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Societal Lifetime Cost of Hydrogen Fuel Cell Vehicles

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ABSTRACT

Various alternative fuels and vehicles have been proposed to address transportation related environmental and energy issues such as air pollution, climate change and energy security. Hydrogen fuel cell vehicles (FCVs) are widely seen as an attractive long term option, having zero tailpipe emissions and much lower well to wheels emissions of air pollutants and greenhouse gases than gasoline vehicles. Hydrogen can be made from diverse primary resources such natural gas, coal, biomass, wind and solar energy, reducing petroleum dependence. Although these potential societal benefits are often cited as a rationale for hydrogen, few studies have attempted to quantify them.

This paper attempts to answer the following research questions: what is the magnitude of externalities and other social costs for FCVs as compared to gasoline vehicles? Will societal benefits of hydrogen and FCVs make these vehicles more competitive with gasoline vehicles? How does this affect transition timing and costs for hydrogen FCVs? We employ societal lifetime cost as an important measure for evaluating hydrogen fuel cell vehicles (FCVs) from a societal welfare perspective as compared to conventional gasoline vehicles. This index includes consumer direct economic costs (initial vehicle cost, fuel cost, and operating and maintenance cost) over the entire vehicle lifetime, and also considers external costs resulting from air pollution, noise, oil use and greenhouse gas emissions over the full fuel cycle and vehicle lifetime. Adjustments for non-cost social transfers such as taxes and fees, and producer surplus associated with fuel[1] and vehicle are taken into account as well.

Unlike gasoline, hydrogen is not widely distributed to vehicles today, and fuel cell vehicles are still in the demonstration phase. Understanding hydrogen transition issues is the key for assessing the promise of hydrogen. We have developed several models to address the issues associated with transition costs, in particular, high fuel cell system costs and large investments for hydrogen infrastructure in the early stages of a transition to hydrogen. We analyze three different scenarios developed by the US Department of Energy for hydrogen and fuel cell vehicle market penetration from 2010 to 2025. We employ a learning curve model characterized by three multiplicative factors (technological change, scale effect, and learning-by-doing) for key fuel cell stack components and auxiliary subsystems to estimate how fuel cell vehicle costs change over time. The delivered hydrogen fuel cost is estimated using the UC Davis SSCHISM hydrogen supply pathway model, and most vehicle costs are estimated using the Advanced Vehicle Cost and Energy Use Model (AVCEM). To estimate external costs, we use AVCEM and the Lifecycle Emissions Model (LEM). We estimate upstream air pollution damage costs with estimates of emissions factors from the LEM and damage factors with a simple normalized dispersion term from a previous analysis of air

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[1] Two different accounting stances are explored for estimating producer surplus for fuels: a US perspective and a global perspective.

pollution external costs. This approach allows us to estimate the total societal cost of hydrogen FCVs compared to gasoline vehicles, and to examine our research questions.

To account for uncertainties, we examine hydrogen transition costs for a range of market penetration rates, externality evaluations, technology assumptions, and oil prices. Our results show that although the cost difference between FCVs and gasoline vehicles is initially very large, FCVs eventually become lifetime cost competitive with gasoline vehicles as their production volume increases, even without accounting for externalities. Under the fastest market penetration scenario, the cumulative investment needed to bring hydrogen FCVs to lifetime cost parity with gasoline vehicles is about $14-$24 billion, and takes about 12 years, when we assume reference and high gasoline prices. However, when externalities and social transfers are considered, the buy-down cost of FCVs in the US could about $2-$5 billion less with medium valuation of externalities and $8-$15 billion less with high valuation of externalities. With global accounting and high valuation of externalities, we would have $7-$12 billion savings on the buy-down cost compared to a case without externality costs. Including social costs could make H2 FCVs competitive sooner, and at a lower overall societal cost.

Keywords: Societal lifetime cost, learning curve, fuel cell system, upstream emissions, buy-down cost

1. Introduction

Current transportation systems face serious and growing challenges, with respect to energy supply adequacy and security, impacts of air pollution on human health and emissions of greenhouse gases linked to climate change.

In the U.S., the world's largest oil consumer, the transportation sector accounts for around two-thirds of oil consumption [1]. U.S. oil imports have grown rapidly since the 1970's, reaching 60 percent of domestic consumption by 2005. Since then, U.S. dependence on petroleum imports has declined slightly, but the net import share of U.S oil consumption is expected to stabilize at 50% by 2020 [2]. From 1970 to 2004, the cumulative direct economic costs of oil dependence – including wealth transfer, potential GDP loss, and macroeconomic adjustment, but excluding the military expenditures on oil supplies protection –exceeded $2.9 trillion in constant 2005 dollars [3].

In addition to the economic impacts of oil dependence, conventional oil extraction, production, and end-use in the transportation sector remain one of the largest sources of urban air pollution (AP) and greenhouse gas (GHG) emissions. These two major environmental externalities directly and indirectly impact human health, reduce visibility, and lead to crop losses, forest damage, water pollution and climate change damage. From the perspective of environmental economics, these externalities, not priced in the current markets, cause the social cost of owning and operating a gasoline vehicle to exceed the private cost. Delucchi [4] estimated the social costs (nonmonetary externalities including air pollution and climate change)[2] of motor-vehicle use including upstream emissions to be in the range of $44-$655 billion per year in constant 2005 US dollars.

Energy insecurity, environmental protection and oil price shocks have spurred an increased interest in developing alternative fuel/propulsion systems. Compressed Natural Gas (CNG), synthetic diesel, methanol, ethanol, Liquid Petroleum Gas (LPG), Liquefied Natural Gas (LNG), F-T liquids, hydrogen and electricity have been widely discussed as alternative transportation fuels. Various powertrain options include spark ignition (SI) engines, compression ignition (CI) engines, battery-electric systems, fuel-cell electric systems, and hybrid electric-engine systems. Recent assessments by MacLean et al. [6], Bandivadekar et al. [7] and the US DOE [8-9], suggest that no single fuel/vehicle pathway will lead to improvements in all metrics, which means that a comparative evaluation of vehicle alternatives will have to assess tradeoffs among fuel economy, vehicle performance, range, cost, emissions, and other externalities. However, electric drive vehicles stand out as offering high efficiency, low emissions and the ability to utilize diverse primary resources [10] though the commercialization of such advanced environmental-friendly vehicles will require policy support and technological innovation, overcoming multiple technical and practical hurdles.

One metric for assessing alternatives is the societal lifetime cost (SLC), which includes the vehicle retail cost (a function of vehicle performance), the cost of energy use (a function of vehicle fuel economy), operating and maintenance costs, externality costs of oil use, damage costs of noise and emissions from air pollutants and GHGs, and other factors. These costs are estimated over the full fuel cycle and entire vehicle lifetime [11] and include adjustments for non-cost social transfers such as taxes and fees, and producer surplus associated with fuel and vehicle [12]. In this paper, we estimate the societal cost of hydrogen fuel-cell vehicles with models of vehicle cost, vehicle performance, fuel cost, and external costs.

We use the Advanced Vehicle Lifetime Cost and Energy-Use Model (AVCEM) model developed by Dr. Mark Delucchi [13] to compare the SLC of hydrogen FCVs with that of conventional gasoline vehicles during a transition to hydrogen. AVCEM provides a self-consistent framework for estimating the SLC. We focus on light duty vehicles, which is

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[2] These costs include the environmental, economic and health damages stemming from 1990/1991 levels of air pollution, climate change damages in the U.S. (later we explain the difference between the U.S. and the global perspective), and water-pollution damages. The air-pollution damages from current motor-vehicle emissions might be lower, but probably not dramatically lower, because while total motor-vehicle air-pollutant emissions have declined substantially since 1990 [5], total exposed population and per-capita income (which affects the per-person willingness to pay to avoid the affects of air pollution) have increased. Climate-change damages from current motor-vehicle use, which are a function of total travel and total wealth, are much higher today.

the largest transportation subsector, and uses over 60% of US transportation energy. To model the hydrogen transition, we employ a learning curve model to estimate fuel cell system costs under a series of scenarios, developed by the US Department of Energy (DOE) [14], for hydrogen and FCVs market penetration from 2010 to 2025. Following the treatment in a recent study by the National Academies [15], we estimate the delivered hydrogen fuel cost using the UC Davis SSCHISM hydrogen supply pathway model [16]. External costs are estimated using AVCEM and the LEM (Lifecycle Emissions Model). Our results show that although the lifetime cost difference between FCVs and gasoline vehicles is initially very large, FCVs become cost-competitive with gasoline vehicles at higher production volumes. The cumulative investment needed to bring hydrogen FCVs into lifetime cost parity with gasoline vehicles – termed the "buy-down cost" – are very sensitive to assumptions made about fuel cell costs, learning curves, gasoline prices and the valuation of externalities. Because the valuation of externality costs is uncertain, we analyze a variety of cases with a range of assumed externality costs.

2. Literature Review

A number of studies assess the viability of various alternative fuel vehicles as potential solutions to problems such as energy insecurity, air pollution and global warming. These studies typically include direct cost estimates, externalities and social cost comparison (not many do social costs). We review recent studies (i.e. published since 2000) that analyze hydrogen FCVs and estimate costs for fuels and/or vehicles.

2.1. Vehicle Well to Wheels Energy Use and Emissions Studies

The Laboratory for Energy and the Environment at MIT conducted a series of comparative analyses with a primary focus on lifecycle energy use and GHG emissions for automotive powertrain options in the near- and mid-term future [17-20]. A typical mid-size passenger car (Toyota Camry) was chosen as a reference. They assumed that both fuel and vehicle would undergo evolutionary improvements over time. Vehicle performance calculations were done by using ADVISOR software developed by AVL, and cost/price estimates were based on a literature review and on consultations with industry experts. These studies concluded that no single "silver bullet" among the technology options available can achieve dramatic reductions in energy use and GHG emissions, and that a strategy called "Emphasis on Reducing Fuel Consumption" (ERFC) will play a significant role in reducing fuel consumption (FC) in the U.S. ERFC is defined as the ratio of FC reduction realized on road to FC reduction possible with constant performance and size. This measures the degree to which technological improvements are being directed toward increasing onboard vehicle fuel economy. These studies focused on direct economic costs and GHG emissions, but did not estimate external costs per se.

A joint European study was conducted by EUCAR, CONCAWE and JRC [21] on well-to-wheel (WTW) energy use and GHG emissions associated with a wide range of automotive fuel and powertrain options for European countries in 2010 and beyond. The study assessed the potential benefits resulting from alternative fuels replacing conventional fuels. A common vehicle platform (a compact five-seater 2002 European 2002) was used as a reference for comparison. The EUCAR members assumed that the vehicle fuel efficiency beyond 2010 would have a certain percentage improvement over the reference. Various vehicle options were assumed to comply with the minimum set of performance criteria and pollutant emission regulations in force in Europe (EURO III for 2002 and EURO IV for 2010 on). Using ADVISOR, the group simulated fuel consumptions and GHG emissions under European type-approval driving cycles. Macroeconomic costs to the EU, expressed as the cost of fossil fuels substitution and CO_2 avoided, were estimated under two separate cost scenarios for crude oil prices of 25 and 50 €/bbl. For vehicle-related cost, the retail price increment expected beyond 2010 was estimated for the various technologies based on a review of the recent literature. No maintenance costs were considered. This study indicates that “a shift to renewable/low fossil carbon routes may offer a significant GHG reduction potential but generally requires more energy,” and a portfolio of various fuels may be expected in the market.

Granovskii et al [22] at University of Ontario Institute of Technology (UOIT) used various published data to compare conventional, hybrid, electric and hydrogen fuel cell vehicles from both economic and environmental perspectives, including fuel utilization and vehicle production and utilization stages under three different electricity production scenarios. The four vehicle options were compared according to economic indicators (vehicle price, fuel costs and driving range), and environmental indicators (air pollution and GHG emissions) for the years 2002 to 2004. Each indicator was normalized so that a value of 1 represented the best economic and environmental performance among the cars considered. The ratios of each car’s performance to the best performance gave the normalized indicators for each performance category. The product of the calculated normalized indicators was the overall indicator for each car type. The analysis shows that hybrid and electric cars perform better than the other options and that the electricity generation mix substantially affects the economics and environmental impacts of electric cars. They also found that on-board electricity generation from a fuel-cell system would improve the economic and environmental ranking of electric cars. However, inconsistent data used in the study, subjective choice of indicators, the simple normalization procedure, and a lack of other evaluation criteria (such as externalities costs) limit the generalization of the conclusions.

