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Lester B. Lave
Carnegie Mellon University

Heather Maclean
Carnegie Mellon University

Rebecca Lankey
Carnegie Mellon University

Satish Joshi
Carnegie Mellon University

Francis McMichael
Carnegie Mellon University

See next page for additional authors

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Authors

Lester B. Lave, Heather Maclean, Rebecca Lankey, Satish Joshi, Francis McMichael, Arpad Horvath, and Chris Hendrickson

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Lester B. Lave

Graduate School of Industrial Administration, Carnegie Mellon University

H. MacLean, R. Lankey, S. Joshi, F. McMichael, A. Horvath, & C. Hendrickson

Green Design Initiative, Carnegie Mellon University

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ABSTRACT

We compare the life cycle inventories of near-term fuel-propulsion technologies. We analyze fossil fuels (conventional and reformulated gasolines, low sulfur diesel, and compressed natural gas (CNG)), ethanol from biomass, and electricity, together with internal combustion engines (port and direct injection, spark and compression ignited) and electric vehicles (battery-powered, hybrid electric, and fuel cell). The fuel economy and emissions of conventional internal combustion engines powered by gasoline continue to improve. Unless emissions of pollutants and greenhouse gases (GHG) are stringently regulated or gasoline prices more than double, gasoline powered internal combustion engines will continue to dominate the light duty fleet. Two appealing alternative fuels are CNG and biomass ethanol. CNG cars have low emissions, including GHG and the fuel is less expensive than gasoline. Biomass ethanol can be renewable and have no net carbon dioxide (CO₂) emissions. The improved fuel economy and lower emissions of hybrid and fuel cell vehicles do not justify their higher costs. We conclude that neither fuel availability nor environmental emissions need prevent personal transportation vehicles from dominating urban transportation over the next two decades.

INTRODUCTION

We examine seven fuel-propulsion technology pairs as shown by the columns of Table 1. Other options, such as biodiesel, are given less attention. Choosing among the options requires examination of four categories of vehicle attributes, as shown by the rows in Table 1. Of principal concern to current regulators are the implications of these new technologies for air emissions, particularly ozone precursors. Car buyers have focused on the fuel cost, vehicle cost, and range. Likely to become more important are emissions from the entire fuel cycle, global warming, energy independence, and

fossil fuel depletion. Alternative fuels cannot become important without solving infrastructure problems.

Table 1: Evaluation of Attributes for Fuel-Engine Combinations Relative to a Conventional Automobile

ANALYSIS METHODS

Evaluating each of the alternatives requires a life cycle perspective, from materials extraction to processing, manufacture, use, and end-of-life [MacLean98,98b]. For example, the California Air Resources Board is requiring the introduction of zero emissions vehicles in order to reduce urban ozone. Whether these vehicles improve overall environmental quality depends on their entire life cycle, not just their tailpipe emissions [Lave96,95]. Estimating the material and energy inputs and environmental discharges of each phase is difficult and time-consuming. The technology for the vehicles and their fuels and components change constantly, making evaluation uncertain. For example, hybrid-electric vehicles are just being introduced and fuel cell vehicles will not be introduced for some time.

Life Cycle Analysis: The life cycle inventory for each vehicle is calculated using our Environmental Input-Output Life Cycle Analysis software (EIO-LCA) [EIO-LCA99, Lave98,95b, Hendrickson98]. The EIO-LCA software allows us to investigate the entire supply chain, back to the extraction of materials and fuels, for 485 sectors of the U.S. economy. This software provides detailed estimates of resource and energy use as well as environmental discharges for the producer and the entire supply chain. The principal limitation of the EIO-LCA software is the 485-sector disaggregation of the U.S. economy. For example, petroleum refining is one sector, incapable of giving detail about gasoline, lubricating oil, and other petroleum products. Future

technologies, such as biomass-ethanol, are completely absent from the data. We use process model studies to provide detailed information for the technologies not included in EIO-LCA.

