueling station dispensing H_2 at 345 bar to FCVs at a rate of 1 million scf/day.

[f] For a CO_2 disposal rate of 57 kg CO_2/GJ H_2 and a CO_2 disposal cost of $0.28/GJ H_2 (see Table 3a).

FIGURES

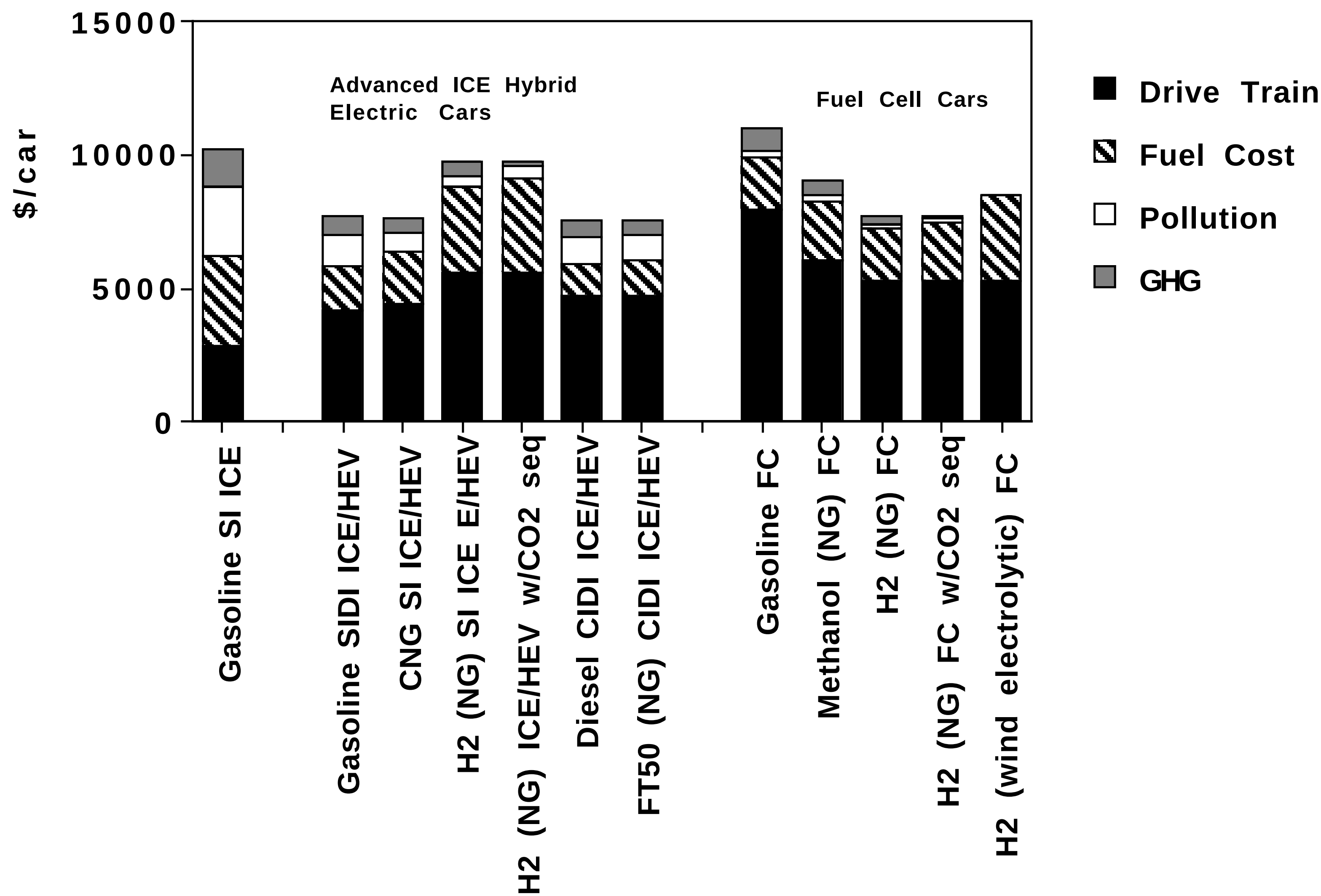

Figure 1. Total Lifecycle Costs for Some Alternative Vehicle/Energy Carrier/Primary Energy Combinations

Costs are from Table 1 with environmental damage costs included.

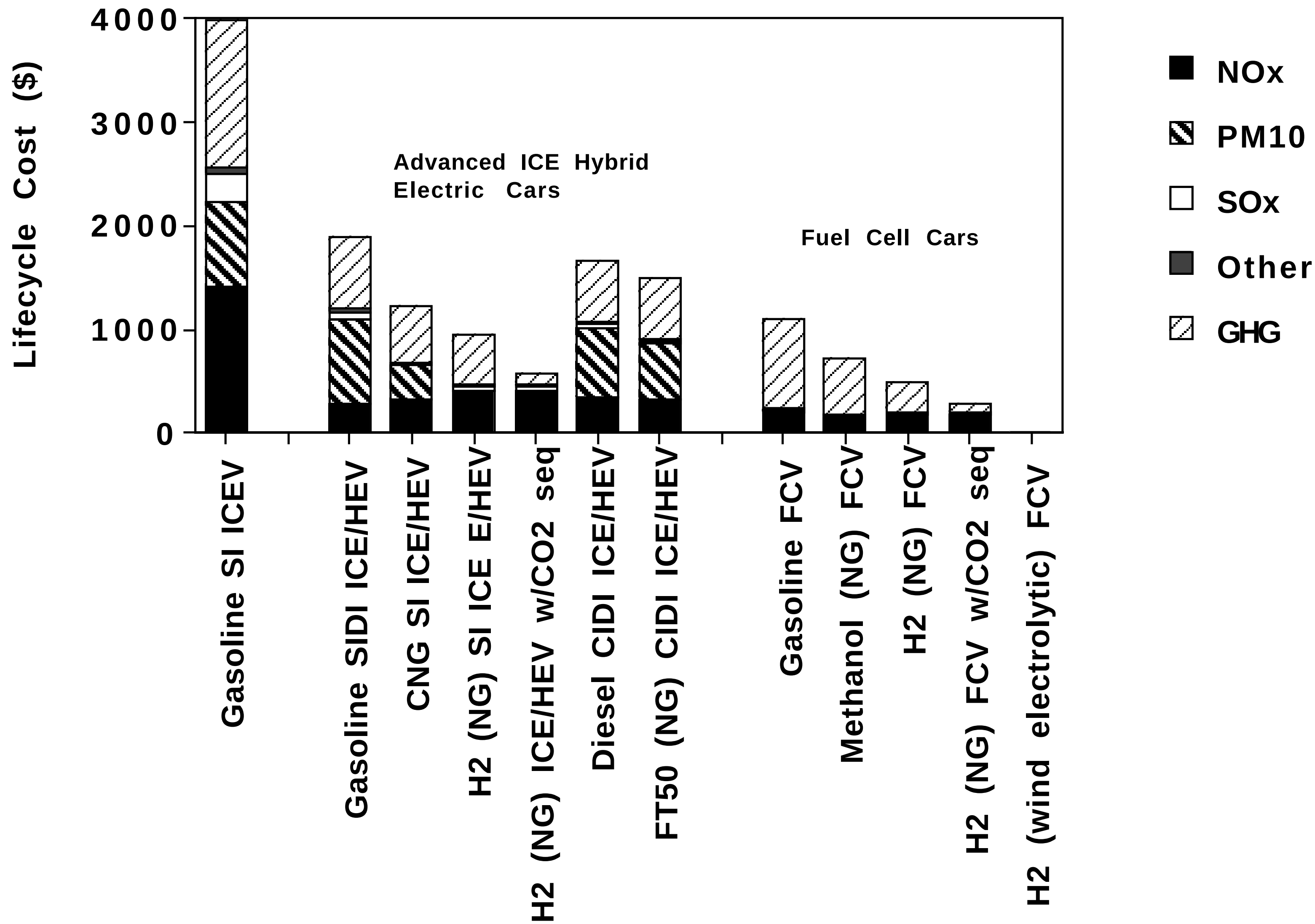

Figure 2. Lifetime Fuel Cycle Environmental Damage Costs for Alternative Vehicle/Energy Carrier/Primary Energy Combinations