2.2. Hydrogen Transition Studies

To evaluate the three hydrogen and FCVs market penetration scenarios developed by the US DOE, Greene et al. [23] at Oak Ridge National Laboratory (ORNL) analyze hydrogen infrastructure and deployment with the DOE’s integrated market simulation model (HyTrans). They evaluated policy options to support the transition to hydrogen-powered transportation, and estimated the costs associated with policy implementation. Two key economic barriers were addressed: the current lack of hydrogen infrastructure and the high cost of FCVs at low production volumes. Hydrogen production pathway costs were obtained by using HYPRO model from Directed Technologies, Inc. (DTI). Their analysis assumes the DOE technical targets are met, meaning that fuel cell vehicle systems would achieve \$45/kW by 2010 and \$30/kW by 2015 in the laboratory with a five-year time lag for implementation in mass production. A composite learning curve was used to model how drivetrain production costs would decrease as a function of technological progress and production volumes. Glider costs are taken as constant for all technology types. The study indicates that targeted deployment policies could allow the FCV market share to grow to 50% by 2030 and 90% by 2050, and that beyond 2025 no policy support would be needed for a sustainable, competitive market for hydrogen FCVs. The estimated cumulative costs of alternative government policies for a successful transition to hydrogen FCVs were from \$10 to \$45 billion for the period from 2012 to 2025.

Using the ORNL learning curve model and the UC Davis SSCHISM infrastructure model, the NRC (2008) presents several hydrogen scenario analyses in detail. They project potential reductions in petroleum use and carbon dioxide emissions in 2020 and beyond, the investments needed to bring hydrogen FCV technologies to cost competitiveness with gasoline vehicle technology, and the costs for a future hydrogen infrastructure. For the "Hydrogen Success" scenario, the Committee concludes that "oil displacement is about 0.8 percent in 2020, rising to 24 percent in 2035 and 69 percent in 2050," and GHG emissions reduction is about 0.7 percent in 2020, 19 percent in 2035, and 60 percent in 2050. The investment costs (the difference in vehicle prices plus the difference in fuel costs) for hydrogen FCVs to reach cost competitiveness are about \$22 billion though this number depends on many key assumptions. The estimated cost of fully building out hydrogen supply to fuel 220 million FCVs by 2050 is more than \$400 billion.

2.3. Estimates of Societal Costs of Alternative Fueled Vehicles

Ogden and colleagues at Princeton University [11] performed one of the few studies that estimate the total societal cost of various alternatives to petroleum-based fuels. They used the "societal lifecycle cost" (the same as our societal lifetime cost [SLC]) as a basis for comparing alternative automotive engine/fuel options that are meant to address concerns about air pollution, climate change, and oil supply insecurity. The societal lifecycle cost per vehicle was defined as the sum of vehicle first cost and the present value of lifetime costs for fuel, non-fuel operation and maintenance, full fuel-cycle air-pollutant and GHG damages and oil supply insecurity. They assumed that the fuel infrastructure is fully developed, that all vehicles have the same performance, and that future drivetrains are mass produced. Vehicle first costs and fuel economies were obtained from an extensive literature review. Non-fuel operation and maintenance costs were thought to be the same across all options and so were not included in the analysis. Most estimates of upstream air-pollutant and GHG emissions were from the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model [24], and estimates of in-use emissions from advanced vehicles were from other analyses and the authors' calculation. The damage costs from air pollutants and GHG emissions were estimated by adjusting ExternE estimates [25-26] to U.S. population density (Southern California was chosen as the US norm). Oil supply insecurity cost was simply calculated with the U.S. military expense for Persian Gulf and fraction of Persian Gulf exports to the United States. To account for the uncertainties in these externality valuations, they presented the societal lifecycle cost of several engine/fuel options separately with low, median and high estimates of externality costs. The analysis found that most advanced options have lower lifetime costs than today's new cars when external costs are internalized. And at high valuations of externalities, the hydrogen FCV with hydrogen derived from fossil fuels with sequestration of CO2 would have the lowest lifetime societal cost among all options with the lowest externality costs.

A life cycle cost analysis of hydrogen by Lee et al. from South Korea [27] by Lee et al. examines several key factors for the economical feasibility of hydrogen as an alternative option. Four hydrogen pathways are considered for life cycle cost calculations and compared with conventional fuels. The life cycle cost includes well-to-tank costs, tank-to-wheel costs and external costs from air emissions and GHGs. A base case in 2007 and a future scenario in 2015 are discussed for a Hyundai sport utility vehicle (TUCSON). Data for the fuel pathways are drawn primarily from publications in South Korea and Hyundai Motors. External cost estimates are based on a review of the literature. This study indicates that hydrogen life cycle costs depend on FCV price, production capacity, fuel efficiency, social costs and hydrogen pathways, and that all hydrogen pathways are expected to be economically feasible by 2015.

Another recent study by H2Gen [28] compares the societal benefits of various alternative transportation options in terms of reductions on local air pollution, GHG emissions, and oil consumption. The analysis includes gasoline, diesel, ethanol, hydrogen, and grid electricity. Twelve different alternative fuel/vehicle combinations are analyzed including battery-powered vehicles, hybrid electric vehicles (HEVs), plug-in hybrids (PHEVs) and FCVs. The GREET model was used to calculate emissions of local air pollution and GHGs, and oil consumption with some GREET input parameters modified to "reflect the changing methods of producing ethanol, hydrogen and electricity, particularly when carbon constraints are introduced." The unit health costs from urban air pollution or air pollution reduction costs were derived from the average of several estimates in the US and Europe. The GHG damage cost was assumed to be \$25 per metric tonne of CO_2 in 2010, increasing linearly to \$50/tonne by 2100. A societal cost of \$60/barrel was assumed for oil consumption. The analysis concludes that hydrogen FCVs would be the only option to achieve significant GHGs reduction and nearly eliminate all controllable urban air pollution. The only solutions to energy "quasi-independence" would be hydrogen vehicles (fuel cell or hydrogen ICE) and all-electric vehicles. According to the analysis, the societal cost savings from hydrogen FCVs justify the hydrogen infrastructure costs. However, this study didn't address the consumer cost. Also, averaging external cost estimates for different regions may not be accurate.

Based on detailed computer simulations, Thomas [29] at H2Gen concludes that all-electric vehicles would be the ultimate solution to achieving the US energy security and climate change reduction goals. Thomas compares FCVs and battery-electric vehicles in terms of weight, volume, GHGs and cost, and finds that fuel cell electric vehicles are superior to advanced lithium-ion battery electric vehicles in most aspects: they weigh less, cost less, emit fewer GHGs, use less WTW energy (with natural gas or biomass feedstocks), and have shorter refueling time. However, battery electric vehicles have lower fuel cost, use less WTW wind or solar energy on a per-mile basis, and in the early years would have greater access to fueling capability.

In contrast with Thomas' conclusion, an earlier study on cost comparison of fuel cell and battery electric vehicles [30] based on U.S. government studies indicated that a battery electric vehicle (BEV) is more efficient, cleaner, and less expensive in terms of manufacturing and refueling costs. Similarly, a newly published study by Offer et al. [31] concludes that both BEVs and fuel-cell plug-in hybrid vehicles (FCHEV) would have significantly lower lifetime costs (capital and running costs) than hydrogen fuel-cell vehicles in 2030. This comparative analysis, based on cost predictions from International Energy Agency and Department of Transport (DfT), assumes a single vehicle platform with 80kW peak power and 20kW mean power. Offer et al. report powertrain (capital) and fuel (running) costs in 2010 and 2030, but do not estimate social costs.

The US DOE Multipath Study [8] assesses eleven pathways and constructs ten scenarios for light-duty-vehicle transportation futures from the perspectives of oil and GHG saved. The study also considers vehicle costs, infrastructure issues, criteria emissions and risk associated with discontinuous development, high costs and unsuccessful market. Their results show that the FCV pathway could have the highest oil savings by 2050. Further work on the Multipath Study [9] has focused on costs and scenario analysis, using the National Energy Modeling System (NEMS), an automotive system cost model, and oil security metrics model (OSMM). The Multipath study concludes that successful development of advanced vehicle technologies will require strong government intervention unless industry is able to radically reduce costs.

All the studies mentioned above are summarized in Table 1. Most of these studies focus on estimating energy use and GHG emissions for future vehicle options at a specific time point. Some studies consider vehicle initial costs, running costs, and a range of external costs, but some consider vehicle cost only and some include only certain externality costs. In most studies vehicle performance is not modeled explicitly, but in a few studies, performance is simulated with ADVISOR. None of the studies use a detailed cost model for vehicle components to examine key cost drivers; none of them have a combined energy-use and vehicle cost model to ensure consistency between the cost and performance estimates; and none of them consider operating, insurance, and maintenance costs. Some studies use the GREET model to estimate air pollution and GHG emissions without careful examining the default parameters in GREET. Few studies systematically address the damage costs from upstream air pollution, and no studies have a comprehensive estimate of the external costs of oil use.

Table 1 Summary of recent studies of the cost and impacts of FCVs and other advanced vehicles

Study group	MIT	ORNL	NRC	EUCAR	UOIT
Region	U.S. and several European countries	U.S.	U.S.	Europe	N.A.
Timeframe	2020, 2030, 2035	2012-2025	2010-2050	2010+	2002-2004

Vehicle type	Mid-size car (Toyota Camry) Light-truck (Ford F-150)	Light-duty vehicle	Light-duty vehicle	Compact 5-seater European sedan	Toyota Corolla, Prius, RAV4 EV, Honda FCX
Fuels	Gasoline, Diesel, CNG, FT diesel, methanol, H2, Electricity	H2	Gasoline, bio-fuel, H2, electricity	Gasoline, diesel, CNG, biogas, LPG, ethanol, bio-diesel, DME, CH2/LH2	Gasoline, electricity, H2
Powertrains	ICE, hybrid, plug-in hybrid, battery, fuel cell	Fuel cell	ICE, hybrid, fuel cell	ICE, hybrid, hybrid fuel + reformer	ICE, Hybrid, battery, fuel cell
Feedstocks	Petroleum, NG, National power grid	NG, coal, biomass, ethanol	Petroleum, NG, coal with CCS, biomass, water, corn, cellulose	Crude oil, NG, biomass, sugar, wheat, cellulose, coal, water	Crude oil, renewable, NG
Vehicle energy-use model	ADVISOR simulation	No formal model	No formal model	ADVISOR simulation for fuel consumptions and GHG emissions	No formal model
Vehicle cost	Retail price and OEM cost estimates from literatures and conversation with industry experts: $3000-$5300 for incremental retail price of Future FCV relative to future ICE	Drive train cost estimate by a composite learning curve (HyTrans model) with constant glider cost (assume DOE technical targets are met for fuel cell system)	ORNL learning curve model for estimates of fuel cell vehicle cost and investment costs	Vehicle retail price increment expected beyond 2010 at 50K vehicles per year; maintenance costs not considered	Estimates based on published price projections: Conventional: $15,300 Hybrid: $20,000 Electric: $42,000 FCV: $100,000 in regular production; 10-year vehicle life
Fuel cost	Sum of 3 steps in fuel cycle for fuel cost estimates in 2020 with large uncertainties	H2 pathway costs from DTI's HYPRO model ($2.5~$3.25/kg)	UC Davis SSCHISM	WTT and TTW costs Only direct costs (related to purchasing feedstocks, building plants, infrastructure and vehicles) included for two cost scenarios, market price for internationally traded resources	Average prices from EIA 1999-2004: Gasoline $1.51/gal Electricity 4.84¢/kwh H2 $1.57/kg assuming same as gasoline on a LHV basis
Vehicle lifecycle	Energy use and emissions from vehicle life cycle	Not included	Not included	TTW approach for energy expended and associated GHG emitted	Not included
Fuel lifecycle	Fuel cycle energy consumption and GHG emissions from published data	Not included	WTW GHG emissions	WTW energy use and GHG emissions	Lifecycle GHG and air pollution from literature review
External costs	Not included	Not included	Not included	Not included	Air pollution and GHG from fuel cycle and vehicle cycle, relative to best vehicle

