Environ. Sci. Technol. **2000**, *34,* 3598−3605

Life-Cycle Analysis of Alternative Automobile Fuel/Propulsion Technologies

LESTER LAVE,*,† HEATHER MACLEAN,‡ CHRIS HENDRICKSON,# AND REBECCA LANKEY§

Graduate School of Industrial Administration, Department of Engineering and Public Policy and Department of Civil and Environmental Engineering, Carnegie Mellon University, Schenley Park, Pittsburgh, Pennsylvania 15213-3890

We examine the economic and environmental implications of the fuels and propulsion technologies that will be available over the next two decades for powering a large proportion of the light duty fleet (cars and light trucks). Since R&D change is rapid, we treat the uncertainty about future technologies using bounding calculations. A life-cycle perspective is used to analyze fossil fuels [conventional unleaded and reformulated gasolines, low sulfur reformulated diesel, and compressed natural gas (CNG)], ethanol from biomass, and electricity together with current and advanced internal combustion engines (ICE, indirect (port) and direct injection, spark, and compression ignited) and electric vehicles (battery-powered, hybrid electric, and fuel cell). Technological advances continue to improve the efficiency and environmental performance of ICE automobiles powered by low sulfur fossil fuels. Absent a doubling of petroleum prices or stringent regulation [due, for example, to intense concerns about greenhouse gas (GHG) emissions], ICE using fossil fuels will dominate the market for the next two decades. CNG cars have low emissions, including GHG, but must be redesigned to store enough CNG to achieve the current range. Battery-powered cars have limited range and are expensive, and the life-cycle of battery components leads to discharges of toxic materials. Although both hybrid and fuel cell vehicles promise better fuel economy and lower emissions, in the near term these do not justify their higher costs. If global warming becomes a major concern, CNG offers carbon dioxide emission reductions of up to 30%, and bioethanol could provide a fuel with no net carbon dioxide emissions, although the bioethanol price would be more than twice current petroleum prices.

Introduction

The choice of a fuel/propulsion system for a light-duty vehicle (LDV) influences vehicle emissions, fuel production, vehicle performance−cost characteristics, and social issues. These four categories can be disaggregated into 11 specific categories, as shown by the rows in Table 1. Mass market fuel/propulsion combinations available over the next two decades, shown as the columns of Table 1, will compete on the basis of these attributes. The matrix entries show improvement relative to a conventional automobile and are developed in this paper and in related work (*1*−*6*). Our intent is to highlight desirable options and research priorities for LDV in the next decades.

We consider vehicles designed specifically for each fuel/propulsion system combination. Introduction of such vehicles can have significant infrastructure implications. The investment in infrastructure for gasoline and diesel is immense, from oil wells to refineries, transport, storage tanks, and retailers. That infrastructure was modified, at a cost of billions of dollars, in response to regulations concerning underground storage tanks, control of vapors during refueling, and the introduction of unleaded gasoline. However, as long as the transition to alternative fuels is not rapid and as long as service stations do not have to offer a wider range of fuels than at present, the infrastructure changes are unlikely to impose heavy burdens on the economy. Relying on an alternative fuel/engine option requires automobile manufacturers, fuel suppliers, transport operators, and retailers to agree and coordinate the large investments required to offer the vehicles and fuels. Without this agreement, automakers will not be able to sell vehicles using a new fuel; without having these cars on the road, fuel suppliers will not produce the needed fuel.

Analysis Methods

The entire life-cycle, from materials extraction to processing, manufacture, use, and end-of-life, determines whether the environmental performance of a vehicle with a particular fuel/engine combination is superior to another (*5, 6*). Unfortunately, estimating the material and energy inputs and environmental discharges of each phase is difficult and time-consuming. When vehicles are not yet produced commercially, as with fuel cell cars, constructing the life-cycle is even more difficult. Figure 1 is a simplified diagram of the automobile life-cycle stages and shows the components of the use life-cycle stage (fuel cycle, vehicle operation, vehicle service, and fixed costs) that we analyze here.