From calculations presented in Table 1.

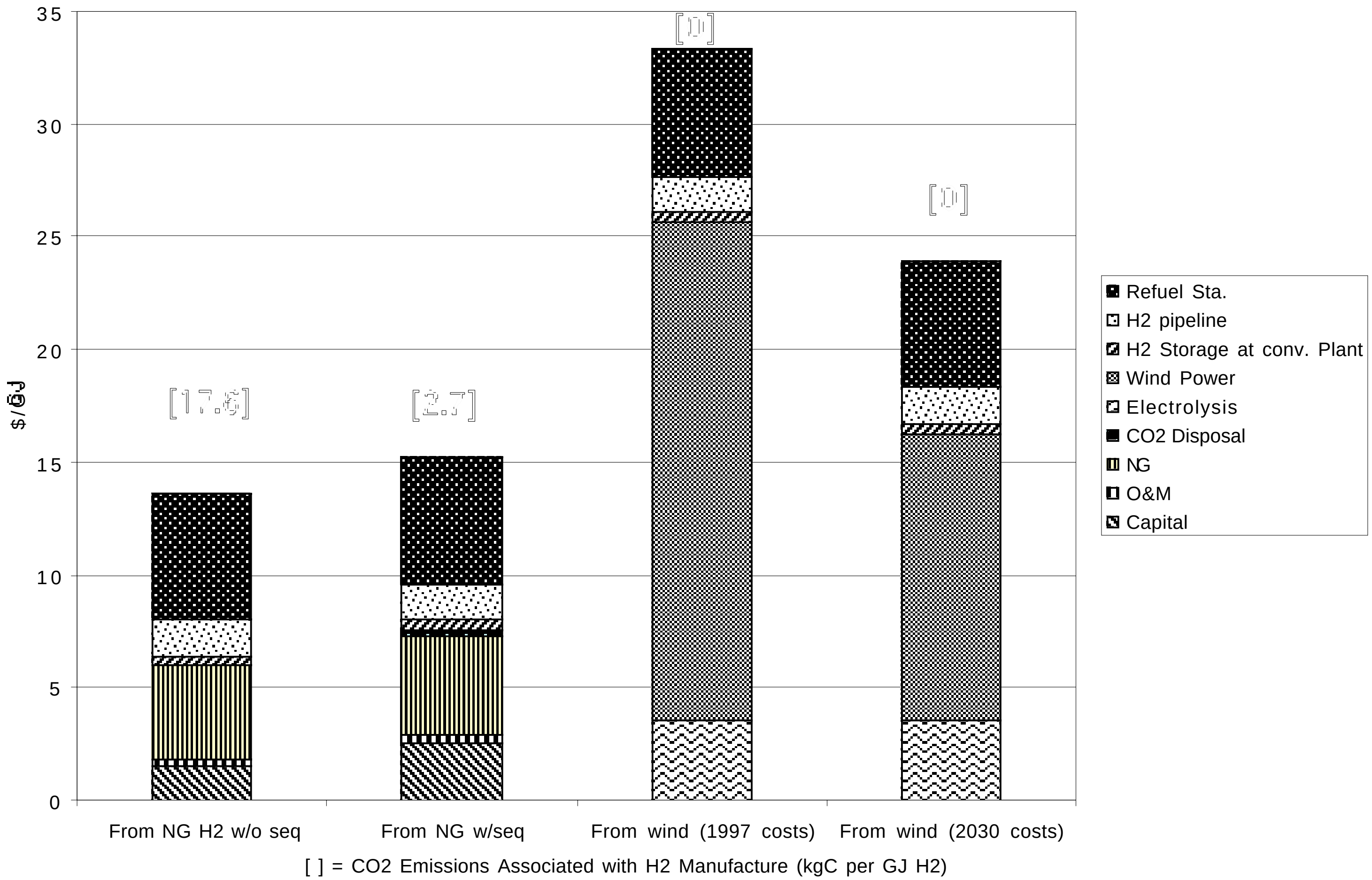

Figure 3. Cost of Hydrogen Delivered to a Refueling Station with Alternative Options for Making Hydrogen at a Centralized Factory

The first two bars are for H_2 produced thermochemically from natural gas, without and with CO_2 sequestration. The two bars on the right are for H_2 produced electrolytically from wind power at wind power prices for 1997 and projected for 2030 in the United States. Costs for natural gas-derived H_2 are from Table 3. Costs for H_2 generated electrolytically from wind power are from Table 1, note e.

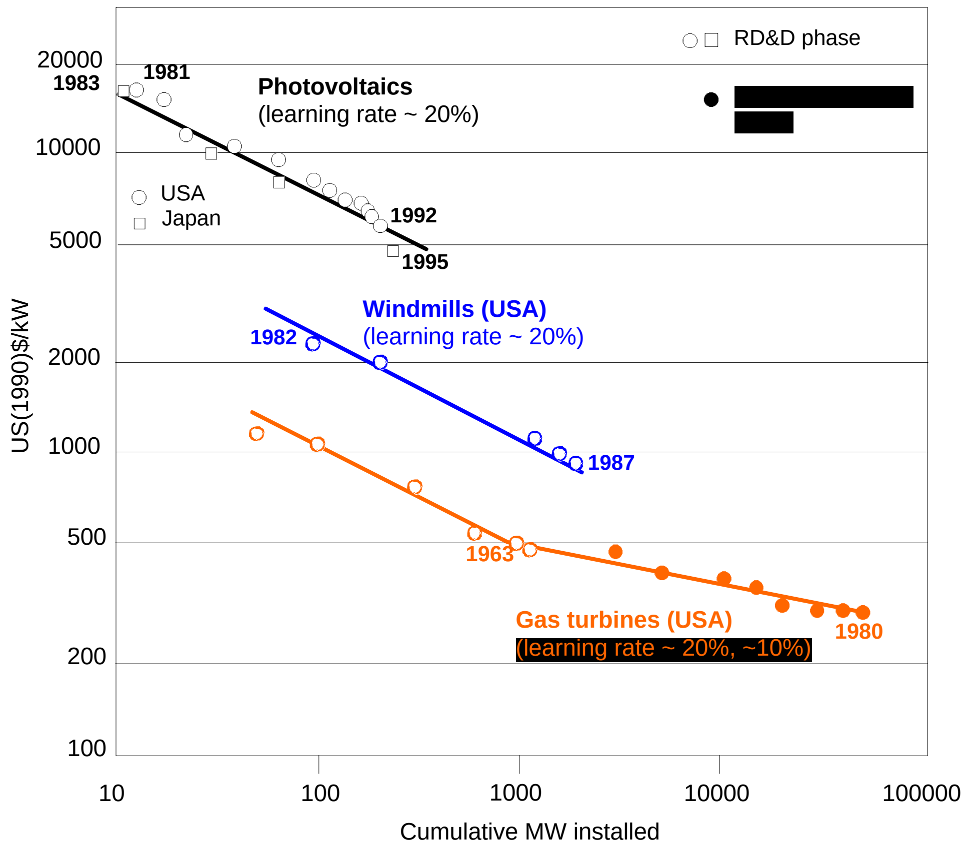

Figure 4. Learning Curve Relationships for Photovoltaics, Wind Generators, and Gas Turbines