Table 1 continued

Study group	Ogden	South Korea	Thomas	Offer
Region	U.S. (Southern California)	Korea	U.S.	UK
Timeframe	Not specified	2007, 2015	2005-2100	2010, 2030
Vehicle type	Mid-size automobile	Sport utility vehicle	Light-duty vehicle	Saloon car

	(4-5 passengers)			
Fuels	Gasoline, CNG, diesel, FT50, methanol, H2	H2, gasoline, diesel	Gasoline, diesel, ethanol, hydrogen and grid electricity	Gasoline, hydrogen and grid electricity
Powertrains	ICE, hybrid, fuel cell	ICE, fuel cell	ICE, hybrid, plug-in hybrid, battery, fuel cell	ICE, fuel cell, battery, and fuel cell plug-in hybrid
Feedstocks	Crude oil, NG, coal, wind, water	Crude oil, NG, water	Petroleum, NG, coal, nuclear, renewable, corn, cellulose, hemi-cellulose, biomass	Petroleum, NG, coal, gas, nuclear and wind
Vehicle energy-use model	No formal model	No formal model	No formal model	No formal model
Vehicle cost	Vehicle first cost estimates based on engineering and cost models from several sources (retail costs of drive-train and body); 10-year vehicle life	Vehicle price estimated from the data given by Hyundai Motor Company; 160,000 km vehicle life	Use the cost estimates by Kromer and Heywood at MIT [19] for FCV and electric vehicle	Powertrain cost data from other reports; 100,000-mile vehicle life
Fuel cost	Lifetime fuel cost calculated from fuel economy and levelized fuel price (8% discount rate, driven 12,000 miles/year, 10 years)	Fuel utilization costs calculated based on fuel efficiency and driving distance with data from Hyundai motors	DOE H2A model H2 cost ($3.33/kg) from NRC study at hydrogen fueling system breakeven point	Optimistic and pessimistic assumptions regarding fuel price, based on literature review
Vehicle lifecycle	Not included	Not included	Not included	Not included
Fuel lifecycle	Full fuel-cycle (WTW) air pollution and GHG emissions considered	WTW costs, regulated air emissions and GHGs from field data, literature and pilot plant data in Korea	WTW energy efficiency, WTW urban air pollution and GHG emissions from GREET model	Not included
External costs	Damage costs from air pollution & GHG emissions and oil supply insecurity costs	Damage or prevention costs from GHGs and regulated air emissions	External costs from urban air pollution, GHG emissions and oil imports	Not included

This paper builds on previous research and attempts to fill in some of the gaps identified above. We use AVCEM, SSCHISM, and other models to estimate the societal lifetime cost, including both consumer cost and external costs, for hydrogen FCVs and conventional gasoline internal combustion engine vehicles (ICEVs). Vehicle performance, energy use and all costs are modeled in detail within AVCEM, a standalone framework for consistency between the performance and cost estimates. Vehicle operating, insurance, and maintenance costs are also included in consumer cost. AVCEM is a vehicle performance and design model that allows users to design a vehicle to exactly satisfy performance and range specification with no more power and storage than is needed. Cost model is integrated with energy use model so that one can find the design that results in the lowest lifetime costs, with all relevant tradeoffs and factors accounted for explicitly. We model the cost reduction of fuel cell system over time as production volume increases. More important, we systematically estimate the damage costs from upstream air pollution and provide a comprehensive estimate of the external costs of oil use.

3. Societal Lifetime Cost

The societal lifetime cost (SLC) in US dollars per vehicle is defined as the sum of present values of consumer costs and external costs over the vehicle lifetime adjusted for non-cost social transfers. Figure 1 describes our research framework. A typical gasoline car similar to 2006 Ford Taurus is selected as the baseline. The hydrogen FCV version of this vehicle is modeled in detail, with a careful, comprehensive accounting of all of the differences between a hydrogen FCV and a conventional gasoline ICEV. Both lifetime consumer cost (LCC) and external costs are considered. Vehicle fuel economy is calculated using a detailed energy-use simulation (similar to but not as detailed as ADVISOR) within AVCEM given performance requirements and propulsion characteristics. The fuel cell system cost is simulated at the component level by a three-factor learning curve model. Vehicle ownership and operating costs are included in LCC. Externalities include air pollution, noise, oil use and GHG emissions. The damage costs from upstream air pollution are treated differently from vehicle-use air pollution. Finally, non-cost social transfers are taken into account for societal lifetime cost estimates from both national and global perspectives.

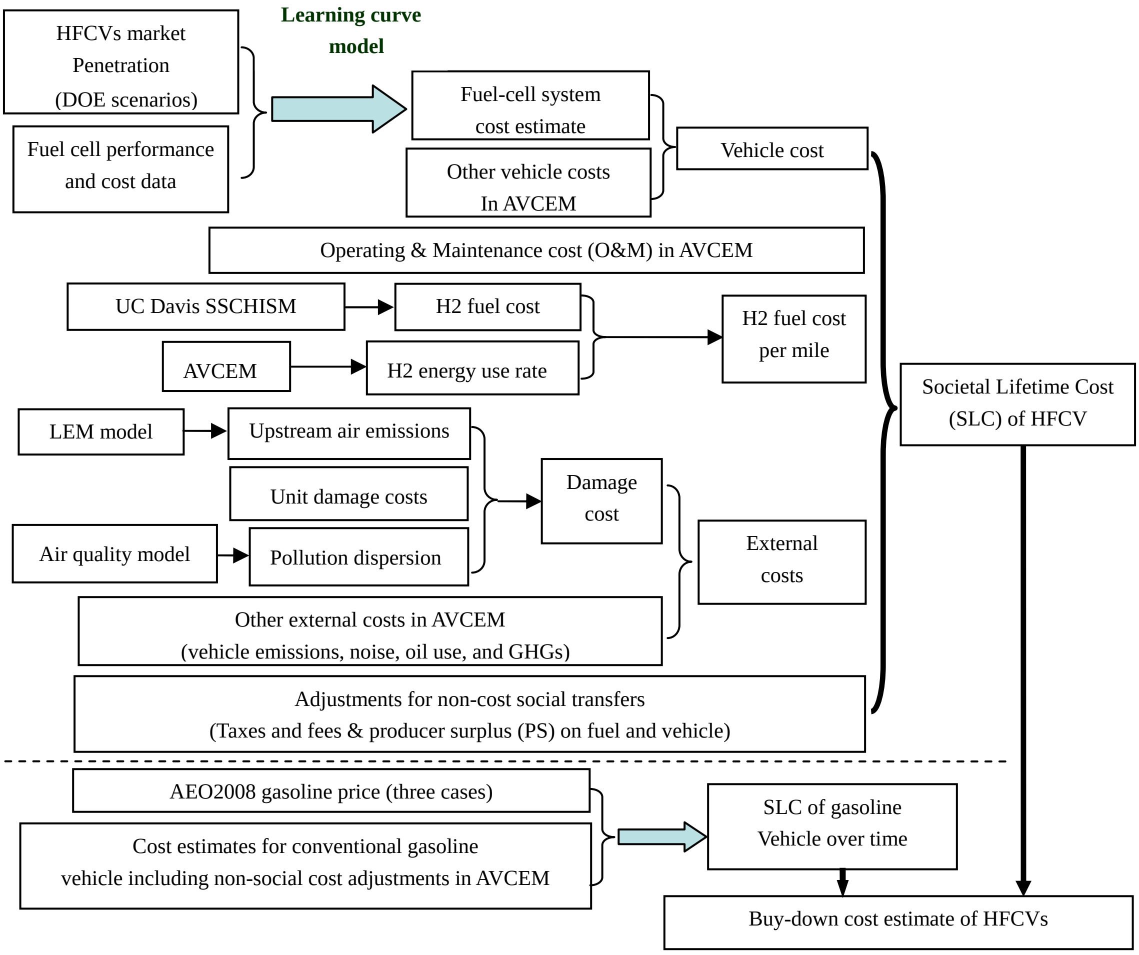

Figure 1 Research Framework

Consumer lifetime cost includes initial vehicle cost, fuel cost and operation and ownership cost from the time of vehicle purchase to the time of scrappage. External cost takes into account the damage costs of air pollution, oil use, noise, and GHG emissions from the full fuel cycle and vehicle operation. Non-cost social transfers include taxes and fees and producer surplus in revenues from the sale of fuels and vehicles. Producer surplus (PS) is an economic measure of the benefit that a producer receives for selling a good in the market; specifically, it is any revenue *above* the total long-run cost including a normal rate of return. The baseline conventional gasoline ICEV we choose is equivalent to 2006 Ford Taurus[3] [32]. A performance summary of the reference vehicle is included in Table 2, and the cost details are presented in Table 3. The final retail cost to consumer[4] for the baseline gasoline vehicle is $22,198 in 2005 dollars.

Table 2 Performance summary of our baseline gasoline car

Parameter	**Units**	**Value**	**A/C[a]**	**Notes**
Vehicle weight	Kg	1540	C	Actual in-use weight including payload and part-filled fuel tank
Engine power	kW	108	A	3.0 liter 6-cylinder with compression ratio of 9.7
Frontal area	m^2	2.00	A	Assumed according to literatures
Drag coefficient	-	0.25	A	MY2006 Ford Taurus: Cd=0.30
Fixed rolling-resistant	-	0.0075	A	Average of 2006 NA-SI and 2030 value assumed in MIT study[5]
Fuel Economy	MPG	18.6/32.3	C	FUDS/Highway, 2006 Ford Taurus: City (20)/Highway (27)

[a] A = assumed, C = calculated.

Table 3 Cost summary of our baseline gasoline car

Component – manufacturing cost	**2005 US $**	**Notes**
Powertrain (engine+transmission)	$1,960	Powertrain adjusted for improvements in power and efficiency and reductions in weight, supposed to a 2006 powertrain
Body	$1,953	Baseline adjusted for changes in safety equipment, drag, and weight, supposed to a 2006 one
Chassis	$3,098	Baseline adjusted for changes in weight, emission control systems, and air conditioning and heating systems, supposed to a 2006 one
Assembly	$1,741	Labor wages based on analysis of industry data; labor time based on previous estimate adjusted for assumed increases in automation
Total manufacturing cost	***$8,752***	***Sum of the above costs***
Division cost	$5,364	Engineering, testing, advertising, etc.; estimated relative to manufacturing cost
Corporate cost	$3,465	Executives, capital, R&D, cost of money and true profit
Dealer cost	$3,446	Dealer margin minus warranty cost
Manufacturers’ suggested retail price	$21,027	Manufacturing cost plus division, corporate and dealer costs
Shipping cost	$524	Proportional to vehicle curb weight ($0.16/lb)
Sales tax	$647	Sales tax
Retail cost to consumer	***$22,198***	***Division and corporate costs, profit, dealer cost, shipping cost and sales tax included***

AVCEM is useful for designing a variety of fuel/propulsion options to meet specified vehicle

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[3] The baseline vehicle is obtained by weight and cost adjustments on 1989 Ford Taurus in AVCEM. See reference 19 for details.

[4] This is slightly different from retail price to consumer that includes license fees, all mark-ups and taxes.

[5] See reference 19.

performance and range requirements. The model starts with vehicle parameters like those in Table 2, sizes all the components in the vehicle for a wide range of vehicle types. The model can calculate the initial retail cost and total private and social lifetime cost in present-value terms that include vehicle cost, fuel cost, periodic ownership and operating costs during the whole vehicle lifetime and external costs over the fuel lifecycle. To model the effect of economies of scale, technological progress, and manufacturing progress on the manufacturing cost of key parts such as electric drive-train, battery, fuel cell, hydrogen fuel storage tank and so forth, AVCEM uses a single cost versus annual production volume function. However, in this paper, we treat these three factors (economies of scale, technological progress, and learning-by-doing) separately. For fuel cell systems, each component cost is the product of a long-run potential cost and the three factors. Here, technological progress is a time-dependent variable, economies of scale depend on annual production, and learning-by-doing is expressed as a function of cumulative production. This method is similar to the approach in the HyTrans model [33] for estimating fuel cell vehicle drive-train costs.

On the basis of US DOE scenarios for hydrogen and FCV market penetration from 2010 to 2025, we employ a learning curve model with these three factors to estimate fuel cell system cost reduction over time. Following the treatment by the NRC [15], we estimate hydrogen fuel cost with the UC Davis Steady State City Hydrogen Infrastructure System Model (SSCHISM), and estimate upstream air pollution damage cost and other external costs with AVCEM and the LEM, and other social-cost work (see section 3.6) done at UC Davis.