Life-Cycle Calculations. Our life-cycle analysis draws on two sources. The first is our Environmental Input−Output Life-Cycle Analysis software (EIO-LCA) (*7*−*10*). This 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. The 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; there is no detail about gasoline, lubricating oil, and other petroleum products. Future technologies, such as biomass to ethanol, are completely absent from the data. The second life-cycle approach uses process model studies designed to provide these disaggregate data.

Vehicles. In comparing vehicles with different fuel/propulsion technologies, two elements must be controlled. First, consumers must regard all vehicles as being "performance equivalent", that is, having attributes such as style, interior space, acceleration, range, and safety, being equivalent in their view. A small Geo Metro is not performance equivalent to a large Ford Expedition.

Second, vehicles must be assumed to have sufficient sales so that each alternative is a dedicated, optimized vehicle. For example, almost all alternatively fueled vehicles currently

* Corresponding author phone: (412)268-8837; fax: (412)268-7357; e-mail: lave@andrew.cmu.edu.

† Graduate School of Industrial Administration.

‡ Department of Engineering and Public Policy.

Department of Civil and Environmental Engineering.

§ Presently an AAAS Environmental Sciences and Engineering Fellow at the U.S. Environmental Protection Agency.

10.1021/es991322+ CCC: $19.00
Published on Web 08/04/2000

TABLE 1. Evaluation of Attributes for Fuel/Propulsion Technologies Relative to a Conventional Automobile[a]

	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	2	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

[a] −5, worst; *, comparable; +5, best. Baseline: unleaded, non-oxygenated, non-reformulated gasoline, tier 1 automobile.

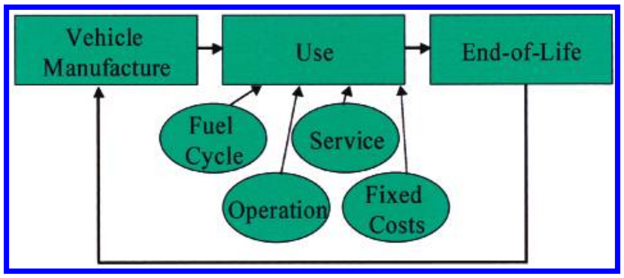

FIGURE 1. Simplified automobile life-cycle model.

sold are designed to be able to run on two or more fuels (battery-powered cars are the notable exception). With current technology, an engine using both an 87 octane fuel (gasoline) and a 115 octane fuel (natural gas) cannot be optimized for both. Shown in Table 2 are the expected efficiencies of each internal combustion fuel/engine combination relative to conventional unleaded gasoline in a spark ignition, indirect (port) injection (SIII) engine. For example, an SIII engine optimized for compressed natural gas (CNG) has the potential to be 10% more efficient than the baseline fuel/engine combination because of the higher octane and other fuel properties of natural gas; this is a substantial improvement over the efficiency of CNG in current SIII vehicles. A CNG spark ignition direct injection (SIDI) engine is estimated to be up to 28% more efficient than the baseline vehicle. Direct injection engines have the potential to operate more efficiently than conventional port injection engines since they operate lean, requiring less fuel. However, direct injection engines produce more nitrogen oxides, and so there is a tradeoff between meeting strict emissions standards and operating at a high efficiency.

The baseline vehicle for our study is a 1998 Ford Taurus sedan fueled by conventional unleaded gasoline and meeting the tier 1 emission standard. Each of the internal combustion fuel/engine automobiles we examine is a mid-size sedan with 595 km range, meeting the California Ultra-Low-Emission Vehicle (ULEV) standard, lasting 225 300 km and 13.7 yr (*11*). It is likely that conventional diesel-fueled vehicles will not attain the ULEV standard, so we consider the low sulfur, reformulated ARCO emissions control (EC) diesel. Some port-injected CNG and gasoline engines have been certified for ULEV; the other engine/fuel combinations are expected to meet the standard, although there is considerable doubt about the compression ignition engine. For the hybrid and fuel cell vehicle, our comparison is based on the Toyota Prius (the first commercial hybrid vehicle) and the conventional gasoline-fueled Toyota Corolla. We take fuel properties from refs *12* and *13*.