These curves illustrate the well-established industrial phenomenon that, for new technological products that are amenable to the economies of mass production, production costs tend to decline with cumulative production (cost-cutting via "learning by doing"). Typically costs will be reduced 10 to 30 percent for each doubling of cumulative production of the technology. For all three of the technologies illustrated here costs declined initially at rate of about 20 percent per doubling (an "80 percent progress ratio")—which means that increasing cumulative production from 1000 units to 2000 units will reduce costs by 20 percent; increasing cumulative production again from 2000 to 4000 units will reduce costs another 20 percent, and so on. A progress ratio of 80 percent is the median value for a large number of industries.

Although all three technologies in the above graph have similar progress ratios initially, it is notable that after 1963 the progress ratio for gas turbines increased substantially, indicating attenuated learning effects as the technology matured. (Note that gas turbines also have fuel costs and associated capital investment that are not shown here.)

Source: Nakicenovic et al (1998).

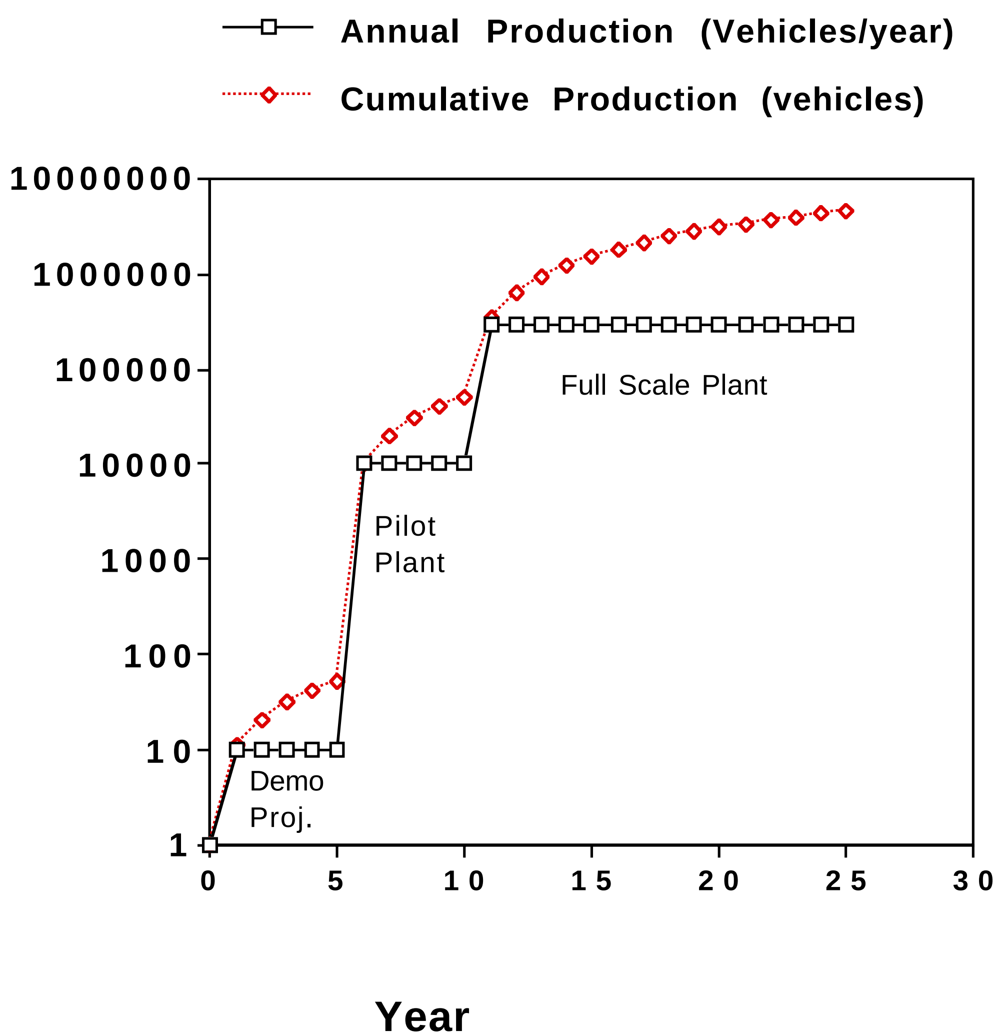

Figure 5. Annual Production (*Vehicles/Year*) and Cumulative Production (*Vehicles*) for Fuel Cell Cars During the Buy-Down Process for the Scenario Described in the Text

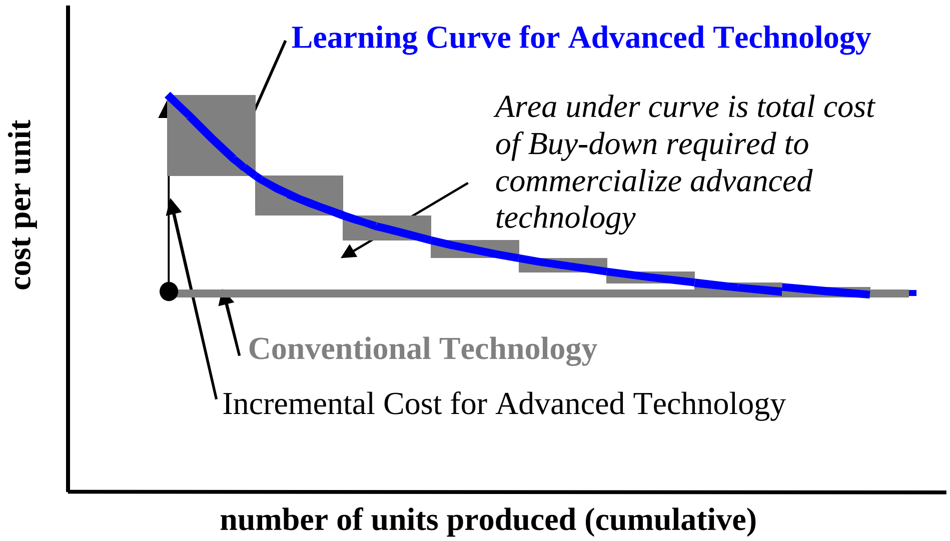

Figure 6. Learning Curve and Buy-Down Cost for an Advanced Energy Technology

The incremental cost for buying down the cost of the advanced technology relative to the conventional technology is shown, as the advanced technology moves along its learning curve. The triangular area between the curves indicates the total cost for buying down the cost of the advanced technology to the level at which the advanced technology is competitive with the conventional technology. As noted in the text, the point at which cost of the advanced technology equals the cost of the conventional technology is not necessarily the assymptotic (long-term) market price for the advanced technology.