3.1 Fuel Cell System Cost Estimate

We define the fuel cell system as including the fuel cell stack and the balance of plant (BOP), but not the hydrogen storage system. This study analyzes hydrogen FCVs that are not hybrids with peak power device such as battery. The fuel cell system cost depends upon fuel cell stack performance, catalyst cost, stack materials, balance-of-plant design, manufacturing process and economies of scale. Several studies [34-36] have clearly shown that pressure, temperature, humidity and stoichiometry are important parameters that affect fuel cell power output and efficiency. In AVCEM, we specify seven fuel cell polarization curves with data points (voltage vs. current density) from a recent study [34] under combinations of different cathode pressure and air stoichiometric ratio (shown in Figure 2). The balance of plant includes air management, water management, thermal management and fuel management. It is especially important to model the air management system accurately, because it consumes more than 50% auxiliary power. AVCEM assumes a variable-speed compressor and at each point picks the operating regime (compression and stoichiometry) that minimizes the total system energy consumption. To reduce compressor parasitic power requirements, an expander can be included to recover energy from the cathode exhaust for the current technology. However, the benefit is relatively small and does not justify the added cost and complexity of the expander [37], so we do not include an expander in our analysis. We adjust the system performance to be roughly consistent with the assumptions by Directed Technologies, Inc. (DTI) [38] as shown in Table 4.

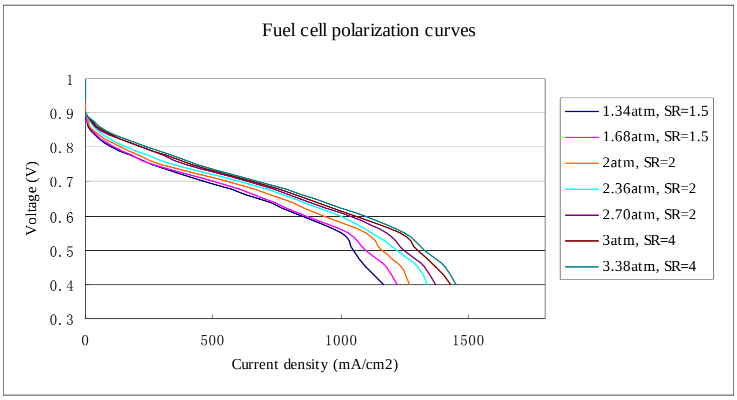

Figure 2 Fuel-cell V-I curves used in AVCEM

Catalyst cost is determined by the catalyst loading and the price of the platinum catalyst. The price of platinum has been volatile: it rose above US$1,000 per troy ounce after 2006, declined sharply in late 2008, and then climbed gradually to $1,200 in early 2009. This volatility, which is due to a number of unpredictable factors that affect both supply and demand, makes it difficult to estimate future platinum prices. Nevertheless, we have assumed that increased demand for platinum in the automotive sector will cause platinum prices to increase. To estimate this, we first examined the recent behavior of global platinum markets, and then employed a logistic function to model the platinum price change with global platinum demand (details will be described in another paper). The upper limit is $2,400 per troy-ounce.

Catalyst loadings significantly affect the cost of fuel cell stack. In a recent report by the California Air Resources Board [39], the total platinum loading among the FCVs in a current demonstration was between 0.8~0.9mg/cm^2. However, the US Department of Energy FreedomCAR Program [40] has set a target of 0.2mg/cm^2 for total catalyst loading at both electrodes. Fuel cell developers estimate loadings could be as low as 0.1~0.5mg/cm^2 after 2015 without adversely affecting life and durability [39]. We assume that catalyst loadings decline with production volume over time, as shown in Table 4.

Table 4 Fuel cell system performance assumptions in DTI and AVCEM[a]

	Current Technology (2006)		**2010 Technology**		**2015 Technology**	
	DTI	AVCEM	DTI	AVCEM	DTI	AVCEM
System net output power	80	69.3	80	64.5	80	61.7
Power density (mW/cm^2)	700	694	1000	837	1000	989
Total Pt loading (mg/cm^2)	0.65	0.63	0.29	0.40	0.19	0.20
Anode catalyst loading	0.3	0.23	0.09	0.12	0.04	0.04
Cathode catalyst loading	0.35	0.40	0.2	0.29	0.15	0.16
Air compression	Twin Lobe Compressor, Twin Lobe Expander		Centifugal Compressor, Radial Inflow Expander		Centifugal Compressor, No Expander	
Air compressor (kW) (net of expander)	8.29	9.87	5.31	7.51	4.81	7.72

[a] Values shown under "AVCEM" are calculated by the model. We assume that the fuel cell performance improves over time.

To estimate how the costs of fuel-cell system components change over time, we use a learning curve model, shown in equation (1), in conjunction with U.S. DOE scenarios of FCVs introduction rates, shown in Figure 3. The learning-curve model estimates the cost of the fuel-cell membrane, gas diffusion layer (GDL), electrode, bipolar plate, and auxiliary subsystems, as a function of three factors: technological change A(t), scale effect S(Q), and learning-by-doing L(N):

$$C(t,Q,N) = C(LR) * A(t) * S(Q) * L(N) \qquad (1)$$

where $C(LR)$ is the long-run OEM cost per unit, t is time (year), Q is annual production, and N is cumulative production. We use the detailed cost data points from DTI to calibrate these factors for each fuel cell component. The technological advances in Table 4 are assumed to be implemented in mass production of fuel cell systems five years later than DTI's assumptions. The three learning-curve factors, A(t), S(Q), and L(N), are estimated as follows:

$A(t) = \exp\{a*(t-t_0)+b\}$ for $t < t_0$, otherwise $A(t) = 1$, t_0 is the base year, and a and b are parameters

$S(Q) = \exp\left(\ln\left(\frac{Q}{Q_0}\right)^c + d\right)$ for $Q < Q_0$, otherwise $S(Q) = 1$, Q_0 is the base annual production, and c and d are parameters

$L(N) = \left(\frac{N}{N_0}\right)^{\log_2(1-lr)}$ for $N < N_0$, otherwise $L(N) = 1$, N_0 is the base cumulative production, and lr = learning rate.

Figure 4 presents our estimated fuel cell system cost change over time for the three U.S. DOE Scenarios (shown in Figure 3). Under scenario 3 when cumulative production volume is about 10 million in 2025, the fuel cell system cost (stack and BOP) is about \$58 per peak kW stack power output. Further system cost reduction would depend on technology advances on materials, power density, catalyst loadings improvements, and simplification of BOP. The estimated fuel cell system cost is much higher than the DOE targets (\$45/kW by 2010 and \$30/kW by 2015), but is consistent with DTI's estimate that at an annual production rate of 500,000 in 2015 a fuel-cell system would cost \$59/kW [38].

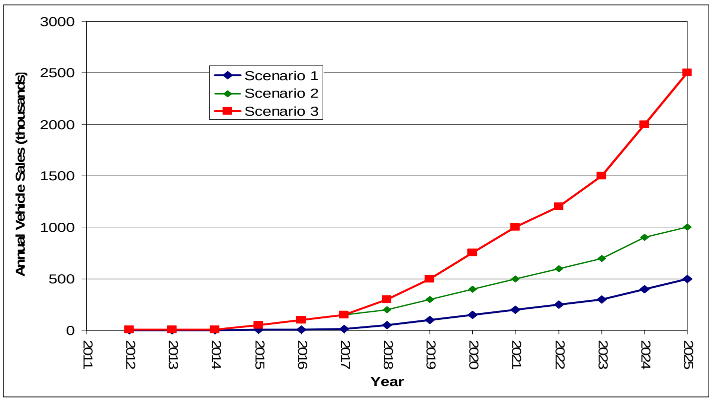

Figure 3 Three US DOE [14] FCVs introduction scenarios

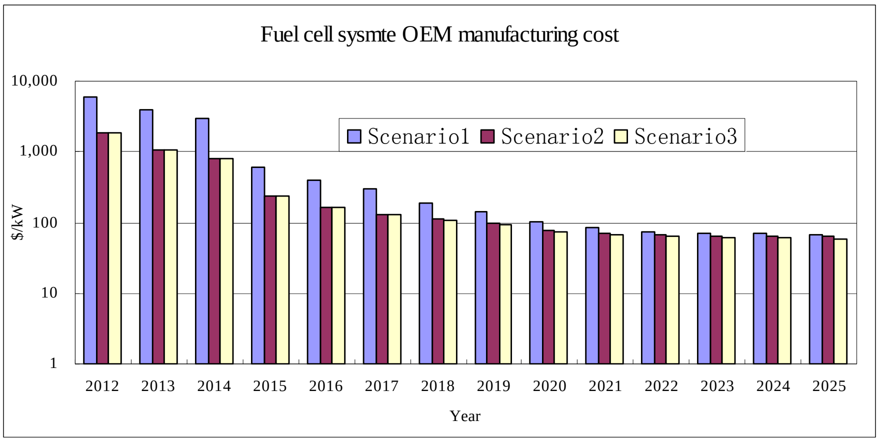

Figure 4 Our estimated fuel cell system cost for the three FCV introduction scenarios in Figure 3 ($/kW)

3.2 Hydrogen on-board storage system cost

We assume that hydrogen on-board FCVs will be stored at high pressure (up to 10,000 psi) in fiber-wrapped pressure vessels. AVCEM estimates the hydrogen storage tank cost in dollars per cubic feet of inner capacity of storage tank per 1000 psi of storage pressure, as a function of the storage pressure (psi) and production scale. The coefficients in the AVCEM functions have been adjusted to make the results approximately consistent with the literature estimates reviewed below. A reduced form of the calculations in AVCEM estimates the tank cost (mass production) at a given storage pressure (10,000 psi) as a function of the weight of hydrogen (equation 2):

$$\text{H2 tank cost (2005 constant US \$)} = 467.76*\text{full tank H2 fuel (kg)} + 50 \qquad (2)$$

Assuming a range of 300 miles over the Federal Urban Drive Schedule, the calculated full-tank hydrogen weight is about 4kg in 2025 for Scenario 3. Putting this into equation (2) results in a tank cost of about $1,900 or about $12/kWh-hydrogen, which is comparable to some other estimates in the literature. For example, TIAX [41] and Argonne National Laboratories (ANL) estimated that for a mid-size vehicle with a 370-mile range in combined urban/highway driving, requiring 5.6 kg of hydrogen, a 5,000-psi tank cost $1,948, or $8.8/kWh, and a 10,000-psi tank cost $2,458, or $11.1/kWh. Carbon fiber was the major cost component. Similarly, Quantum [42] indicates that hydrogen storage tank cost is in the range of $10-$17/kWh and carbon fiber contributes about 65% of system cost. More recently, TIAX, Argonne and other national labs [43] conducted an independent cost assessment of hydrogen storage technologies based on the "Bill of Materials" plus an assumed processing cost, and estimated that a 10,000-psi tank system holding 5.6 kg of hydrogen costs about $3,450 or about $15.6/kWh.

According to the above studies, given the current technology, an on-board hydrogen storage system costs $9-$17/kWh. This hydrogen storage cost value is within the range ($8-$16/kWh) estimated by an expert panel convened by the California Air Resources Board [39], but significantly higher than the US DOE's goals of $2-4/kWh for hydrogen storage.

It is important to note that these cost estimates are based on a large production scale, typically an annual production volume of 500,000. Costs increase rapidly at lower production volumes. For example, the estimated storage system cost in AVCEM under scenario 3 decreases from \$59.5/kWh at 1,000 units per year to \$12.2/kWh at 2.5 million units per year.

3.3 FCV Vehicle Modeling Results from AVCEM

Table 5 presents the cost summary of our hydrogen FCV modeled in AVCEM for year 2025 under DOE Scenario 3, when each fuel-cell system component achieves its long-run cost, i.e. each cost factor in equation 1 is reduced to 1. For DOE Scenarios 1 and 2, hydrogen FCV retail cost to consumer is over \$100,000 initially, and decreases sharply in the first 5-7 years (Figure 5) as production volume increases over time, mainly because of fuel cell system cost reduction.