When the weight of the fuel tank, engine, or other components of the car change, the structure of the car must be adjusted as well. We assume if the fuel system weight increases 10 kg, total vehicle weight will increase 15 kg (*14*). On the basis of expert judgment (*14*) and our previous work (*3, 6, 15*), we adjust fuel economy for a sedan to reflect weight changes by assuming that the ratio of new to old fuel economy equals the ratio of new to old weight to the 0.72 power:

$$(\mathrm{mpg}_2/\mathrm{mpg}_1) = (w_1/w_2)^{0.72} \quad (1)$$

Vehicle Manufacture. We calculate the life-cycle implications of manufacturing the baseline automobile using the Motor Vehicle and Passenger Car Bodies sector of EIO-LCA (*7*) estimating the producer price as the invoice price [This price does not include taxes, destination charge, dealer advertising fee, or consumer rebates.] (including common options) of $18 000 (1998$) (*16*). We deflate all final demand values to 1992$ using industry deflators.

Since none of the alternatively fueled vehicles is shown as a sector in EIO-LCA, we use a materials-based method to analyze the manufacturing differences between the alternative fuel and baseline vehicles. These materials differences are then analyzed using the appropriate materials sectors within EIO-LCA. For the internal combustion engine (ICE) options, the greatest manufacturing difference (from the baseline) is associated with the CNG vehicle (resource use and environmental discharges). However, we find that these differences among ICE vehicles are small (most less than 10%) as compared with the overall amount resulting from vehicle manufacture.

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 greenhouse gases (GHG) resulting from automobile use, including carbon dioxide, methane, and nitrous oxide based on lifetime fuel use and data in ref *17*.

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. We estimate on- and off-cycle emissions in this work but do not estimate the fraction of emissions that are expected to result from vehicle malfunctions. To determine on-cycle

TABLE 2. Estimated Fuel/Engine Efficiencies for Internal Combustion Engine Vehicles Meeting California Ultralow-Emission Vehicle Standards (% Change in Efficiency from Baseline)

fuel/engine technology	spark ignition, indirect injection (SIII)	spark ignition, direct injection (SIDI)	compression ignition, direct injection (CIDI)
gasoline[a]	baseline	*g*	*g*
reformulated gasoline (CaRFG2)[b]	0,[c] 0[d]	8−18,[d] 5−15,[c] 5−15,[c] 10−15[e]	*g*
EC diesel[f]	*g*	*g*	20−25,[c] 20−23[d]
ethanol 100[h]	*g*	15−25,[c] 13−28[d]	*g*
compressed natural gas[i]	−10,[c] 10,[c] 10[d]	5,[c] 13−28,[d] 15−25[c]	*g*

[a] Conventional Federal unleaded (non-reformulated, non-oxygenated) gasoline. Lower heating value (LHV) is 115 000 btu/gal at 60 °F; wt % carbon is 85. [b] California Phase 2 Reformulated Gasoline. LHV is 111 600 btu/gal at 60 °F; wt % carbon is 84. [c] Ref *44.* (Two different groups, therefore double entries for some combinations.) [d] Ref *45.* [e] Ref *46.* [f] ARCO Emission Control (EC) diesel, currently in a demonstration project in California. LHV is 126 763 btu/gal; wt % carbon is 87. [g] Combination is unattractive. [h] Neat ethanol (E100). LHV is 76 000 btu/gal; wt % carbon is 52.2. [i] Compressed natural gas. We analyze CNG at 3000 psig, LHV is 24 720 btu/gal at 60 °F, wt % carbon is 75.

emissions, we use a method based on the certification standards (tier 1 for the baseline vehicle and California ULEV for the “other ICE cars”) and assume linear deterioration of emissions and engine control over the vehicle lifetime. We examine test results from an off-cycle driving cycle to determine rates for these emissions (*18*). For additional details, refer to ref *3*.

Life-cycle vehicle emissions of EPA-designated toxic air pollutants (benzene, 1,3-butadiene, formaldehyde, and acetaldehyde) are calculated based on data from ref *19*. For diesel exhaust, we report particulate matter emissions, calculated based on the ULEV standard, assuming that the emissions are at the 100 000-mi certification rate over the vehicle lifetime. As Vachon (*20*) reports, there is little data on the other toxics from diesel exhaust.