Source: PCAST Panel on International Cooperation in ERD[3] (1999).

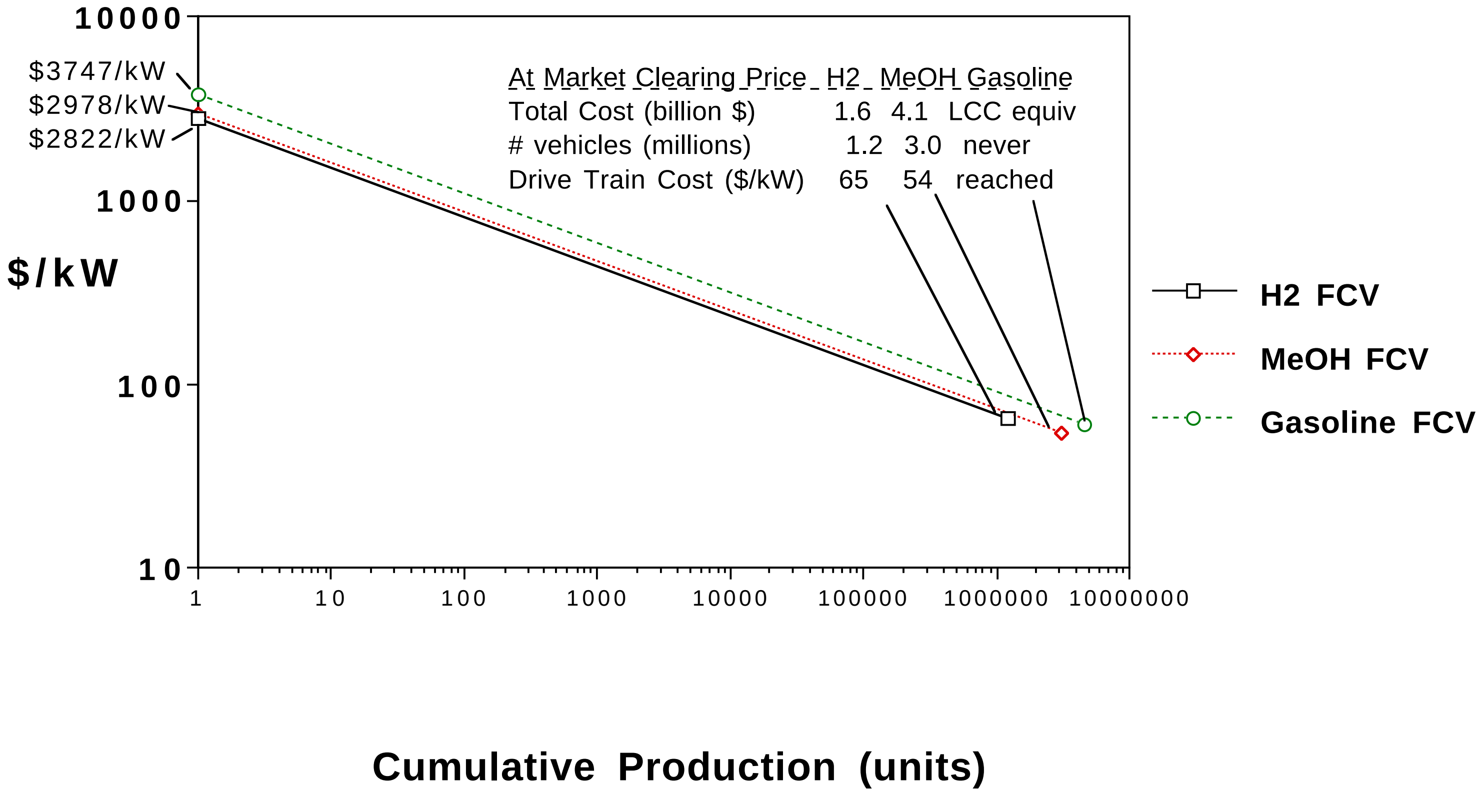

Figure 7. Costs of Fuel Cell Drive Trains Versus Cumulative Production for Hydrogen, Methanol and Gasoline FC Cars

The costs of FCV drive trains are shown initially and at market-clearing levels. The numbers of vehicles needed to reach LCC parity with gasoline ICE/HEVs and the total buy down costs are also indicated. For reference, the assumed gasoline ICE/HEV drive train cost is $48/kW. The FCVs are lifecycle cost-competitive with gasoline ICE/HEVs even with higher drive train costs ($54/kW for MeOH FCVs and $65/kW for H_2 FCVs vs. $48/kW for gasoline ICE/HEVs).

For each FCV technology, the production cost projected by the "learning curve" analysis equals to the levelized cost for a plant manufacturing 300,000 drive trains per year after cumulative production has reached 1.2 million vehicles. The learning curve projects that at the end of the 15-year life of the factory the cost would be 2/3 of the levelized production cost.