Making Vehicles Comparable: It makes no sense to compare vehicles of very different size, cost, or other attributes. As MacLean [00b] explains, comparability can be defined in terms of identical physical attributes or by consumers evaluating the vehicles as "comparable." Our baseline is a 1998 Ford Taurus powered by an indirect (port) injection engine burning conventional unleaded gasoline. We insert the alternative propulsion system and fuel storage into this vehicle, preserving range at 595 km. Each vehicle is assumed to meet the California Ultra Low Emission Vehicle (ULEV) standard and last 225,300 km. There is considerable doubt that the diesel engine will be able to meet ULEV emissions standards. If a diesel could meet the standard, it would have to use a refined a low sulfur, reformulated fuel, such as ARCO Emissions Control (EC) diesel. For the hybrid and fuel cell vehicle, we compare the Toyota Prius (the first commercial hybrid vehicle) with the conventional gasoline-fueled Toyota Corolla.

A second element of comparability is that we assume that all vehicles are produced and sold in sufficiently large quantities that each is optimized for its fuel and propulsion system. The inherent efficiencies of each fuel-engine combination are shown in MacLean [00]. For example, an engine optimized for CNG has the potential to be 10% more efficient than the baseline fuel-engine because of the higher octane and other fuel properties of natural gas; this is a substantial improvement over the efficiency of CNG in a current dual-fuel vehicle. A CNG direct injection engine is up to 28% more efficient than the baseline vehicle. Direct injection engines have greater efficiency, but are inherently more polluting.

When the weight of the fuel tank, engine, or other components of the car changes, the structure of the car must be adjusted as well. A 10 kg increase in fuel system weight increases total vehicle weight 15 kg [Brinkman99]. An increase in weight lowers fuel economy as in the equation [MacLean00].

$$(mpg_2 / mpg_1) = (w_1 / w_2)^{0.72}$$

Vehicle Manufacture: The materials, energy use and discharges for the baseline vehicle are calculated with the EIO-LCA software. To estimate the manufacture of the alternative vehicles, we estimate the differences in materials between the baseline vehicle and each alternative. We then use the software to calculate the reduction in inputs and environmental discharges from removing components of the baseline vehicle and the increase from adding the new components. As might be expected, the differences among internal combustion engine cars are less than 10% of the overall manufacturing phase. Given the uncertainties in the analysis, we assume the life cycle inventories for the

manufacture of each internal combustion engine vehicle to be the same.

Vehicle Operation: For the vehicle use life cycle stage, operational energy is calculated for each of the vehicles based on the lifetime distance traveled, combustion energy of the fuel, and the fuel economy. We calculate lifetime emissions of GHG resulting from automobile use, including CO₂, methane, and nitrous oxide based on lifetime fuel use and data in [EPA99].

Vehicle exhaust emissions include those resulting from on-cycle driving (driving conditions included in the Federal Test Procedure (FTP)), off-cycle driving (conditions other than those in the FTP, e.g., high speed, high load), and those resulting from malfunctioning emissions control systems [MacLean00].

Life cycle vehicle emissions of EPA-designated toxic air pollutants (benzene, 1,3-butadiene, formaldehyde, and acetaldehyde) are calculated based on data from [AQIRP96]. For diesel exhaust, we report particulate matter emissions, calculations are based on the ULEV standard, assuming that the emissions are at the 100,000 mile certification rate over the vehicle lifetime. As Vachon [97] reports, there is little data on the other toxics from diesel exhaust.

Fuel Cycle: We calculate expected fuel use over the vehicle lifetime and then estimate the life cycle inventory for each fuel [Joshi00, MacLean99]. Concern over pollution from fossil fuels, GHG emissions, and the U.S. dependence on foreign fuel sources has encouraged analysis of renewable fuels. Currently, small volumes of biofuels are produced from corn and soybean-based biomass. Joshi [00] and MacLean [99] find that these sources are not feasible for producing large volumes of fuel. Ethanol from corn and biodiesel from soybeans are attractive only where the remaining corn protein and oil and soybean cake are highly valued and the corn starch and soybean oil are in excess supply. A major disadvantage of these sources is that they use cropland that could be used for growing food. Transforming food into motor fuel will not be viewed positively in a world with six billion people and rapid population growth. Here, we restrict our attention to ethanol produced from woody and herbaceous biomass, such as poplars and switch grass. Woody and herbaceous biomass need not be grown on cropland and so do not reduce the food supply.