Fuel Cycle. We calculate average fuel use over the vehicle’s lifetime by dividing miles traveled by fuel economy. We work backward in the fuel cycle to calculate the resource use and pollutant discharges associated with each process required to get this amount of fuel to the consumer. The processes include extracting raw materials, refining, processing, transporting, and retailing the fuel. We draw upon refs *21−31* for our analyses of the efficiencies, GHG emissions, and conventional air pollution emissions for each of the fuels. For additional details, see MacLean (*4*).

Concern over fossil fuel consumption, GHG emissions, and the U.S. dependence on foreign fuel sources has led to the investigation of renewable fuel sources for automobiles. Currently, small volumes of biofuels are produced from corn- and soybean-based biomass. MacLean (*4*) finds that these sources are unlikely to be feasible for producing fuel for large volumes of vehicles. Ethanol from corn and biodiesel from soybeans are attractive only where the coproducts are highly valued and the corn starch and soybean oil (from which the fuels are produced) 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 6 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. Additionally, these crops require less maintenance than food crops. Burning the lignin portion of the biomass could supply the process heat as well as generate electricity (which could be sold to the power grid) as a coproduct of the process. Methanol also can be produced from biomass sources. However, methanol is highly toxic, causing blindness, neural problems, and teratogenicity. 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.

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 ICE 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 (*32*). 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 refs *5* and *6*.

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 ref *11*, yielding an estimate of $62 640 (1992$). As in ref *5*, 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 (*33*, *34*).

End-of-Life. End-of-life can be broken down into four functions: transportation of the vehicle to a dismantling facility, dismantling, shredding, and disposal of the shredder residue (*35*). We take end-of-life results from Sullivan (*35*) based on the comprehensiveness of the study and the performance equivalence of the vehicles analyzed.

Battery-Powered, Hybrid Electric, and Fuel Cell Vehicles. For battery-powered vehicles, we focus on the metals used in the battery and their recycling. We analyze a hybrid electric vehicle that uses gasoline. The vehicle is based on the Toyota Prius sold in Japan, modified for U.S. performance requirements (*2*). The baseline vehicle for this analysis is the Toyota Corolla since the Prius is more comparable to this vehicle than to the Ford Taurus. The fuel cell vehicle, fueled by gasoline, is modeled from a hybrid electric vehicle with the engine and transmission replaced by a fuel cell stack and reformer.

Results

Following Table 1, we discuss the major fuel/propulsion technologies 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 from ICE vehicles. There has been significant progress in lowering of emissions from reformulated gasoline-fueled SIII automobiles in recent years, and some of these vehicles have been certified to the ULEV and the more strict Super-Ultra-Low-Emission Vehicle (SULEV) standard. SIDI engines are likely to lose some or all of their efficiency advantage to meet the ULEV standard.

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[a]	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 Emissions[b]					
baseline (tier 1)		681	61	36	6
ULEV		340	31	6	6
Fuel Production[c]					
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

[a] Non-methane organic gases (NMOG) for vehicles. Volatile organic compounds (VOC) for fuel production. [b] 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. [c] Fuel production includes stages from raw materials extraction to delivery of fuel at end user.

Compression ignition engines have relatively high emissions of nitrogen oxides and particulate matter, and experts disagree on whether vehicles with these engines will be able to meet strict emissions standards even with reformulated, low sulfur fuels. In addition, the U.S. Environmental Protection Agency classifies diesel particulate matter as an air toxic and probable human carcinogen (*36*). Table 3 shows estimated emissions of air pollutants for the entire vehicle lifetime, including the fuel cycle and use phase, for the ICE options. 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.

The estimated prices of each fuel are shown in Table 4. Also shown in the table are the expected consumer expenditures over the vehicle lifetime, assuming uniform use of the fuel during the lifetime. The reformulated gasoline SIII vehicle results in higher lifetime expenditures than conventional gasoline, reflecting higher refining costs and lower fuel energy density. The high efficiency of the diesel vehicle allows for fuel savings; however, there is uncertainty concerning the cost of high-volume production of low sulfur reformulated diesel (*37*).

The importance of range as a vehicle characteristic is illustrated in Figure 2. The curb weight of each ICE vehicle is shown for ranges of 160 and 595 km. A major advantage of diesel and gasoline fuels is their high energy density; increasing the range of the vehicle hardly increases its weight.