Table 5 Cost summary of our hydrogen FCV car as compared to our baseline gasoline vehicle (Table 3)

Component – manufacturing cost	2005 US \$	Incremental costs compared to our baseline gasoline vehicle
Electric Powertrain (Motor + controller + transmission)	\$348	-\$1,612 No engine
Fuel cell system (stack + BOP)	\$4,027	\$4,027 Extra component for FCV
Hydrogen storage system	\$1,978	\$1,978 Extra component for FCV
Body	\$2,008	\$55 Greater reduction in weight than ICEV
Chassis	\$2,425	\$-673 No exhaust emission control system
Assembly	\$1,733	-\$8 About the same as ICEV
Total manufacturing cost	***\$12,519***	***\$3,767 Sum of the above incremental costs***
Division cost	\$6,057	\$693 0.3% increase per 1% increase in manufacturing cost
Corporate cost	\$3,841	\$376 0.15% increase per 1% increase in manufacturing plus division costs
Dealer cost	\$3,946	\$500 0.5% increase per 1% increase in factory cost
Manufacturers' suggested retail price	\$26,362	\$5,336 Incremental manufacturing plus division, corporate and dealer costs
Shipping cost	\$402	\$-122 Proportional to vehicle curb weight (\$0.16/lb)
Sales tax	\$803	\$156 Incremental sales tax
Retail cost to consumer	***\$27,567***	***\$5,369 Total incremental retail cost to consumer***

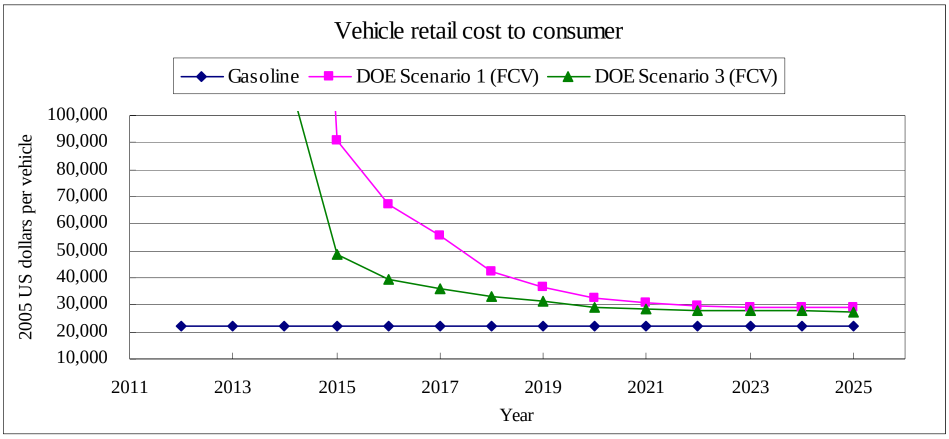

Figure 5 Vehicle retail cost to consumer versus time

3.4 Hydrogen Fuel Cost Per Mile

One of the major concerns for vehicle purchase is fuel cost, which depends on two aspects: fuel economy (energy use per miles) and fuel cost per unit of energy. The former is determined by vehicle performance and the latter by fuel production and delivery costs.

AVCEM contains a detailed energy use simulation model to calculate the amount of energy required for a vehicle with particular characteristics to move over a specified drive-cycle. All forces acting on the vehicle are simulated on a second-by-second scale over a specified drive cycle. The Federal Urban Drive Schedule (FUDS) is a relatively low speed drive cycle with average speed of 19.5 mph. In AVCEM, an adjusted FUDS shown in Figure 6 is created by multiplying the FUDS velocity points by 1.25. According to the simulation result under the adjusted FUDS, the fuel economy of FCVs would achieve 57 miles per gasoline-equivalent gallon (mpgge) for the current technology, several-fold better than the 20.1 mpg of the baseline conventional gasoline vehicle[6]. Although FCVs have higher fuel economy than gasoline vehicles, in the calculation of the fuel cost per mile this is somewhat offset by the higher cost per unit energy. The fuel cost is relatively high in part because hydrogen refueling stations have not yet been put into large-scale commercial operation, and fuel cost is higher in the early stages of infrastructure development [15].

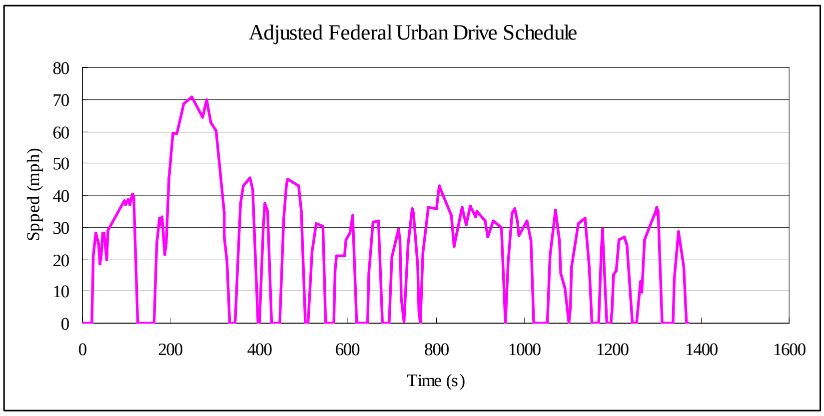

Figure 6 Adjusted FUDS in AVCEM

We use the NRC results [15] for delivered hydrogen fuel costs. Using SSCHISM, the NRC study made several assumptions for a phased introduction of hydrogen infrastructure matching the hydrogen demand in each city, and costs and performance are based on H2A's technology assumptions for year 2015 from the H2A model developed by the U.S. DOE. Initially, five percent of existing gasoline stations is the minimum number of hydrogen stations to ensure adequate coverage and consumer convenience. At this point, station capacity is only 100kg/day with hydrogen from the existing industrial hydrogen system. Then, as demand begins to grow, 500 kg/day onsite steam methane reformers (SMRs) are built. As demand grows further, each station expands to be 1,500 kg/day. Later on, new hydrogen stations are added to meet more demand. The station capacity factor is assumed to be 70%. The estimated hydrogen fuel costs for scenarios 1 and 3 are shown in Figure 7, compared with

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[6] The AVCEM estimate is very close to the EPA-reported combined fuel economy of the 2006 Ford Taurus (20mpg) [44].

the pretax gasoline price from the reference case of the EIA's AEO 2008 [2] (our reference case).

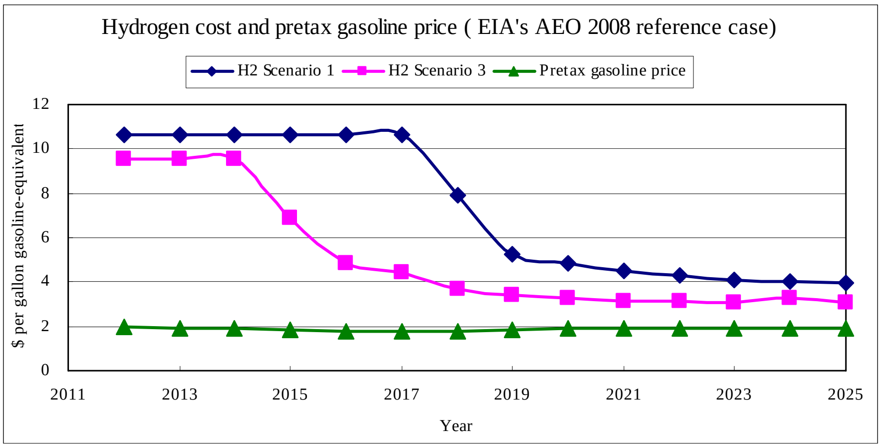


Figure 7 Delivered hydrogen fuel cost as estimated by NRC with SSCHISM

3.5 Periodic ownership and operating costs

The operating and maintenance cost (O&M), discussed in detail by Delucchi [45], includes insurance, maintenance and repair, registration, fuel excise taxes, tires replacement, accessories and other fees, some of which are related to vehicle value, weight, and VMT (vehicle miles traveled). We use these results from AVCEM without any adjustments.

3.6 External Costs

3.6.1. Overview. We use the AVCEM model and additional analysis to estimate the external costs associated with oil use, air pollution, climate change, and noise. Oil-use costs comprise the cost of the Strategic Petroleum Reserve (SPR), macroeconomic costs from oil price shocks, wealth transfers from U.S. consumers to foreign oil producers (a cost only in the U.S. national accounting), the military costs of oil use, and the cost of water pollution due to oil use. Air pollution costs comprise health effects (such as premature mortality), reduced visibility, crop losses, and damages to forests and materials. The external costs of air pollution include the impacts of emissions from the "upstream" lifecycle of fuels as well as emissions from vehicle themselves, and the external costs of climate change include the impacts of emissions from the vehicle lifecycle as well as from the full lifecycle of fuels. The upstream lifecycle of fuels includes energy feedstock production, transportation and storage, and fuel production, transportation, storage and distribution. The vehicle cycle includes vehicle assembly and the lifecycle of materials used in vehicles.

3.6.2. External costs of oil use. Here, the external costs of oil use per mile are calculated simply as the external cost per gallon of petroleum divided by the fuel economy. The fuel economy is calculated within AVCEM. The external cost per gallon is based upon a base-year value and an assumed rate of change, as shown in Table 6. Most of the estimates of the external cost per gallon are based on extensive analyses done by researchers at UCD and elsewhere [46-51].

Table 6 External costs of oil use ($/gallon except as indicated)

Oil-use cost	*Low*	*Best*	*High*	*BY*	*ROC*	*Source of base-year estimate*	*Basis of ROC estimate*
SPR	0.0004	0.0010	0.0052	1991	2.5%	Delucchi (2004f)	Assume increases with GDP
Defense of oil	0.030	0.090	0.160	2004	0.0%	Delucchi & Murphy (2008a, 2008b) estimate $0.03 to $0.15 per gallon of motor fuel, including about 6% non-petroleum components on average; thus, dividing by 0.94 yields the cost per gallon of oil.	Delucchi & Murphy's (2008a, 2008b) analysis suggests that total cost increases at the rate of increase in fuel consumption, which suggests a stable $/gallon cost.
Pecuniary externality	0.033	0.088	0.155	2000	1.5%	Leiby (2007) estimates "monopsony" or demand-related wealth-transfer costs of $2.77 to $13.11 (best: $7.41) per bbl of imported oil, and reports that imported oil is 58.6% of total oil demand; thus, we assume that 58.6% of motor fuel comes from imports. However, it appears that Leiby's (2007) estimate includes what we estimate as producer surplus; to account for this, we reduce Leiby's (2007) estimates by 15%.	Assume increases with price of oil.
Price-shock GNP cost	0.029	0.064	0.103	2005	1.5%	Leiby (2007) estimates "macroeconomic disruption /adjustment costs" of $2.10 to $7.40 (best: $4.59) per bbl of imported oil, and reports that imported oil is 58.6% of total oil demand; thus, we assume that 58.6% of motor fuel comes from imports.	Base year from Leiby (2007). Factor increase assumed to be rate of increase in oil prices.
Water pollution	0.0023	0.004	0.0076	1991	2.5%	Delucchi (2000, 2004a).	Assume increases with GDP.

Notes: BY = base year, ROC = annual rate of change in base-year value

Recall that in this analysis we calculate social costs both from a US perspective and from a global perspective. The pecuniary externality (Table 6), which results from oil price changes, is a real cost to the US from the perspective of the US, but from a global perspective it is an international wealth transfer and not a social cost (to be deducted).

3.6.3. External costs of air pollution. As mentioned above, we make separate estimates of air pollution damage costs due to emissions from motor-vehicles and air-pollution damage costs due to emissions from the upstream lifecycle of fuels. In general, the air pollution damage cost per miles is the product of a per-mile emission rate (e.g., g/mile) and a per-gram damage cost (e.g., $/g). Our estimates of g/mile motor-vehicle emissions are for model-year 2015 light-duty gasoline vehicles from the LEM [52]. We use half of the estimated values for our calculations in AVCEM as shown in Table 7, assuming that vehicles reach the midpoint of their lives (in about year 2020).

Table 7 Motor-vehicle emissions in g/mile used in AVCEM

Air pollutant	Emission rate
NMOC tailpipe	0.125
NMOC evaporative	0.110
NOx	0.235
CO	1.750
SOx	0.017
PM	0.010

Our estimates of the per-gram damage costs of motor-vehicle emissions, shown in Table 8, are based on detailed models of the relationships between emissions, air quality, physical impacts, and economic welfare [53-55], updated from their original 1990 baseline as described in Delucchi (2006) [56].