Methanol can be produced from natural gas or biomass. Its toxicity prevents methanol from becoming a major automobile fuel. Small quantities of methanol can cause blindness, neural problems, and reproductive difficulties. While spills would be subject to relatively rapid chemical transformation, a high spillage rate, such as occurs with gasoline today, is likely to lead to high levels of public concern. Spills of reformulated gasoline with methyl tertiary butyl ether (MTBE) led to banning this additive.

Automobile Service: We assume that the EIO-LCA sectors, Automotive Repair Shops and Services and Automotive Services (except repair and car washes) adequately represent the service for all of the internal combustion options available to the automakers. Although there will be some differences in vehicle parts and frequency of repair, these issues are likely to be small in comparison with the normal variability in service even among the conventional automobiles [DOE96]. Therefore, we assume there are no significant differences in the service over the lifetime for any of the ICE options and calculate a producer price for use in the EIO-LCA model based on expected parts and fluids required over the vehicle lifetime, assuming manufacturer production and service. For additional details, see MacLean [98,98b].

Fixed Costs: Fixed costs include automobile insurance, license fee, depreciation, and finance charge. For the baseline vehicle, we calculate lifetime fixed costs from data in [Davis97], yielding an estimate of \$65,560 (1992\$). As in [MacLean98], we assume that except for insurance, the fixed costs have few economy-wide environmental concerns and so use the Insurance Carriers sector in EIO-LCA to estimate the economy-wide implications. The alternative ICE options should have fixed costs similar to those of the baseline automobile [Liss98, Robinson98].

End-of-Life: End-of-life can be broken down into four functions [Sullivan98]: transportation of the vehicle to a dismantling facility, dismantling, shredding and disposal of the shredder residue. We take end-of-life results from [Sullivan98] based on the comprehensiveness of the study and the comparability of the vehicles analyzed.

Battery-Powered, Hybrid Electric, and Fuel Cell Vehicles: For battery-powered vehicles, we focus on the toxic metals used in the battery and their recycling. We analyze the first hybrid electric vehicle, the Toyota Prius [Lave00]. The baseline vehicle for this analysis is the Toyota Corolla, a car of comparable size. The fuel cell vehicle is modeled from a hybrid electric vehicle with the engine and transmission replaced by a fuel cell stack and reformer, and using gasoline as the fuel. The lifetime costs of fuels are shown in Table 2, net of tax. Current prices range from \$2,660 for CNG to \$8,980 for ethanol from biomass. If the price of gasoline at the refinery were to double, the price would be about the same as the price of ethanol from biomass.

Table 2: Near Term Fuel Prices and Lifetime Expenditure on Fuel for Internal Combustion Engine Options

Following Table 1, we will discuss the major fuel/engine combinations in terms of the various objectives with respect to vehicle emissions, fuel characteristics, vehicle performance and social issues, focusing attention on large differences from conventional vehicles.

Reformulated gasoline and diesel have been promoted as a means to reduce emissions of internal combustion engine vehicles. Automobiles using reformulated gasoline have been certified to the ULEV standard. However, even with a reformulated, low sulfur diesel, such as ARCO's EC Diesel, it is unclear whether a diesel can attain ULEV. Table 3 shows estimated emissions of air pollutants for the entire vehicle lifetime, including the fuel cycle and use phase, for the internal combustion fuel/engine combinations. For the fossil fuels, fuel cycle emissions are similar for each pollutant and roughly equal to the emissions resulting from the lifetime of driving the vehicle. The exception is carbon monoxide where fuel cycle emissions are small. In the near term, the estimates of the air pollutants resulting from the bioethanol fuel cycles are higher than those from the fossil fuel cycles. However, in our judgment this is not a significant concern since it is possible to lower these emissions by using cleaner fuels in the production processes or by installing emissions control systems on farm and transport equipment.

Table 3: Air Pollutants Resulting from Life Cycles of Fossil Fueled Automobiles

Compressed Natural Gas (CNG) is attractive for five reasons. (1) It is the only fuel cheaper than gasoline or diesel. (2) It has inherently lower air pollution emissions. (3) It has lower greenhouse gas emissions. (4) Its use extends petroleum supplies, and (5) there are large quantities of the fuel available in North America. The difficulties with CNG arise from vehicle range, fuel storage, infrastructure costs, and ensuring sufficient supply.