Turning to social issues: the current infrastructure is for petroleum fuels. Large investments would be required to change it. The significant portion of U.S. crude oil that is imported (*11*) reduces energy independence. The amount of GHG (carbon dioxide equivalent) generated by the life-cycle of vehicles fueled by gasoline and diesel is large (e.g., approximately 100 000 kg for the reformulated gasoline port injection option) (*4*). Estimated global warming potentials for fuel cycles and vehicle operation of the automobile alternatives are shown in Figure 3. The GHG emissions resulting from fuel production are 20−30% of those resulting from vehicle operation. Compared to the gasoline baseline vehicle, the greater efficiency of the diesel engine results in lower energy use and 25% lower global warming potential.

TABLE 4. Near-Term Fuel Prices and Consumer Lifetime Expenditure on Fuel

fuel	lifetime energy required (GJ)	price[a] (1999$/GJ)	consumer lifetime expenditure (1999$)
gasoline SIII[b]	740[c]	10.13[d]	7 495
CaRFG2 SIII	740	10.95[d]	8 100
CaRFG2 SIDI	650	10.95[d]	7 115
EC Diesel CIDI	570	8.89[e]	5 065
ethanol SIDI herbaceous biomass	595	25.44[f]	15 140
ethanol SIDI woody biomass	595	25.44[f]	15 140
CNG 3000 psig SIII	720	8.09[g]	5 820
CNG 3000 psig SIDI	640	8.09[g]	5 175

[a] Assumes use of current technology for fossil fuel production and near-term technology for herbaceous and woody biomass fuels. Fuel prices based on following sources for prices net of taxes, transport, and retail markup. We add $0.60/gal to the liquid fuel prices for taxes, transport, and retail markup. For CNG, we add taxes and retail markup based on those for gasoline converted to a $/GJ basis. [b] Fuel and engine technology abbreviations as in Table 2. [c] 6Number of significant digits in the table is for calculation purposes and does not represent the accuracy of the figures. [d] On the basis of October 1999 refinery gate cost of $0.629/gal for unleaded gasoline and estimated additional premium for CaRFG2 *(38)*. [e] Calculated from conventional diesel price plus small premium *(38)*. [f] Assumes near-term ethanol cost of $1.44/gal for herbaceous and woody biomass sources *(27)*. [g] On the basis of October 1999 city gate price of $3.5/MCF.

Compressed natural gas (CNG) is an attractive fuel as compared to gasoline or diesel because of five attributes. (i) Historically, it has been cheaper [there is a fuel cost saving through the use of CNG (see Table 4)]. (ii) It has lower air pollution emissions from the engine (it is an inherently cleaner fuel than gasoline and diesel; CNG vehicles were the first to be certified to ULEV and SULEV). (iii) It has lower GHG emissions (CNG has less carbon per joule than gasoline or diesel; with a range of 595 km, the SIDI CNG vehicle has the potential to lower lifetime GHG emissions by approximately 30% as compared to the baseline vehicle, see Figure 3). (iv) Its use extends petroleum supplies. (v) There are large quantities of the fuel available in North America. The difficulties with CNG arise from vehicle range, infrastructure costs, and ensuring sufficient supply. CNG vehicles face large penalties in increasing their range from 160 to 595 km (Figure 2). To maintain interior and trunk space equivalent to those of the baseline vehicle, the CNG vehicle would have to be enlarged to accommodate the storage cylinders. The additional weight of storage cylinders requires extra chassis weight, requiring still more fuel and storage cylinders. Compared to the baseline vehicle, CNG is relatively more attractive for a 160-km range than for a 595-km range.

A large increase in the number of CNG vehicles would require new gas pipelines and other infrastructure. However, a greater concern is whether there is sufficient gas at extraction costs close to present levels to supplant gasoline.