Table 8 Vehicle-related air pollution damage cost from AVCEM (in 2005 dollars per tonne)

	Low	High	Medium
NMOC tailpipe	1410	46248	8075
NMOC evaporative	1410	46248	8075
NOx	3624	72798	16242
CO	14	141	45
SOx	17766	240856	65414
PM	19881	269874	73249
Benzene	160	1599	506
Formaldehyde	0	0	0
1,3-butadiene	1808	29827	7343
acetaldehyde	0	1185	0

Note: Medium value is the geometric average of low-cost and high-cost.

Our estimates of upstream fuelcycle emissions (g/mile) are from the LEM, for the year 2020. Table 9 shows the LEM estimates and estimates from GREET [57] for comparison. Most LEM values are higher than those from GREET, on account of differences in assumptions and methods in the two models. GREET projects higher upstream PM emissions than the LEM because the LEM takes into account emission reductions due to emission controls while GREET does not.

Table 9 Upstream air pollution in grams per mile from LEM and GREET 1.7

	LEM (2020)		GREET 1.7 (2020)	
Air pollutants	Gasoline	FCV	Gasoline	FCV
NMOCs	0.149	0.015	0.124	0.021
NOx	0.301	0.197	0.208	0.113
CO	0.262	0.134	0.070	0.051
SOx	0.206	0.065	0.103	0.091
PM	0.009	0.005	0.056	0.065

Note: NMOCs=nonmethane organic compounds, NO_x=nitrogen oxides, and PM=particulate matter

To estimate \$/g damages of emissions from the upstream lifecycle of fuels, we adjust our estimates of motor-vehicle \$/g damage costs for differences in exposure to motor-vehicle air pollution versus upstream air pollution. This adjustment is done on the basis of the analysis of Delucchi and McCubbin [58], who develop a Gaussian dispersion air quality model to estimate a set of normalized terms. These terms are the fraction of emissions from each upstream source reaching the ambient air quality monitors, relative to the fraction of direct emissions of fine PM from light-duty gasoline vehicles reaching the ambient air quality monitors. The normalized dispersion terms, or ratios, are the contribution to ambient pollution per unit of emission for each pollutant and emission-source category, relative to the contribution of light-duty gasoline motor-vehicles. To account for considerable uncertainties and site variabilities, low and high values are assumed for the estimated ratios. According to this definition, a higher value of the normalized term for non-motor-vehicle sources results in a lower dollar cost of motor-vehicle air pollution and vice versa. Here we apply the ratios estimated for urban monitors within an US average county for our analysis and assume that, in general, three of the emission categories are matched with the three upstream fuel-cycle stages, as shown in Table 10. An important exception is hydrogen production. Because we assume hydrogen from onsite SMR, we match hydrogen production with the fuel-storage, distribution, and dispensing stage instead of the fuel-production stage. As the estimated ratios are almost the same across their studies pollutants, we use only one set of values for the five pollutants presented in Table 8.

Table 10 Relative contribution of upstream air pollution to ambient air quality

Stage of upstream	Emission-source category	low	high
Feedstock activities	Agricultural and forestry, and managed burning; natural gas extraction	0.42	0.12
Fuel production	Chemistry and allied product manufacturing; metals processing; petroleum refining; other industry	0.38	0.06
Fuel storage, distribution, and dispensing	Solvent utilization, storage and transport; waste disposal; recycling, onsite hydrogen production	0.59	0.20

Note: Low and high refer to motor-vehicle-related damage costs from air pollution.

The upstream air pollution damage costs for the three stages (feedstock activities, fuel production, and fuel storage, distribution and dispensing) shown in Table 11 are estimated by multiplying the vehicle-related damage costs in Table 8 by the corresponding damage ratio in Table 7. For instance, under a low case, the damage cost of the CO emission from feedstock activities in dollars per metric ton is 14 times 0.42.

Table 11 Upstream air pollution damage cost (in 2005 constant dollars per metric ton)

Stage	Air pollutant	Low	High	Medium
Feedstock activities	NMOCs	592	5550	1813
	NOx	1522	8736	3646
	CO	6	17	10
	SOx	7462	28903	14686
	PM	8350	32385	16444
Fuel production	NMOCs	536	2775	1219
	NOx	1377	4368	2452
	CO	5	8	7
	Sox	6751	14451	9877
	PM	7555	16192	11060
Fuel storage, distribution, and dispensing	NMOCs	832	9250	2774
	NOx	2138	14560	5579
	CO	8	28	15
	SOx	10482	48171	22471
	PM	11730	53975	25162

Table 12 presents the upstream air pollution for each stage, as a percentage of the total upstream emissions, for the two vehicle options. For each pollutant, we multiply these percentages by the total upstream emissions in Table 9 to obtain the emissions from each stage, which are then multiplied by per-unit damage costs from Table 11 to obtain the total upstream damage cost in dollars per mile.

Table 12 Fractions of air pollution from each stage of upstream activities from LEM

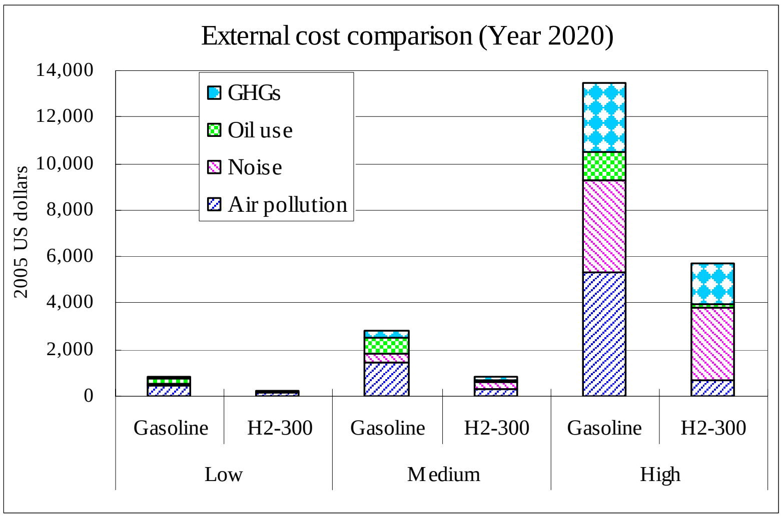
		NMOCs	NOx	CO	Sox	PM
Gasoline	Feedstock activities	0.21	0.60	0.71	0.73	0.55
	Fuel production	0.07	0.34	0.24	0.21	0.43
	Fuel storage, distribution, and dispensing	0.72	0.06	0.05	0.06	0.02
FCV	Feedstock activities	0.79	0.51	0.74	0.19	0.72
	Fuel production	0.11	0.27	0.15	0.22	0.11
	Fuel storage, distribution, and dispensing	0.10	0.22	0.11	0.59	0.17

3.6.4. External costs of climate change. The cost per mile of damages due to climate change is calculated as the product of g/mile GHG emissions from the fuel and vehicle lifecycle and $/g damages from emissions of GHGs. Estimates of lifecycle CO_2-equivalent GHG emissions are from the LEM. The *global* climate-change damage cost in dollars per metric tonne carbon

($/tC) is assumed to be $5/tC in the low case, $16/tC in the medium case, and $150/tC in the high case, based on Tol's result [59] from an assessment of 28 published studies on marginal cost of CO_2 emissions and recent work by Repetto and Easton [60]. The climate-change damage cost to the U.S. alone, which is relevant when takes a U.S.-only as opposed to a global perspective, is much lower, partly because the U.S. is wealthier than the rest of the world and partly because the US might suffer less severe effects than will some other countries. On the basis of a review and analysis of the literature [47, 60-62], the GHG damage cost in the US is assumed to be $0/tC in the low case, $1.2/tC in the medium case, and $17.4/tC in the high case.

3.6.5. External costs of vehicle noise. Estimates of the damage cost per mile of noise from gasoline vehicles are from Delucchi and Hsu [63]. AVCEM assumes that hydrogen FCVs produce slightly less noise, and hence have slightly lower noise-damage costs, than do gasoline ICEVs, because electric powertrains generally are quieter than engines.

3.6.6. Comparison of total external costs. Figure 8 shows our low, medium and high estimates of the present value of the external costs of gasoline ICEVs and hydrogen FCVs. The discount rate for externalities is set at 3% for present value calculations. Hydrogen FCVs have significantly lower external costs of air pollution, climate change, and oil use. The present value of this difference is less than $1,000 in the low-external-cost case, but is over $2,000 in the medium-external-cost case and over $7,000 in the high-external-cost case. Air-pollution damage cost is the biggest external cost for gasoline vehicles. Noise-damage cost is a major cost in the high-external-cost case because we assume the $/mile damage cost of noise in the high case is ten times that in the medium case.



Note: H2-300 refers to hydrogen FCV with a range of 300 miles

Figure 8 External costs comparison in present values (Global accounting)

3.6.7. Comparison with other estimates of FCV external costs. As stated in the literature review section, Ogden et al. include externality valuations of damages from air-pollutant and GHG emissions and of oil supply insecurity and their estimates show that advanced gasoline vehicles have about $2,800 more external costs than hydrogen FCVs with medium valuation of externalities. Thomas estimates that FCVs will achieve total societal cost savings from reductions in urban air pollution, GHGs and oil consumption by a factor of about 8-20 relative to ICEVs. That Korea study shows that all hydrogen pathways studied can yield the fuel lifecycle cost-savings of about $10,000 to $15,000 compared to conventional gasoline with the average value of social costs from GHGs and regulated air emissions. All these three studies do not include the damage cost of noise. Regarding the external cost of oil use, Ogden et al. considers the US military cost for defending Persian Gulf oil only, and Thomas estimates the reduced oil consumption only, while the Korea study does not consider it at all. For air pollution, both Ogden and Thomas used the results from the GREET and air-pollutant damage costs were from the literature.

In contrast, we quantify the external cost associated with oil use in great details and include more cost items as shown in Table 6. The damage costs of air pollution from upstream fuelcycle and vehicle operation are treated differently. Particularly, we estimate the total external costs of air pollution, GHGs, oil use and noise in a self-consistent framework.

3.7 Non-cost social transfers

Expenses such as taxes, producer surplus on payments for fuel, and producer surplus on payments for vehicles are costs to consumers but are wealth transfers from the perspective of society. Hence, these three items should not be treated as social costs per se.

Using information from FHWA (Federal Highway Administration), AVCEM calculates the current fuel taxes on gasoline on a cost-per-miles basis that includes federal, state, and local excise taxes. A scaling factor, which is specified by the user, represents the cost-per-mile excise taxes ratio of other vehicles to gasoline vehicle. The ratio is set as one in the base case, i.e. all vehicles pay the same fuel taxes per mile. Although initially fuel tax policy might be used to give an advantage to alternative fuels, ultimately the revenues from the fuel tax would have to be replaced if alternative fuels became important. Fuel taxes are counted in the O&M cost category as a cost item of consumer cost, and deducted in the social-cost accounting.

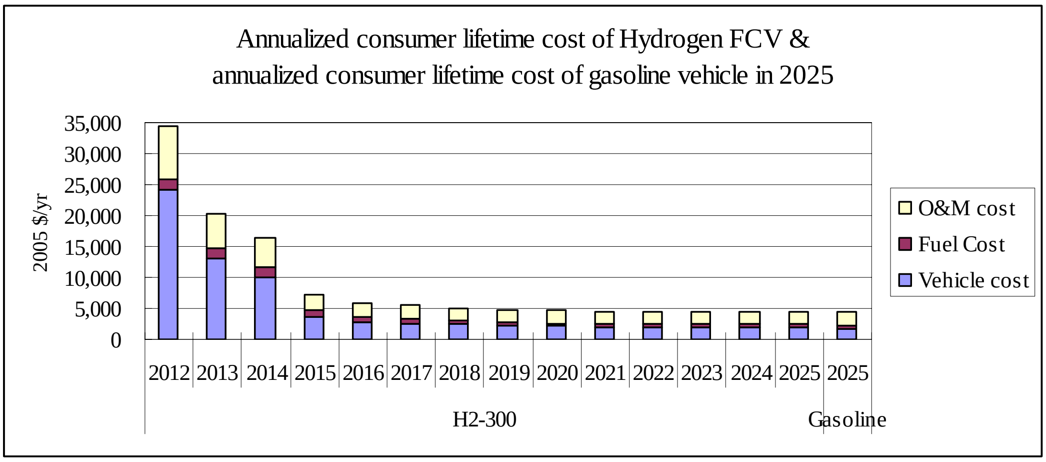
Producer surplus (PS) is any revenue *above* the total long-run cost including a normal rate of return. When estimating the PS associated with various fuels, AVCEM makes a distinction between a U.S. national accounting (in which, for example, wealth transfers outside of the U.S. are a cost to the U.S.) and a global accounting (in which all wealth transfers between countries are transfers and not social costs). Thus, the PS received by foreign oil producers is a real cost to the U.S. from the US' perspective, not from a global perspective. Therefore, we deduct PS from fuel cost – that is, we do *not* count is as a social cost – only in the global perspective accounting. To estimate the PS fraction of payments for fuel, Delucchi [64] characterized the long-run marginal cost curve with a nonlinear function developed by Leiby [65] for U.S. oil producers, OPEC, and the rest of the world. In our analysis, we assume the PS fraction for domestic producers is 0.35 for gasoline and 0.07 for hydrogen, and for foreign producers 0.40 for gasoline, 0.10 for hydrogen. The fraction of fuel from the US producers is further assumed to be 0.50 for gasoline and 0.80 for hydrogen.