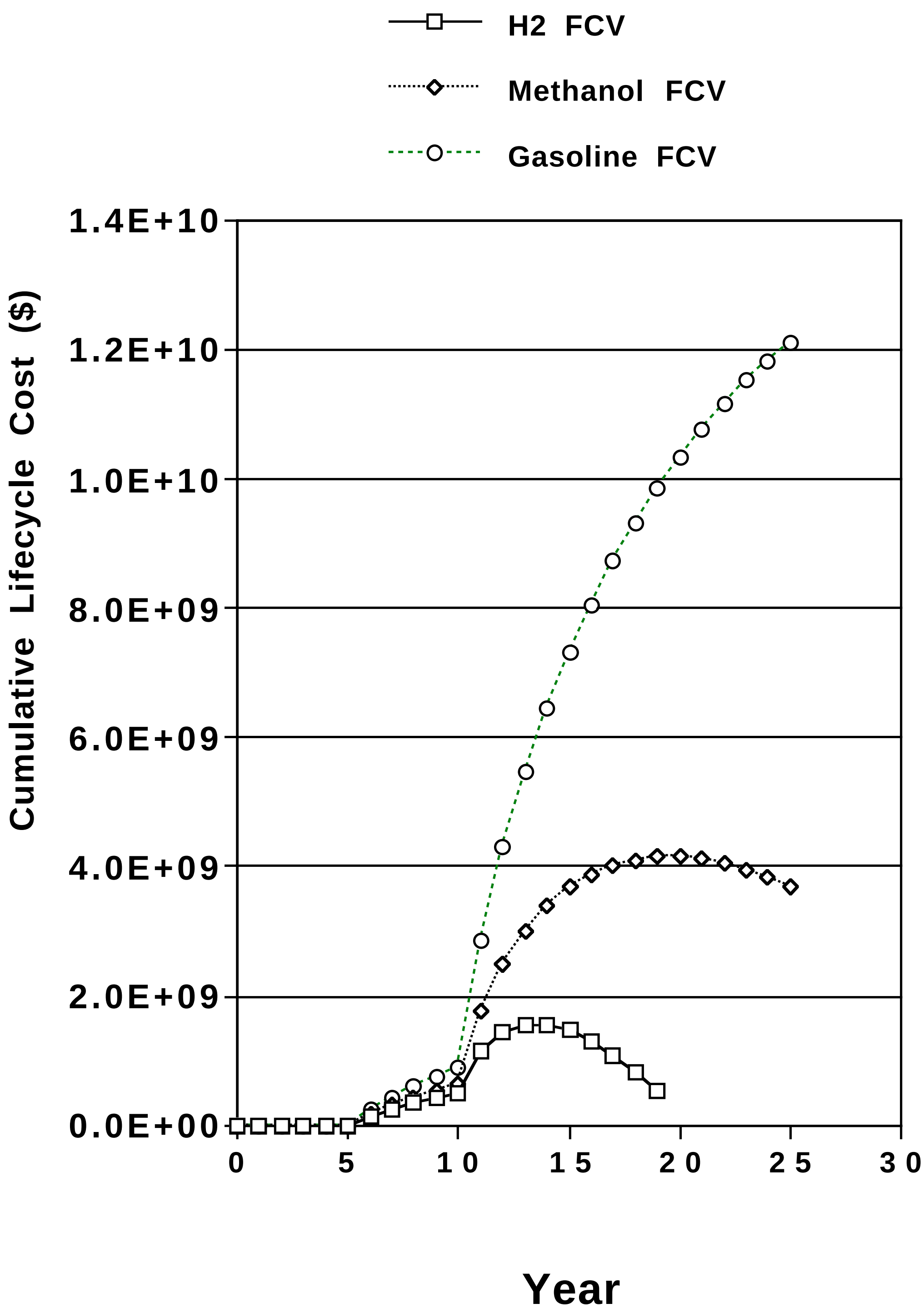

Figure 8a. Cumulative Lifecycle Cost Differences between FCVs and Gasoline ICE/HEVs, with Air Pollutant and GHG Emissions Damage Costs Included

For the drive-train production scenario shown in Figure 5. The maximum point represents, for each FCV option, the "buy-down cost" and the time at which lifecycle cost parity with gasoline ICE/HEVs is reached.

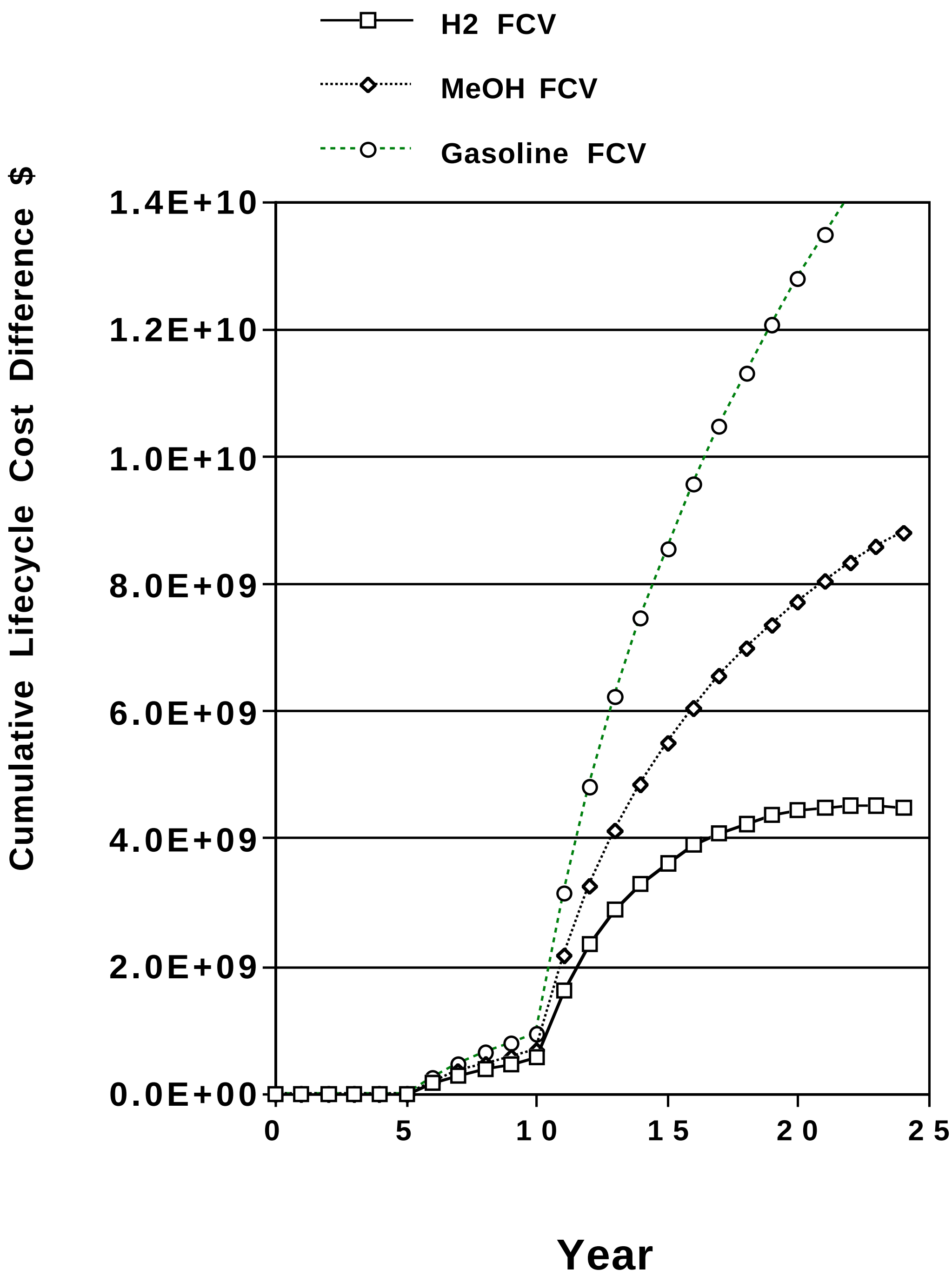

Figure 8b. Cumulative Lifecycle Cost Differences between FCVs and Gasoline ICE/HEVs, with Air Pollutant and GHG Emissions Damage Costs *Not* Included

For the drive train production scenario shown in Figure 5. The maximum point represents, for each FCV option, the "buy-down cost" and the time at which LCC parity with gasoline ICE/HEVs is reached.