Ethanol from biomass has several major advantages: (i) It could be produced within the United States. (ii) It could be produced so that there are no net carbon dioxide emissions (if no fossil fuels are used in the fuel production). (iii) It is a liquid with high energy density (although somewhat lower than that of gasoline or diesel, resulting in additional weight for the same range) (Figure 3). (iv) It is a relatively clean burning fuel. (v) 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 LDV even under the most stringent agreement on limiting GHG emissions. Second, it is advan-

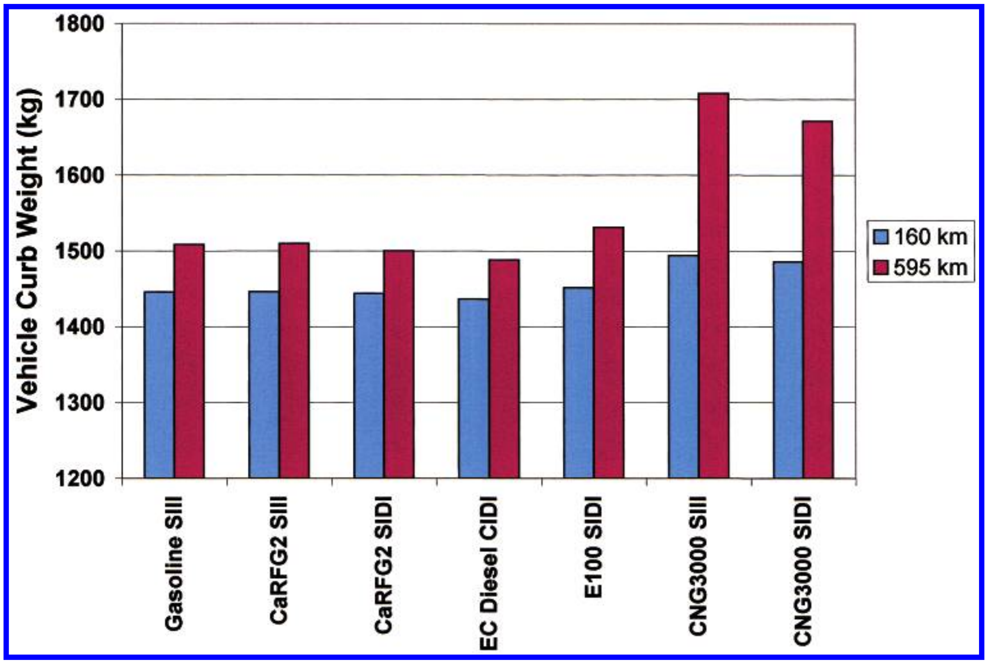

FIGURE 2. Curb weights of 160- and 595-km range internal combustion engine automobiles.

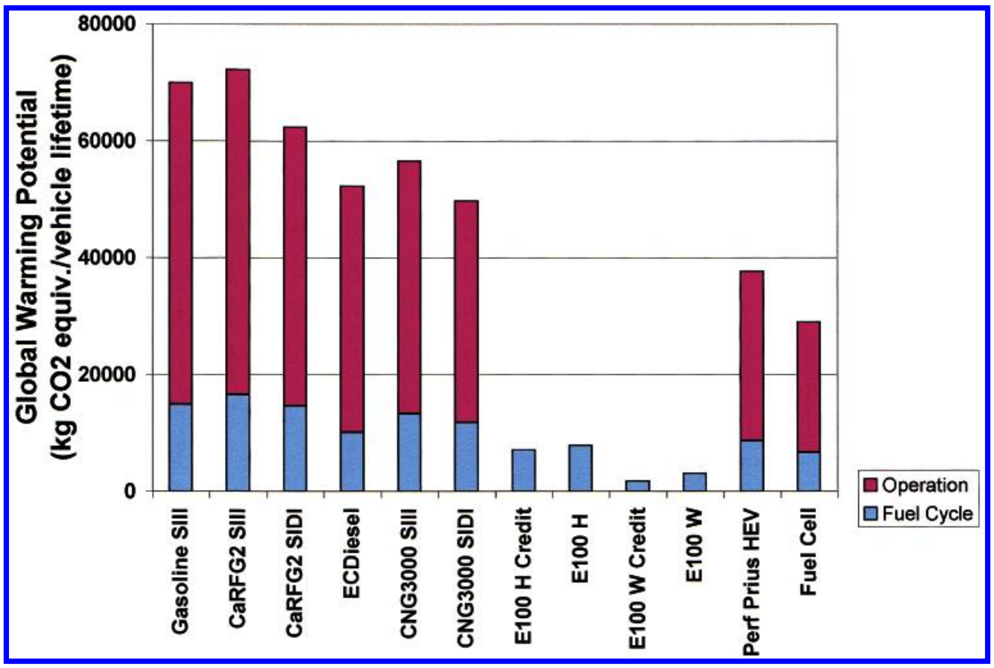

FIGURE 3. Global warming potential of fuel cycle and vehicle operation for automobile alternatives.