The PS portion in the total payment for purchasing an automobile is estimated as the true corporate profit and is assumed to be 3% of the factory invoice price.

4. Results

4.1 Societal lifetime cost results

The consumer lifetime cost (CLC) is the sum of the vehicle cost, fuel cost and O&M cost over the vehicle lifetime. For meaning comparison between a hydrogen FCV and a gasoline vehicle, we multiply consumer lifetime cost in cost-per-mile by annual vehicle miles traveled (VMT) for each vehicle type. The annual VMT is the same for the two vehicles, about 10,000 miles, calculated in AVCEM for gasoline vehicles. Figure 9 presents our estimated annualized CLC of a hydrogen FCV under DOE Scenario 3 (Figure 3), which shows the steepest growth in vehicle production. The annualized CLC of a conventional gasoline vehicle in 2025 is also shown here for comparison. Initially, a hydrogen FCV costs about 14 times more than a conventional gasoline vehicle, the hydrogen fuel cost is about three times of gasoline fuel cost for the first three years, and the FCV has much higher O&M cost than the gasoline vehicle (in AVCEM some O&M cost items are proportional to vehicle value such as insurance). However, as technology advances and production volume increases over time, each cost category dramatically decreases and eventually becomes cost-competitive. More importantly, the annualized lifetime hydrogen fuel cost in dollars per vehicle turns out to be much lower than for gasoline after 2019 because of the higher fuel economy of FCVs and the reduced hydrogen cost in dollars per kg, as the hydrogen supply system grows, experiencing scale economies of production and delivery. By 2025, the annualized value of FCV lifetime costs is only about $240 higher that of a gasoline vehicle. Note that while the initial vehicle cost is still higher for hydrogen, a FCV (about 17 years) can last longer than a gasoline ICEV (about 15 years), and this has been considered for lifetime cost-per-mile calculations within AVCEM. The longer lifetime tends to offset the higher initial cost for FCVs.



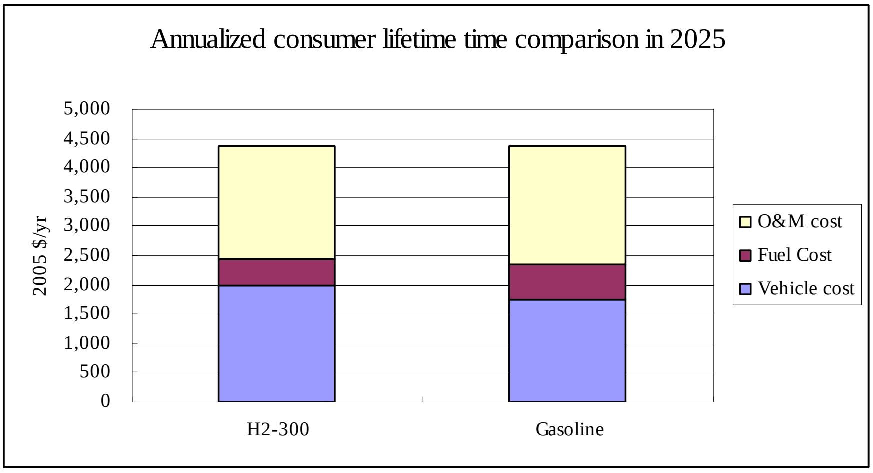


Figure 9 Consumer lifetime cost (present value) comparisons

Some key cost and performance information for the two vehicle options is included in Table 13, in which the fuel economy of gasoline vehicles is assumed to improve beyond 2006 according to the recent NRC study. The fuel economy of FCVs is calculated in AVCEM over the adjusted FUDS as shown in Figure 6. Compared with the NRC study, this result is more aggressive early on and less aggressive for long term. Our fuel cell vehicle retail cost results are similar to those from ORNL [32], MIT [18], and the NRC (2008) [15] (See Table 14).

Table 13 Cost and performance for gasoline vehicle and hydrogen FCV

	Gasoline vehicle	Hydrogen FCV
Vehicle retail cost*	$23,203 (remains constant over time)	$350,000 in 2012, reduced to $28,500 in 2025 by learning curve model. (Incremental cost $5,000)
Fuel economy (mpgge)	20.1 in 2006, improve 2.6% per year to 32.7 in 2025, then 1.7% increase per year to 38.8 by 2035	57.0 in 2012, 64.3 in 2015, 66.9 in 2020, 67.7 in 2025 and beyond, calculated in AVCEM based on assumed fuel cell system performance above

* Vehicle retail cost to consumer, calculated in AVCEM, is the present value of CLC of vehicle purchase, about 2.65 times OEM cost for gasoline vehicle and about 2 times OEM cost for hydrogen FCV.

Table 14 Comparison with other studies on fuel cell cost estimates

	Baseline gasoline vehicle	Fuel cell vehicle
ORNL	- -	DOE fuel cell target: $45/kW by 2015, $30/kW by 2020 (onboard H2 storage included) $350,000 in 2012, $56,500 in 2015, $35,000 in 2020 and $25,000 in 2025
MIT	- Fuel economy: 26 in 2006, 42.8 in 2030	OEM incremental cost compared to the 2030 gasoline vehicle: $3,600 ~ $5,100 Fuel economy (mpgge): 97 in 2030
NRC (2008)	Retail price: $23,050 constant; Fuel economy: 25.2 mpg in 2015, 42.4 mpg in 2050	Vehicle incremental retail price: from initially over $100,000 to $3,600 (learned out); Fuel economy: about 2 times that of gasoline vehicle 57.2 mpg in 2015 -> 84 mpg in 2050

To compare the vehicle options in terms of societal cost, we add external costs to and deduct non-cost social transfers from the CLC. Figure 10 presents the societal lifetime cost (SLC) in present value for the U.S. national accounting in the years 2012 and 2025 with medium-case external costs. The external costs are quite small compared to fuel costs and also smaller than those estimates by Ogden [11], Lee [26] and Thomas [27], primarily because we assume much lower GHG damage costs, especially for the US accounting. Non-cost transfers that are to be deducted are shown below the x-axis as negative values. For conventional gasoline vehicles, about 17.5% of gasoline fuel cost is a wealth transfer from consumers to producers within the U.S, and about 38% is a transfer globally. In Figure 11 we actually deduct the non-cost transfers from the appropriate category to end up with what we call an adjusted cost, as follows: vehicle cost less the PS on vehicle purchase is "vehicle cost adj," fuel cost less the PS on fuel purchase is "fuel cost adj," and O&M cost less taxes and fees is "O&M cost adj". As can be seen from Figure 11, the difference between the SLC of the hydrogen FCV and the SLC of the gasoline ICEV is greater in the global accounting than in the US accounting. This is because in the global accounting the societal cost of gasoline is less than in the US accounting, and some costs from the US perspective are non-cost transfers from a global perspective.

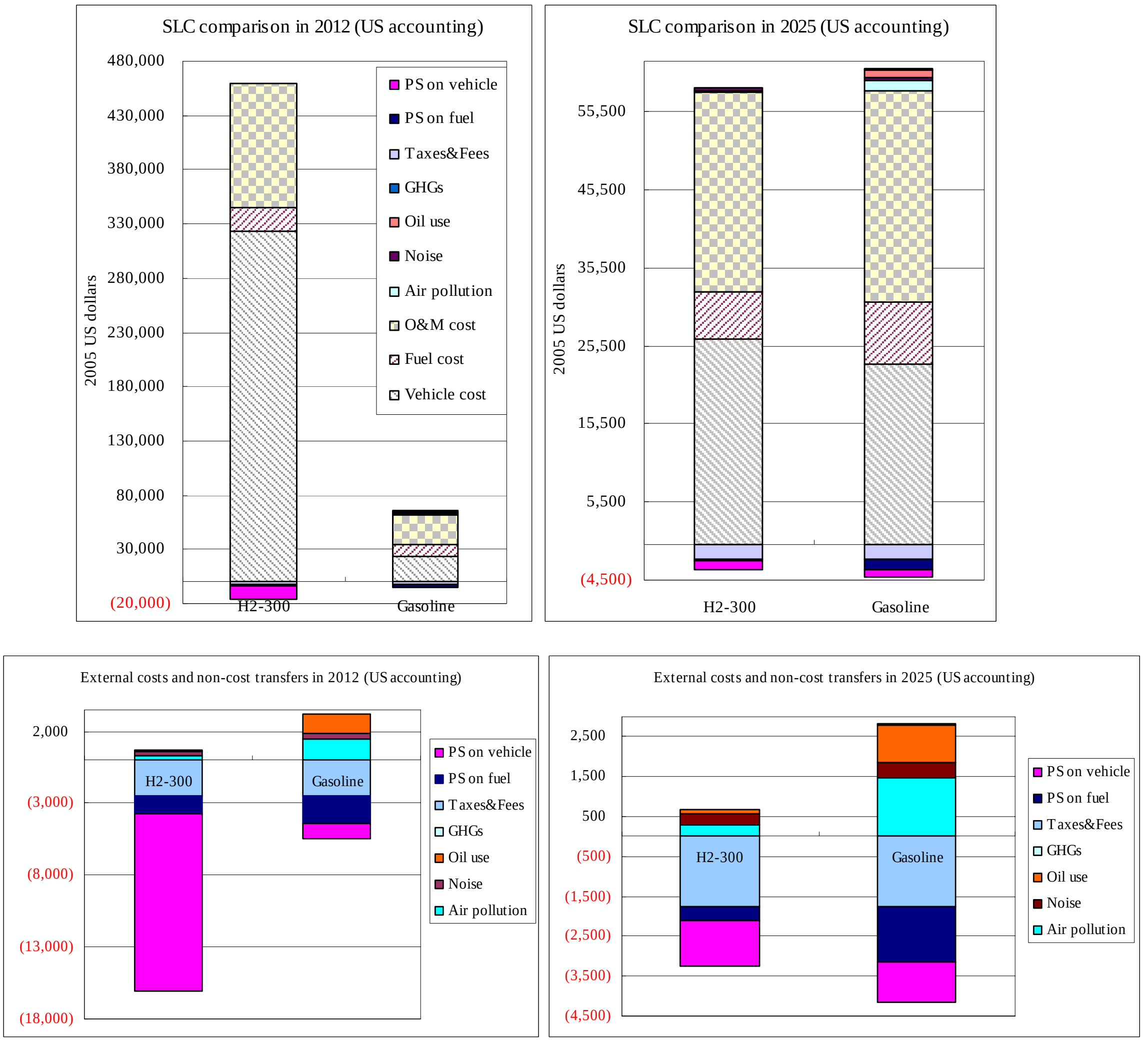


Figure 10 Societal lifetime cost comparison in present value (U.S. national accounting)