The importance of range as a vehicle characteristic is illustrated in MacLean [00b]. The curb weight of each ICE vehicle is examined for ranges of 160 and 595 km. A major advantage of diesel and gasoline fuels is their high energy density; increasing the range of a vehicle hardly increases its weight. The lower energy density of ethanol results in considerable weight increase with range. Both battery and CNG vehicles face large penalties in increasing their range from 160 to 595 km. In both cases, the additional weight of batteries or storage cylinders requires considerable extra chassis weight, requiring still more fuel and storage cylinders or batteries.

A large increase in the number of CNG vehicles would require new gas pipelines and other infrastructure. Although natural gas reserves are large, it is not clear whether extraction could be doubled over many years without an increase in extraction cost.

Ethanol from Biomass has several major advantages: (1) It could be produced within the U.S., (2) it can be produced so that there are no net CO₂ emissions, (3) it is a liquid with reasonably high energy density, (4) it is a relatively clean fuel for internal combustion engines, and (5) currently, vehicles able to run on ethanol receive significant fuel economy credits in the Corporate

Average Fuel Economy (CAFE) calculations. Thus, ethanol from biomass offers two major benefits to automakers. First, it can provide fuel for light duty vehicles even under the most stringent agreement on limiting GHG emissions. Second, it is advantageous for automakers' CAFE calculations. For large vehicles with low fuel economy, biomass ethanol provides a fuel that can avoid violating CAFE standards with the associated dollar penalties and social censure.

For any fossil-fueled ICE vehicle option, the amount of CO₂ equivalent generated from its entire life cycle is large (ranging from 77,000 kg for the CNG direct injection to 100,000 kg for the reformulated gasoline port injection). The following results are taken from MacLean [99]. The vehicle operation GWP dwarfs that from all other life cycle stages. The GHG emissions resulting from fuel production are 20 to 30% of those resulting from vehicle operation. Compared to the gasoline baseline, the greater efficiency of the diesel engine results in lower energy use and 25% lower GWP. CNG has less carbon per joule than gasoline or diesel, and so its GHG emissions are lower than its energy use. Even with a range of 595 km, the direct injection CNG vehicle has the potential to lower lifetime GHG emissions by 30% compared to the baseline. Lowering the range to 160 km would increase fuel economy (and reduce GHG emissions) by 9 percentage points.

Biofuels have the potential to offer the much greater GHG reductions necessary if there is a greater focus on these emissions [Joshi00, MacLean99]. Ethanol from biomass sequesters carbon in plants, resulting in zero net carbon emissions from the fuel cycle and vehicle operation, if the fuel cycle is arranged so that no fossil fuels are used. The USA has sufficient land to replace most of the 100 billion gallons of gasoline used each year to fuel light duty vehicles, even after subtracting cropland and developed land

Battery Powered, Hybrid and Fuel Cell Vehicles all result in reductions in direct vehicle emissions. However, with a few exceptions that we analyze in this section, the other life cycle stages continue to use resources and discharge pollutants similar to those of conventional vehicles. Each of these vehicles would be more expensive than conventional vehicles in lifetime costs given current and near term expected technologies.

Battery Powered Vehicles have an electric engine that is inherently more efficient than an ICE, although energy is lost in electricity generation and transmission, as well as in charging the batteries. The weight of the batteries (400-500 kg) lowers fuel economy and the range of the vehicles is a barrier to their consumer acceptance. Toyota is the only manufacturer that quotes replacement price and life for EV nickel metal-hydride batteries. They guarantee these batteries for three years and expect them to last for five years, perhaps 50,000 miles. The replacement price is 2.5 million yen, about \$30,000. Thus, these batteries cost about \$0.60 per mile. The cost of electricity for charging the batteries is 0.5 to 1

cent per mile. We conclude that the battery powered vehicles are too expensive to compete with conventional vehicles. Their extensive use of toxic battery metals means they are an environmental liability, even though they have zero tailpipe emissions.

Lankey [00] concludes that the increase in metals demand for 5 million vehicles would be several times the 1997 level of demand for most metals, and almost the 1997 level of production for several of the metals. At present, battery recycling is in a primitive state [McMichael98, Lankey00]. A large increase in the use of nickel metal-hydride or lithium-ion batteries would require a much-improved recycling program that recovered the secondary metals in these batteries.