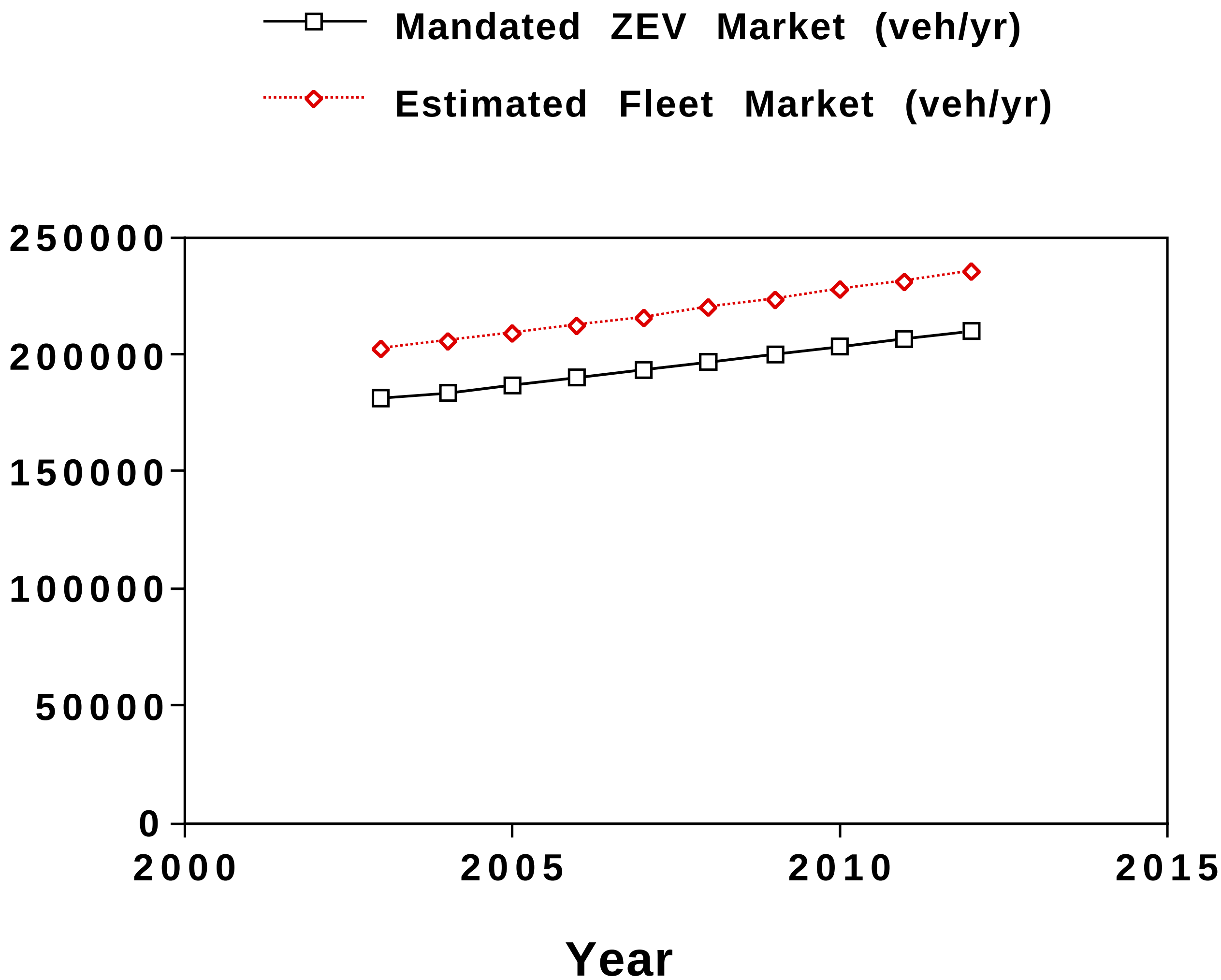

Figure 9. Mandated ZEV Markets and Estimated Centrally Refueled Fleet Markets in California, New York, Massachusetts and Vermont

The ZEV mandate market is based on the assumption that 10% of new cars must be ZEVs.

APPENDIX: Estimating Air Pollution Damage Costs; Discussion of Uncertainties; and Comparison of Findings with Those of Other Studies

The environmental damage cost estimates presented in Table 1 indicate that for today's gasoline internal combustion engine car air pollution damage costs are high—comparable to fuel costs. These estimates of air pollution damage costs are based on analyses of Spadaro and Rabl (1998a) and Rabl and Spadaro (2000). Health effects dominate air pollution damage costs, accounting for about 98% of the total. (Spadaro and Rabl estimate that air pollutant impacts on crops and materials represent a small fraction of total damage costs.) The largest single health impact from air pollution is chronic mortality[32] from direct particulate emissions and secondary particulates (nitrates and sulfates) formed in the atmosphere from gaseous precursor emissions of NO_x and SO_2. These account for 87% of health effects (or 85% of total damage costs) from air pollutant emissions of gasoline-fueled automobiles. Similar estimates have been developed in McCubbin and Delucchi (1999) and Delucchi (2000).[33]

This appendix: (*i*) provides background relating to the present state of understanding of environmental damage costs, (*ii*) outlines the methodology of estimating damage costs and the uncertainties in these damage cost estimates, and (*iii*) compares the findings of the present study with those of other studies.

Background

Until the mid-1990s, studies estimating health damage costs of air pollution focused on short-term effects. However, recently several studies have been carried out that focus on long-term effects—notably the "Harvard six cities study"(Dockery *et al*. 1993), an American Cancer Society (ACS) study (Pope *et al*. 1995), and a recent study by Abbey *et al*. (1999). A major finding of these studies is that chronic exposure to fine particles at levels found in US cities results in significantly increased illness and mortality from respiratory and cardiovascular disease and lung cancer. The earlier of these studies provided a basis for stricter EPA regulations on particulate emissions in 1997.

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32 Spadaro and Rabl (1998a) found that the risk of death associated with automotive air pollution from a conventional car is comparable to the risk of having a fatal traffic accident in that car.

33 Delucchi (2000) considered a variety of environmental externalities associated with transportation, including air pollution (human health effects, visibility, noise, crop damage, material damage, forest damage), water pollution, noise, and climate change. Air pollution is the largest contributor to damages, accounting for 80% of the environmental external costs estimated [see Table 6 in Delucchi (2000); for an assumed valuation of global climate change at $10/tonne of CO_2 ($37/tonne of C), CO_2 emissions represent the second largest external cost, accounting for an estimated damage cost of about 10% of the total.] Air pollution impacts on human health account for 90% of total air pollution costs. Of the various air pollutants considered, particulates (including direct particulate emissions, and aerosols formed in the atmosphere from primary emissions of SO_2, NO_x and VOCs) account for 97% of health-related air pollution costs in the US [see Table 2 in McCubbin and Delucchi (1999)]. In contrast, health impacts resulting from direct exposure to ozone, NO_x and CO, account for 0.9%, 0.9% and 1.2% of total health-damage costs, respectively. Of the health related particulate damages, mortality accounts for 72% of particulate damage costs and chronic illness 23%; the remaining 5% is due to acute illnesses like asthma and to economic effects of respiratory restricted activity days.

These epidemiological studies indicate strong correlations between chronic health impacts and exposure to fine particulates. However, the mechanisms of action are not well understood; it is difficult to identify causes by epidemiology because people are exposed to a mix of pollutants and different pollutants tend to be correlated with each other (Rabl and Spadaro, 2000).

Recently the Health Effects Institute conducted a critical reanalysis of the Harvard six cities study and the ACS study (HEI, 2000). This reassessment upheld the basic conclusions of the original studies and found that they were robust to a series of sensitivity analyses. It is now widely accepted that there is a demonstrable and significant link between particulate exposure and human illness and mortality, although the specific chemical culprits in particulates responsible for these health effects have not yet been identified.