tageous for automakers' CAFE calculations. For large vehicles with low fuel economy, biomass ethanol (as well as methanol, CNG, and electricity) provides a fuel that can avoid violating CAFE standards with the associated dollar penalties and social censure.

As we show in Table 4, biofuels have the principal disadvantage of being considerably more expensive than petroleum fuels. Government agencies have estimated the costs of producing ethanol from biomass. Wooley (*27*) reports a near-term production cost for ethanol from woody biomass as \$1.44/gal (+\$0.20, −\$0.08), or assuming best of industry technologies, \$1.16. In terms of gasoline equivalent gallons, these costs are \$1.73 and \$1.39, respectively. This compares to an October 1999 refinery gate cost of about \$0.629/gal for unleaded gasoline (*38*). In other words, the price of petroleum would have to double or triple in order to make ethanol from biomass competitive.

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 (*23*, *25*, *26*). 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.

Biofuels have the potential to offer the much greater GHG reductions necessary if there is a greater focus on these emissions. Ethanol from biomass makes use of the carbon sequestered in plants; when the plants regrow, the emitted carbon is recaptured, 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. Figure 3 reports global warming potential based on sustainable production for the biofuels (no fossil fuel use in their production). The global warming potential reported for the bioethanol fuel

TABLE 5. Metals Demand for Electric Vehicles[a]

battery type	multiple of 1997 demand
lead acid	
lead	0.86
nickel metal hydride	
nickel	3.33
cobalt	3.01
cerium	16.42
lithium ion	
lithium	7.43
cobalt	11.22

[a] 5 million battery-powered vehicles or 50 million hybrid electric or fuel cell vehicles.

cycles is due to the non-carbon dioxide GHG emissions. The entries labeled "credit" include an electricity credit that assumes displacement of electricity from more polluting sources, with the electricity generated as a coproduct of the biomass ethanol production (*23, 25*). The bioethanol entries not labeled credit assume that there is no electricity credit. The near-term attractiveness of the ethanol from woody biomass as compared to that from herbaceous results from the assumption of a larger land use change carbon sequestration rate and a larger electricity credit as compared to those for the herbaceous biomass (*25*). The United States has sufficient land to replace the 100 billion gal of gasoline used each year to fuel LDV with biomass ethanol, even after subtracting cropland and developed land (*4*).

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 with respect to lifetime costs, given current and near-term expected technologies.

Battery-powered vehicles have an electric motor that is inherently more efficient than an ICE, although energy is lost in generation, in transmission, and in charging the batteries. The weight of the batteries (400−500 kg) lowers fuel economy. Achieving the range of a conventional vehicle (595 km) is not feasible with battery-powered automobiles. The range for the General Motors EV-1 is less than 150 km. Toyota is the only manufacturer that quotes replacement price and life for electric vehicle nickel metal-hydride batteries. They guarantee these batteries for 3 yr and expect them to last for 5 yr, perhaps 50 000 mi. The replacement price is 2.5 million yen, about $30 000. Thus, these batteries cost about $0.37/km ($0.60/mi). At an off-peak rate of $0.05/kWh, the cost of electricity for charging the batteries is approximately $0.006/km ($0.01/mi).

Shown in Table 5 is the metal use for 5 million batteries as compared to the 1997 U.S. use of these metals. Assuming that lead-acid batteries are replaced four times and that nickel metal-hydride and lithium-ion batteries are replaced twice during the life of a car, this production would support 15 million lead-acid or 30 million nickel metal-hydride or lithium-ion battery cars (11% and 22% of the fleet, respectively). While the increase in the demand for lead might not pose large supply problems, the increased demand for the other metals would be difficult to meet, leading to price increases. The increase is particularly significant for cerium or cobalt. Several of these metals are byproducts in mining nonferrous metals such as lead. A large increase in demand would result in these metals becoming the primary product of mining. Since the metals are in such low concentrations in ores, mining and smelting would be extremely expensive, particularly if the dominant metal (lead) were in excess supply.