Hybrid Electric Vehicles are heavier and more expensive than similar, conventional internal combustion engine automobiles. However, the electric drive allows greater fuel economy in start and stop traffic because of regenerative braking and shutting off the engine when the vehicle is stopped. The hybrids have a smaller amount of batteries than the battery-powered cars but larger than the current starter-lighting-ignition battery. The Toyota Prius has a 48-kg nickel-metal-hydride battery, one-fifth the size of the EV battery [EPA98]. Assuming the Prius battery lasts 100,000 km and costs \$2,100 (the estimated cost at large-scale production assuming technology advances), it would cost \$ 0.02/km (\$0.03 per mile). The fuel economy of the Prius was 48.6 mpg in EPA tests [EPA98]. Lave [00] adjusts the Toyota Corolla tested by EPA to have an automatic transmission, like the Prius. The Prius is a slightly smaller car with much less power (0-60 mph in 14.2 seconds compared to 9.5 second for the average subcompact car).

The Prius has lower pollutant and CO₂ emissions than the Corolla. Matthews [99] summarizes the social valuations placed on abating these emissions. In the remainder of the analysis, Lave [00] assumes that car owners are charged the social costs of their emissions of pollutants and GHG.

Shown in Table 4 is the price of gasoline, pollutant emissions, or CO₂ emissions that would be required to pay for the \$4,000 initial price difference and battery replacement of the Prius. If the price of gasoline were \$6.28 per gallon and car owners were charged for their pollution and CO₂ emissions, the Prius and Corolla would be equally costly. Alternatively, if air pollution emissions were valued at 42 times current levels or CO₂ emissions were \$320 per ton, the owners of the two cars would find them to cost about the same amount over their lifetimes.

Lave [00] also evaluates an advanced hybrid-electric car that gets 50% better fuel economy than the Prius and has the same emissions. This advanced hybrid is still not attractive at a price premium of \$4,000 over the Corolla, unless gasoline is priced at \$3.47 per gallon or

pollutants are valued at 31 times their current level or CO₂ is valued at \$141 per ton.

Table 4: Gasoline Prices and Social Valuations of Emissions and Carbon Dioxide that Make a Hybrid Electric Vehicle and Corolla Comparable

Fuel Cell Vehicle environmental performance depends on the fuel used. Aside from possible problems in fuel generation and storage, a hydrogen-powered fuel cell would have no GHG emissions, only water vapor emissions. However, it is difficult to store sufficient hydrogen to give the vehicle the range of current cars so manufacturers are looking to methanol or gasoline as the initial fuel. In our judgment, the toxicity of methanol rules it out as a fuel for mass use.

The use of liquid fuels in fuel cell vehicles requires a reformer to extract hydrogen for the fuel cell and so there are emissions of conventional air pollutants and GHG in the reforming process, as well as a loss in efficiency. To have a comparable vehicle, the weight of the fuel cell, reformer, and storage tank, as well as batteries and electric motors must be compared to the weights of the comparable systems for an ICE. Since the fuel cell system is heavier, with current technology, the size of the engine and fuel economy must be adjusted. In addition, a reformer and fuel cell cannot adjust quickly to changing driver demands. As a result, the vehicle will have to be designed as a hybrid with a large battery to give rapid response while the fuel cell charges the battery. While the precise efficiency of reformer and fuel cell and their costs are unknown, the current literature and goals give some picture of what can be expected in the next few years. Compared to a hybrid vehicle, a fuel cell vehicle will be more fuel-economic, have lower vehicle emissions, and be more costly [Hanisch 99]. An analysis similar to that done for the hybrid indicates that in the near term the vehicle would not be attractive in terms of its fuel savings or lower emissions. The analysis does not rule out the possibility that the fuel cell or hybrid vehicles might be more attractive in the future. However, for near term technologies these vehicles will have to offer attributes other than fuel economy and lower emissions in order to attract buyers.