To inform properly the air pollution policy debates in the face of the scientific uncertainty, quantification is needed both of the median estimates of damage costs and also of the uncertainties in these estimates. In what follows the methodology for estimating both health damage costs and the underlying uncertainties is briefly reviewed.

Methodology for Estimating Air Pollutant Damage Costs and the Uncertainties Involved

Air pollutant damage costs from vehicles are estimated as follows:

1) A change in vehicle use in a given region is indicated (e.g., an increase in the number of cars in the region).
2) The change in air pollutant emissions both from the vehicle and from fuel processing and transport activities upstream of the vehicle associated with the change in vehicle use is estimated. (Simulation programs are used to estimate vehicle emissions for given vehicle type, engine type, drive schedule, fuel and operating conditions.)
3) Changes in ambient levels of air pollutants associated with the change in emissions are estimated. (To find the change in ambient pollutant levels, a model of pollutant dispersion and atmospheric chemistry is used.)
4) The impacts of changed ambient air pollutant levels are evaluated. The exposure of “receptors” (e.g. people, crops, forests) to pollutants and the impacts of this exposure are estimated. Impacts include human health effects, and damage to crops, forests and buildings. Exposure-response curves derived from epidemiological studies are used to estimate increases in illnesses and mortality due to increased ambient levels of air pollutants.
5) An economic value is assigned to the predicted impacts. For human illness and mortality, costs are estimated based on both direct medical costs and a “willingness to pay” to avoid ill health effects. For acute and chronic mortality, the cost is based on years of life lost due to premature death.
6) Referring back to the projected change in pollutant emissions from step 2), a damage cost in $/kg of pollutant emitted is estimated. The damage cost depends on population density, prevailing winds, the topography of the region, and other regionally-specific features.

Estimating air pollution damage costs involves uncertainties at each step, so that studies of air pollution damage costs typically project a range of costs that span an order of magnitude or more.

The methodology for quantifying the uncertainties involved is rooted in the fact that the cost of damages is estimated as the product of several uncertain quantities:

Damage cost = population
x (change in ambient air pollutant concentration)[34]
x (estimated impacts on human health)
x (economic valuation of health impacts)

The distribution of outcomes for such a multiplicative analysis is typically lognormal—i.e., the log of the variable is distributed normally[35] (Spadaro and Rabl, 1998b).

A lognormal distribution[36] is characterized by the geometric mean μ_g (the median of the distribution[37]) and the geometric standard deviation σ_g. The 68% confidence level is defined by

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[34] To estimate the change in ambient pollutant concentrations due to some change in vehicle use, the calculated change in pollutant emissions from vehicles (and upstream sources such as fuel production plants) is used as input to an atmospheric dispersion and chemistry model. The uncertainty in the ambient air pollution level stems from two sources: (*i*) uncertainties in the input emissions from vehicle and upstream sources, and (*ii*) uncertainties in the atmospheric dispersion/chemistry model. To a good approximation the change in ambient pollutant levels scales linearly with the change in source emission levels. It is assumed that the change in ambient air pollutant concentrations can be written as a product:

(Change in ambient air pollutant concentration) = (change in emissions from sources)
x (factor from atmospheric dispersion/chemistry model that is approximately independent of emissions from source).

[35] A normal probability density distribution for a variable x with a mean value:

$$<x> = \int f(x)\, x\, dx = \mu,$$

and a standard deviation:

$$[<(x - <x>)^2>]^{1/2} = [\int f(x)\,(x - <x>)^2\, dx]^{-} = \sigma,$$

is:

$$f(x) = \{1/[\sigma (2\pi)^{1/2}]\} \exp[-(x-\mu)^2/2\sigma^2].$$

[36] The lognormal probability density distribution is $f(x) = \{1/[\sigma x (2\pi)^{1/2}]\} \exp[-(\ln x - \mu)^2/2\sigma^2]$, from which:

$$<x> = \exp(\mu + \sigma^2/2) \text{ and } [<(x - <x>)^2>]^{1/2} = [(\exp \sigma^2 - 1)(\exp 2\mu + \sigma^2)]^{1/2}.$$

It is customary and more practical to characterize a lognormal distribution by the geometric mean μ_g and the geometric standard deviation σ_g defined by:

$$\ln(\mu_g) = \int f(x) \ln(x)\, dx = \mu, \text{ and } \ln(\sigma_g) = \{\int f(x)\,[\ln(x) - \ln(\mu_g)]^2\, dx\}^{1/2} = \sigma.$$

the range μ_g/σ_g, $\mu_g\ \sigma_g$. (There is a 68% probability than the actual value lies between $1/\sigma_g$ and σ_g times the estimated geometric mean value.) The 95% confidence level is defined by the range μ_g/σ_g^2, $\mu_g\ \sigma_g^2$. (There is a 95% probability than the actual value lies between $1/\sigma_g^2$ and σ_g^2 times the estimated geometric mean value.) Plotted on a linear scale, the lognormal distribution is skewed with the peak toward the left hand side (low values) and a tail to the right (high values) that may include extremely high outcomes, although with a low probability.

In what follows the uncertainties in the estimates of air pollution damage costs are discussed in the context of this methodology, following the discussion in Spadaro and Rabl (1998b, Appendix VIII, p. A104-A111).

Estimates of vehicle emissions. The estimated vehicle emissions vary depending on the vehicle type, engine type, drive cycle, fuel and operating conditions. Several simulation programs have been developed to predict in-use vehicle emissions. The results of these simulations have been compared to emissions data from vehicles for a few vehicle types and fuels. According to Spadaro and Rabl, emissions estimates are probably the least uncertain of the product factors in the overall estimate of damage costs, with a geometric standard deviation of $\sigma_g = 1.1$. (There is a 68% probability than the actual emissions lie between 1/1.1 and 1.1 times the estimated median value.)

Estimates of ambient atmospheric pollution levels. Simulation programs have been developed to predict ambient concentrations of pollutants, given information about sources of emissions, meteorological data, and geographic information. Atmospheric dispersion of primary pollutants from the source is modeled, given the height of the emission source above the ground (this is zero for vehicles, but up to 100 meters for tall stacks in refineries or power plants), wind speed and weather conditions. In addition to dispersion, chemical reactions take place in the atmosphere over time, producing secondary pollutants such as ozone (which depends on the emissions of VOCs and NO_x) and nitrate and sulfate particles (which depend on the emissions of NO_x and SO_2). These programs are complex, and typically have relatively coarse spatial resolution. It is difficult to predict exact ambient levels of air pollutants over time and space, even given source terms for pollution, and information about weather and geography. In most studies, predicted levels are benchmarked against measured pollutant levels to reduce this uncertainty. The uncertainty in these calculations is estimated by Spadaro and Rabl to be $\sigma_g = 2.5$. (There is a 68% probability than the actual ambient concentrations of pollutants lie between 1/2.5 and 2.5 times the estimated median value.)

Impacts of air pollution on human health. Exposure-response curves derived from the Harvard and ACS studies have been used in modeling the health impacts of air pollution in models of air pollution damage costs. The uncertainty in the dose-response function is estimated by Spadaro and Rabl to be $\sigma_g = 1.5$. (There is a 68% probability than the actual dose-response slope lies between 1/1.5 and 1.5 times the estimated median value.)