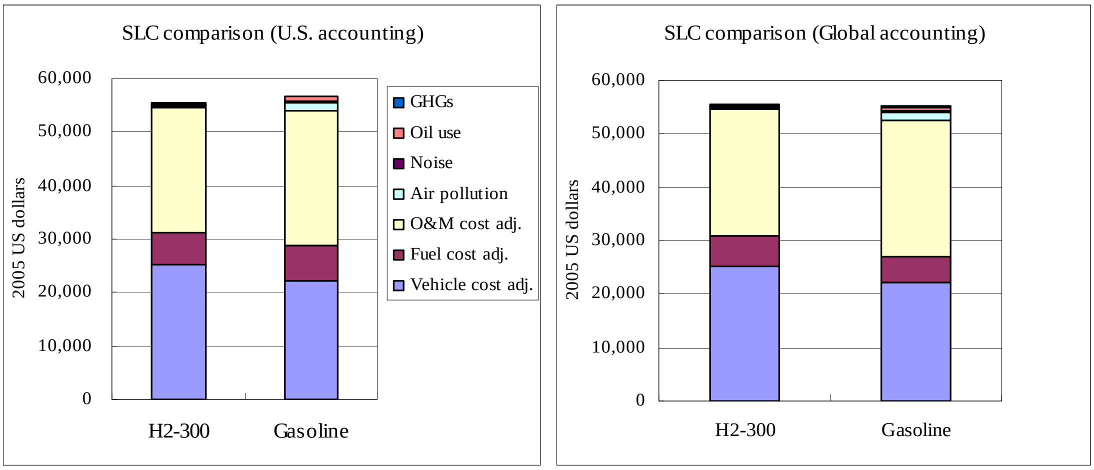


Figure 11 Societal lifetime cost comparison in 2025 adjusted with non-cost social transfers

4.2 Buy-down costs

The buy-down cost (BDC) of hydrogen FCVs is defined as the present value of the incremental expenditures on FCVs (the difference between the lifetime cost of the FCV and the lifetime cost of the gasoline ICEV) accumulated from the time of first market introduction of FCVs to the time at which the lifetime cost of the FCV (which will be declining over time due to leaning and mass production) equals the lifetime cost of the gasoline ICEV, as shown in equation 3. The date when the lifetime cost of the FCV equals the lifetime cost of the gasoline ICEV is designated the "breakeven" year.

$$BDC = \sum_{i=t_0}^{t_e} PV_i\{[LC_i(FCVs)*Q_{fcv} - LC_i(GVs)*Q_{gv}]\} \qquad (3)$$

Where PV refers to present value (year 2012), LC is the cost basis (consumer lifetime cost or societal lifetime cost) in present value[7]. When LC refers to consumer lifetime cost, periodic costs include full fuel cost and O&M cost. This is termed the "CLC". When LC refers to societal lifetime cost, vehicle first cost excludes PS on vehicles and periodic costs exclude taxes and fees and PS on fuel but include external costs. This is termed the "SLC". Q_{fcv} is the annual production volume of FCVs, and Q_{gv} is the annual volume of GVs replaced by FCVs. Note that the calculation of the year-2012 present value involves two steps" taking the year-*t* present value of the lifetime cost stream of vehicles introduced in year *t*, and then converting year-*t* values to year-2012 present values.

We assume FCVs have a 10% longer lifetime than gasoline vehicles [31] as electric motors

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[7] The present value here is calculated using specific vehicle lifetime, which is different from the results shown in Figures 10-11, because we should account for the longer lifetime of FCVs and a smaller number of FCVs replacing ICEVs at the fleet level for the buy-down cost calculation, where we hold fleet-level VMT benefits constant.

last longer than engines[8]. To account for the different lifetime, we assume the number of displaced gasoline vehicles is the same as that of produced FCVs for the first 10 years[9], and then after that the number of gasoline vehicles is 1.1 times the volume of FCVs.

Table 15 presents the calculated buy-down costs in constant 2005 US dollars for the fastest market penetration scenario, where low, medium and high refer to low, medium and high valuation of externalities. The “breakeven” will occur when FCVs achieve the same LC as conventional gasoline vehicles. For our reference case, hydrogen FCVs, on a CLC basis, would reach breakeven in 2022, and the buy-down cost would be $24 billion. However, on a societal lifetime cost (SLC) basis with a US perspective, the breakeven year of FCVs under medium valuation of external costs would be sooner, and the buy-down cost of FCVs would be about $19 billion. At the time of SLC parity in the US, the hydrogen FCV penetration rate is about one million vehicles or 0.5% of the total US vehicle fleet. The SLC buy-down costs thus are significantly lower than the CLC buy-down costs. High valuation of external costs would reduce the buy-down cost by on the order of ten billion dollars. Under medium valuation of external costs, global accounting would have about $6 billion higher buy-down cost than the US accounting. Even under the low-external-cost case, FCVs would achieve SLC breakeven with gasoline vehicles before 2030 with the US accounting stance while global accounting would not. With low valuation of externalities, however, hydrogen FCVs will not achieve cost competitiveness for the global accounting within the time period studied (2010-2050) in terms of present values comparison.

Table 15 Buy-down cost for the reference case (in 2005 US billion dollars)

Basis		Present value		
Consumer lifetime cost (CLC)	Buy-down cost	24.45		
	“Breakeven” year	2022		
Societal lifetime cost (SLC)		Present value		
		Low	Medium	High
US accounting	Buy-down cost	24.44	18.90	9.67
	“Breakeven” year	2022	2022	2020
Global accounting	Buy-down cost	-	25.59	12.19
	“Breakeven” year	>2050	2022	2021

Note: Low, medium and high refer to different valuation of externalities.

The ultimate learned-out cost and performance of FCVs depend upon many factors, including technological advances, market penetration, infrastructure investment, and consumer

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[8] In theory this difference in potential lifetime might affect how much vehicles are driven each year. Likewise, in theory, differences in initial and operating costs between FCVs and gasoline ICEVs might affect how the vehicles are driven. However, we suspect that these effects would be small, mainly because consumers typically have limited alternatives to driving and limited flexibility in travel planning. We do not consider these effects here.

[9] The benefit of the longer lifetime of FCVs won’t take effect until some gasoline vehicles begin to retire, which may take 5 to 10 years.

acceptance. Besides these uncertainties, the future gasoline price is also an important determinant to the buy-down cost of hydrogen FCVs. Table 16 presents the sensitivity analysis when we use low-oil-price case and high-oil-price case from EIA AEO 2008. The projected oil prices per barrel for the period 2010-2030 are $52-$77 under the reference case, $32-$72 under the low-price case, and $80-$94 under the high-price case. The corresponding gasoline prices are $1.72-$2.42/gallon in the low-oil-price scenario, $2.16-$2.52/gallon in the reference-oil-price scenario, and $2.80-$3.47/gallon in the high-oil-price scenario. The results show that gasoline prices have significant impacts on the competitiveness of hydrogen FCVs. As shown in Figure 12 for the US accounting, the x-axis is the ratio of externalities or oil prices to the reference case, and the y-axis is the buy-down cost. The figure visually shows that both oil prices and externality valuations significantly affect the buy-down cost of hydrogen FCVs. In the reference-oil-price scenario, the difference of the buy-down costs for the US between low and high valuations of externality is about $15 billion. With medium external costs, the high-oil-price scenario, compared to the low-oil-price scenario, can have $14 billion savings on the buy-down cost for the US accounting. With the combination of low-oil-price and medium external costs or reference-oil-price and low external costs for the global accounting, hydrogen FCVs would not achieve cost competitive with gasoline vehicles. From the global perspective, however, the high-oil-price scenario with medium external costs could reduce the buy-down cost by $10 billion, and the reference-oil-price with high external costs could cut the buy-down cost by $13 billion, relative to the reference-oil-price with medium external costs.

High oil prices would make FCVs more attractive to consumers beyond 2022 and the buy-down cost on a CLC basis is about $14 billion. To put this in perspective, Delucchi and Murphy [49] estimate that the cost of defending Persian-Gulf oil used by motor vehicles in the US was between $6 billion and $25 billion in 2004. With medium external costs and the US perspective, the buy-down cost difference between the low-oil-price scenario and the high-oil-price scenario is about $14 billion, which is around one-sixth of 2008 capital expenditures for gasoline and diesel infrastructure ($87 billion as estimated by Thomas [27]). With the high-oil-price scenario and the US perspective, the buy-down cost difference between low and high external costs is about $10 billion; with the global perspective, the difference is about $13 billion.

Table 16 Sensitivity Analysis of buy-down cost to changes in gasoline prices

EIA low oil price case

Basis		Present Value		
Consumer lifetime cost (CLC)	Buy-down cost	-		
	“Breakeven” year	>2050		
Societal lifetime cost (SLC)		Present value		
		Low	Medium	High
US accounting	Buy-down cost	-	25.81	13.69
	“Breakeven” year	>2050	2022	2021
Global accounting	Buy-down cost	-	-	15.86
	“Breakeven” year	>2050	>2050	2021

EIA high oil price case

Basis		Present Value		
Consumer lifetime cost (CLC)	Buy-down cost	14.27		
	“Breakeven” year	2022		
Societal lifetime cost (SLC)		Present value		
		Low	Medium	High
US accounting	Buy-down cost	15.86	12.04	5.93
	“Breakeven” year	2022	2022	2019
Global accounting	Buy-down cost	20.41	15.40	7.44
	“Breakeven” year	2022	2022	2020

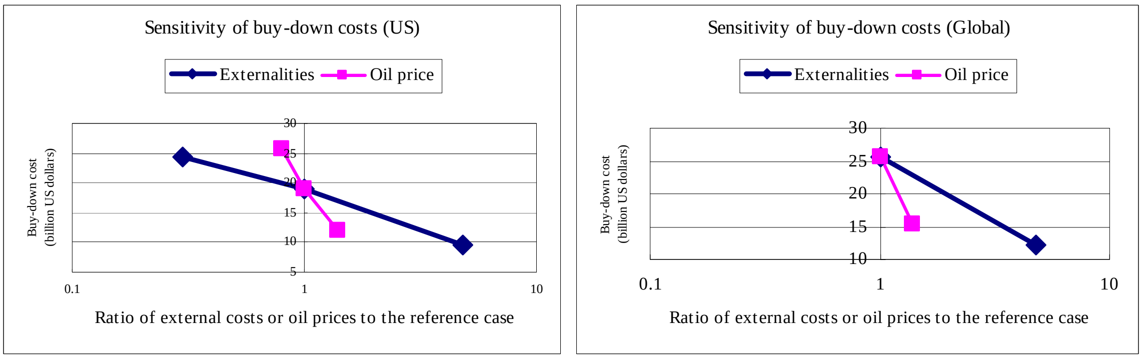

Figure 12 Sensitivity of buy-down costs

5. Conclusion

We have made a careful analysis of the full societal lifetime cost (SLC) of FCVs and gasoline vehicles, including consumer lifetime cost (CLC) (based in part on a learning-curve model), external costs, and adjustments for non-cost social transfers. Our results show that FCVs would have higher initial vehicle cost even when mass produced. For our reference case, the magnitude of externalities for a hydrogen FCV can be $700-$900, about $2,000 less compared to a gasoline vehicle. The external cost savings from FCVs with high valuation of externalities can be about $7,000. On a CLC basis, the buy-down cost of hydrogen FCVs for our reference case is about $24 billion US dollars. When the medium-case value of externalities and non-cost social transfers are included, the buy-down cost from the US perspective is $19 billion and the buy-down cost is $25 billion from a global perspective though the “breakeven” year remains the same. However, with the high-case value of externalities the societal buy-down cost is about $9 billion lower in the US accounting and about $13 billion lower in the global accounting. This indicates that societal benefits of hydrogen and FCVs do make these vehicles more competitive than gasoline vehicles. With medium-value externalities, the buy-down cost from the US perspective would be increased under the low-oil-price scenario and decreased under the high-oil-price scenario by $7 billion, resulting in a spread in the buy-down cost of almost $15 billion between the low-oil-price scenario and the high-oil-price scenario. We conclude that the expenditures required to make hydrogen FCVs cost competitive with gasoline vehicles are quite sensitive to the valuation of externalities and to the future price of gasoline.

Our results are broadly consistent with the NRC study [15], in which the buy-down cost (difference in vehicle capital cost and cumulative fuel cost) in the high-oil-price scenario is about $22 billion and the fuel-cost savings exceed the extra money on vehicle purchase occur in 2023. The NRC study employs a cash flow method for the buy-down cost calculation, However, external costs and social transfers are not included. Including these, as we have done here, reduces the buy-down cost and results in an earlier breakeven year, and hence makes hydrogen FCVs more attractive to society. We estimate the buy-down cost with a present value method for both consumer lifetime cost and societal lifetime cost. For our reference-oil-price scenario, societal cost measure can reduce the buy-down cost of hydrogen FCVs by $5-$15 billion, and shortens the hydrogen transition timing by 1-2 years.

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