Evaluating the Fuel-Powertrain Combinations:

On the basis of this analysis, we can now give our best judgments regarding the entries in Table 1. The scores range from -5 to +5, with the port injection, conventional unleaded gasoline powered internal combustion engine automobile as the baseline (*). Each fuel-technology scores reasonably well in terms of lowering emissions of ozone precursors particulate matter, and air toxics. The ULEV assumption for the combinations results in emissions benefits compared to the baseline vehicle. However, diesel engines have relatively high emissions of nitrogen oxides and particulate matter and there is considerable uncertainty whether these vehicles will be able to meet strict emissions standards even with

reformulated fuels. CNG and diesel cost less than gasoline; all the other fuels cost more, especially bioethanol. The diesel, hybrid, and gasoline powered fuel cell offer greater vehicle range, while the battery-powered EV and CNG offer lower range. The battery EV, hybrid EV and fuel cell vehicles cost more to manufacture than the baseline. Save for gasoline and diesel, all fuel-engine combinations require infrastructure changes. CNG and battery powered vehicles require less change than bioethanol. Bioethanol can be produced domestically and therefore significantly benefits energy independence. The other options, aside from reformulated gasoline (since additional fuel is required), have positive scores due to lower fuel use or domestic fuel production. The CNG and advanced vehicles score better on global warming, but bioethanol has the highest benefit. The scores for global warming potential are similar to those for fossil fuel depletion.

CONCLUSION

There is no dominant alternative, although a range of feasible and attractive fuel-engine combinations exists for personal transportation vehicles. However, all would have trouble displacing gasoline-diesel because of the low price of petroleum, the immense investment in current infrastructure, and the rapid progress that has been made in increasing the fuel economy and lowering the emissions of reformulated gasoline-fueled ICE vehicles.

Direct injection engines offer greater fuel economy (and lower GHG emissions) at the cost of greater engine emissions. They are likely to dominate the market only if their nitrogen oxides and particulate matter emissions are able to meet emissions standards without the vehicles having to substantially relinquish their greater efficiency or use significantly more expensive fuels.

Of the alternative fuels, only CNG has a lower cost than gasoline or diesel. The other fuels will penetrate the market in large numbers only if the refinery gate price of gasoline-diesel is increased several fold or if tailpipe emissions or GHG emissions are restricted significantly. While ethanol from biomass costs about twice as much as gasoline, it offers advantages in terms of lowering dependence on foreign oil and eliminating CO₂ emissions.

CNG and battery-powered cars, and to a lesser extent ethanol powered cars, have practical range limitations. CNG in optimized engines is an attractive fuel in terms of price, tailpipe emissions, fuel availability, and reduced greenhouse gas emissions. Its major disadvantage is a limited range and the current lack of refueling infrastructure. This range limitation is less important for fleet or commuter vehicles. The hybrid does not appear to be attractive in terms of its operating costs or to offer significantly better emissions performance. Fuel cell vehicles with current or near-term technology that are

fueled by gasoline do not offer significant environmental advantages.

While conventional vehicles are likely to predominate in sales for the next few decades, some important research issues emerge from our analysis:

- a. Can direct injection engines and associated control systems be developed that allow vehicles using these technologies to meet strict vehicle exhaust emission standards while operating at high efficiency?
- b. Can storage improve or sufficient low range vehicle sales be generated to allow CNG to become a mass market fuel?
- c. Can the cost of producing ethanol from biomass be reduced, including environmental effects of production and sustainability?
- d. Can the cost and size of fuel cells be sufficiently reduced to become an attractive competitor to conventional engines?

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CONTACT

This is where main author information is typed, if desired, such as background, education, e-mail address, and web address. This is an optional section.

CONTACT

Green Design Initiative
Carnegie Mellon University
Pittsburgh PA 15213
412-268-8837
Lave@andrew.cmu.edu

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Table 2 Near Term Fuel Prices and Lifetime Expenditure on Fuel for Internal Combustion Engine Options, net of taxes

Fuel	Lifetime Energy Required (GJ)	Price ¹ (1992\$/GJ)	Consumer Lifetime Expenditure (1992\$)
Gasoline SIII	740	6.48	4795
CaRFG2 SIII	740	7.19	5320
CaRFG2 SIDI	650	7.19	4670
EC Diesel ² CIDI	570	5.58	3180
Ethanol SIDI Herbaceous Biomass ³	595	15.09	8980
Ethanol SIDI Woody Biomass ³	595	14.08	8380
CNG 3000 psig SIII	720	4.15	2990
CNG 3000 psig SIDI	640	4.15	2660

1. Assumes use of near term technology for herbaceous and woody biomass fuels. Assumes constant fuel price over vehicle lifetime and constant annual fuel use.