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[37] The value of the variable for which the probabilities of being above it and below it are the same.

Economic valuation of damages. Human mortality accounts for a large majority of air pollution damage costs. However a wide range of values have been suggested in the literature for premature mortality linked to air pollution. Spadaro and Rabl suggest that the distribution for economic valuation has a geometric standard deviation $\sigma_g = 3.4$, reflecting this wide range of values. (There is a 68% probability than the actual valuation lies between 1/3.4 and 3.4 times the estimated median value.)

Combining the estimated uncertainties in all these quantities, Rabl and Spadaro (2000) found a total spread of possible values around the median value for air pollutant damage costs of $\sigma_g = 4.0$. (There is a 68% probability that the true damage cost value lies between 0.25 and 4.0 times the median value).

In descending order of importance, uncertainties in the air pollution damage cost arise from uncertainties in: 1) the economic valuation of premature death, 2) the dispersion/atmospheric chemistry model used to estimate ambient air pollution concentrations, 3) the dose-response function, and 4) the estimated emissions.

Comparison of Findings with Those of Other Studies

How do the results of our study compare to other estimates of air pollution damage costs?

In addition to the McCubbin/Delucchi studies referred to above, some other groups have also performed fuel cycle analyses comparing alternative fueled vehicles.

- In a recent study researchers at MIT estimated vehicle fuel economy, full fuel cycle energy use and lifecycle cost of a variety of alternative fueled vehicles, based on projections for the year 2020 (Weiss *et al*., 2000). Full fuel cycle emissions of greenhouse gases were estimated, although air pollutant emissions were assumed to be too small to be of concern.

- Recently, a group at General Motors Corporation in collaboration with Argonne National Laboratory, BP, ExxonMobil and Shell estimated full fuel cycle energy use, vehicle fuel economy and greenhouse gas emissions for a range of vehicle types and fuels (GM et al. 2001). Economics and air pollution emissions have not yet been included in this analysis.

The MIT and GM studies provide points of comparison on energy use and greenhouse gas emissions, but neither includes air pollution effects.

The McCubbin/Delucchi analysis is a comprehensive assessment of external costs of transportation for the United States that is widely cited. That study used a method different from that used in the ExternE studies to calculate ambient air pollution levels and so provides a good contrast to that used in the present study

In Tables A.1 and A.2, estimates from the present (CEES) study of damages from air pollutants emitted by automobiles in Southern California are compared to estimates for the same region developed in McCubbin and Delucchi (1999). In both cases damage costs (in $/kg of pollutant) from Table A.1 are applied to pollutant emissions from a conventional gasoline car [as estimated using the GREET model (Wang, 1999)], and air pollution damage costs are estimated for an assumed 10-year (120,000 mile) vehicle lifetime (Table A.2).

Table A.1 shows that the estimated ranges of damage costs for the two studies are roughly comparable, although the CEES study projects a higher cost for direct particulate emissions and a lower cost for sulfates. The comparison presented in Table A2 of the two studies shows that the median values of both the total lifetime air pollution damage costs for the McCubbin/Delucchi study and the costs for damages caused by all particles (direct PM + nitrates + sulfates) are about 40% less than for the present study.

One important reason for the difference between the two studies is that the McCubbin/Delucchi results for southern California are for an average urban population density of 1,000/km^2 (county-wide average) whereas the present study is based on an average urban population density of 2,000/km^2. (Based on US census data, about 50% of people in the Los Angeles Basin live in areas with population densities of 2000/km^2 or higher.) If the modeling in the present study were instead for an average urban population density of 1000/km^2 (closer to the county-wide population density averages used in the McCubbin and Delucchi model), the median estimate of damages for the present study would be only about 25% higher than that of McCubbin and Delucchi (see Table A2).

The findings of McCubbin and DeLucchi and the present study should be regarded as being in reasonably good agreement in light of all the uncertainties underlying these damage cost estimates.

Table A.1. Comparison of CEES and McCubbin/Delucchi Studies: Estimated Damage Costs of Air Pollutants in Southern California
(*$ per kg of pollutant emitted*)

	CEES Study: ExternE values scaled to southern California population densities (median values shown; the range at 1 standard deviation is 0.25 to 4 x median)	McCubbin/Delucchi study: results for southern California [from Table 2, Delucchi (2000)]; a range of values is shown
Pollutant	Vehicle emissions damage cost ($/kg of pollutant emitted)	
VOC	2.0 (ozone via VOC)	0.51 – 4.34 (organic PM_{10})
CO	0.007	0.03 – 0.18
NO_x	2.8 (ozone via NO_x) 37 (nitrates) 40 (total NO_x)	0.52 - 2.64 (NO_2) 6.05 - 75.83 (nitrate PM_{10}) 6.58 – 78.47 (total NO_x)
PM	650 (direct $PM_{2.5}$ emissions)	58.79 - 638.33 (direct PM_{10} emissions)
SO_x	9.3 (direct SO_2) 23.7 (sulfates) 33 (total SO_x)	Negligible for direct SO_2 34.98 - 226.89 (sulfate PM_{10})
VOC + NO_x	Included in VOC and NO_x categories above	0.05 - 0.40 (ozone production from VOCs and NO_x in 1990)

Table A.2. Comparison of Lifetime Vehicle-Only Damage Costs in Southern California Due To Emissions from a Conventional Gasoline SI Engine Car[a,b,c]

[*$ per car over 10-year (120,000 mile) lifetime*]

	McCubbin/Delucchi (Los Angeles area)			CEES (ExternE costs scaled to southern California population densities; average urban population density = 2000 per km^2; average regional population density = 138 per km^2)			CEES w/average urban population density = 1,000 per km^2; average regional population density = 138 per km^2
Pollution value	low	**median**	High	0.25 x median	**median**	4 x median	**median**
VOC ozone	See below			10.6	**42**	169.6	42
VOC PM_{10}	9	**29**	97				
CO	13	**38**	107	0.9	**3.7**	14.7	2
NO_2	11	**29**	78	0	**0**	0	0
NO_x ozone	See below			19.7	**79**	315	79
Nitrates	134	**549**	2248	259.6	**1039**	4154	1039
PM	57	**217**	825	197.6	**790**	3161	402
SO_2	0	**0**	0	11.5	**46**	184	23
Sulfate	141	**415**	1223	30.3	**121**	484	121
VOC + NO_x ozone	0.3	**3**	23	Estimated above for VOCs and NO_x			
Total cost (*$ per car*)	365	**1279**	4602	530	**2121**	8483	1707
Particle subtotal = PM + VOC PM_{10} + nitrates + sulfates	340	**1210**	4393	487	**1950**	7800	1561

[a] For all cases, emissions (grams per mile) are from the GREET Model (Wang, 1999).

[b] Based on $ per kg damage costs from Delucchi (2000) and McCubbin and Delucchi (1999) and the present (CEES) study (see Table A.1).

[c] For the CEES (scaled ExternE) results, damage costs are discounted at 3%. For the McCubbin/Delucchi low-cost case, a discount rate of 8% is used; for the McCubbin/Delucchi high-cost case, a discount rate of 2% is used. The median value indicated for the McCubbin/Delucchi case is the geometric mean of the high and low values presented in that analysis.

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