2. This price reflects conventional diesel plus a small premium.

3. Ethanol from herbaceous biomass corresponds to near term projections of \$1.20 per gallon and from woody biomass, \$1.13 (net of taxes).

Number of significant digits in the table is for calculation purposes and does not represent the accuracy in the figures.

Table 1: Evaluation of Attributes for Fuel-Engine Combinations Relative to a Conventional Automobile (-5 worst, * Comparable, +5 best)

	Reformulated Gasoline	Reformulated Diesel	Compressed Natural Gas	Ethanol from Biomass	Battery EV	Hybrid EV	Fuel Cell
Vehicle Emissions							
A-1: Ozone: NO _x , VOC	2	-1	3	2	4	3	3
A-2: Particulate Matter	*	-1	*	*	2	1	1
A-3: Air Toxics	1	-3	2	1	3	3	3
Fuel Related							
B-1: Fuel Cycle Emissions	-1	-1	1	*	-1	*	*
B-2: Fuel Cost	-1	1	1	-4	1	*	*
Vehicle Performance							
C-1: Range	*	1	-2	-1	-4	1	1
C-2: Vehicle Cost	*	*	-1	*	-2	-2	-2
Social Issues							
D-1: Infrastructure Cost	-1	-1	-2	-3	-1	*	*
D-2: Energy Independence	-1	1	1	4	1	1	1
D-3: Global Warming	-1	2	1	5	*	2	2
D-4: Fossil Fuel Depletion	-1	1	*	5	1	1	1

Baseline: Unleaded, non-oxygenated, non-reformulated gasoline, Tier 1 automobile

Table 3: Air Pollutants Resulting from Life Cycles of Fossil-Fueled Internal Combustion Engine Automobiles (kg/vehicle lifetime)

	Sulfur Oxides	Carbon Monoxide	Nitrogen Oxides	NMOG/VOC ¹	Particulate Matter (PM ₁₀)
Manufacture	54	82	44	20	6
Service	22	29	16	4	2
Fixed Costs	9	17	7	4	1
End-of-Life	0.3	0.7	0.8	0.2	0.2
Vehicle Exhaust Emissions²					
Baseline (Tier 1)		681	61	36	6
ULEV		340	31	6	6
Fuel Production³					
Gasoline SIII	28	16	24	13	6
CaRFG2 SIII	32	17	26	13	6
CaRFG2 SIDI	28	15	23	11	6
EC Diesel CIDI	24	12	16	5	4
CNG 3000 SIII	10	20	40	6	3
CNG 3000 SIDI	9	17	35	5	2

1. Nonmethane organic gases (NMOG) for vehicles. Volatile organic compounds (VOC) for fuel production.

2. Vehicle exhaust emissions refers to estimates of both on and off-cycle exhaust emissions discharged over the vehicle lifetime. Sulfur oxides are not regulated exhaust emissions and so are not included.

Fuel production includes stages from raw materials extraction to delivery of fuel at end user.

Table 4: Gasoline Prices and Social Valuations of Emissions and Carbon Dioxide that Make a Hybrid Electric Vehicle and Corolla Comparable

Prius Priced \$4,000 More Than Corolla-AT	
Gasoline Price: \$/gal	6.35
Emissions cost multiplier	46
CO ₂ : \$/ton	413

Table entries are the gasoline price, emissions multiplier, or CO₂ social valuation required to equate the lifetime cost of a hybrid electric vehicle (HEV) with those of a Corolla with automatic transmission (Corolla-AT) under the stated assumptions. The gasoline price required under the assumption that the HEV costs \$4000 more than the Corolla-AT, they each have a lifetime of 124,300 miles, the lifetime maintenance is the same, the batteries are replaced, and the discount rate is 6%. The median social costs of emissions are used: NO_x: \$1,060/ton, HC: \$1,400/ton, CO: \$1,050/ton, and CO₂: \$14/ton. The factor by which the median social cost valuations of HC, NO_x, and CO emissions would have to be multiplied to equate the HEV and Corolla-AT lifetime costs.