At present, battery recycling is in a primitive state (*39*). Most consumer batteries are not recycled. Assiduous effort has resulted in the recycling of automobile (lead-acid) batteries rising to the 92−93% level (*40*). Some nickel metal-hydride batteries are recycled but only to recover the nickel. 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 materials in the batteries.

Hybrid electric vehicles are heavier and more expensive than similar, conventional ICE 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 batteries smaller 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-tenth the size of the EV-1 battery (*41*). Thus, the amount of battery metals in Table 5 would support 75−150 million hybrids. Assuming the Prius battery lasts 100 000 km and costs $2100 (the estimated cost at large-scale production assuming technology advances), it would cost $ 0.02/km ($0.03/mi).

The fuel economy of the Japanese version of the Prius was 48.6 mpg in EPA tests (*41*). The Toyota Corolla with manual transmission, a slightly larger car, was tested at 36.5 mpg. We modify the Prius to accelerate from 0 to 60 mph in 10.5 s (similar to the Corolla) rather than the 14.2 s of the Japanese Prius. We refer to this modified hybrid as the performance or "Perf-Prius". Additionally, we modify the Corolla to have an automatic transmission (Corolla-AT). The resulting fuel economies of the Perf-Prius and Corolla-AT are 42.7 and 33.8 mpg, respectively (*2*). At $1.50/gal of gasoline, the fuel cost of a Corolla-AT would be $0.027/km ($0.044/mi) as compared to $0.0218/km ($0.035/mi) for gasoline for the Perf-Prius and $0.02/km ($0.03/mi) for the battery. The Perf-Prius costs $0.015 more per kilometer than the Corolla-AT. Thus, the hybrid saves gasoline but is substantially more expensive to operate than the Corolla.

The Prius has lower air pollutant and GHG emissions than the Corolla. Figure 3 shows the GHG emissions for the Perf-Prius. These emissions have a value from a social perspective. Four states and a number of researchers have estimated the social loss from emitting 1 ton of each of these emissions (*42*). The median values are as follow: $1400 for volatile organic compounds, $1050 for carbon monoxide, $1060 for nitrogen oxides, and $14 for carbon dioxide. Using these values, the lifetime emissions reductions from substituting a Perf-Prius for a Corolla-AT are $121 for air pollutants and $76 for carbon dioxide. Discounting the air pollution emissions gives a present discounted value of $88.

The Prius sells for more than the Corolla in Japan and is an inherently more expensive car to manufacture. We estimate that the Perf-Prius will sell for $4000 more than the Corolla-AT in the United States. The cost of replacing the battery is greater than the fuel savings for a Perf-Prius. Even accounting for the lower emissions of the Perf-Prius, it would have to sell for $340 less than the Corolla-AT in order to be economically attractive. Only if the Perf-Prius did not require a battery replacement would it be worth $1140 more than the Corolla-AT. As shown in Table 6, we calculate the price of gasoline and multipliers for emissions required to pay for the $4000 additional price of the Prius. These prices are very substantial. Also shown in the table is a comparison of an advanced hybrid that has 50% better fuel economy than the Corolla-AT (72.9 mpg). The gasoline savings and lower emissions of this advanced hybrid would be worth a $1116 premium over the Corolla-AT.

While this article was in press, the USA version of the Prius went on sale. This "second generation" hybrid offers

TABLE 6. Gasoline Prices and Social Valuations of Emissions and Carbon Dioxide That Make a Hybrid Electric Vehicle and Toyota Corolla Comparable

vehicle	Perf-Prius	Prius	AHEV[a]
HEV Priced $4000 More Than Corolla-AT[b]			
gasoline price[c] ($/gal)	9.38[d]	6.35	3.53
emissions cost multiplier[e]	51	46	34
carbon dioxide ($/ton)	808	413	188
HEV Priced Same as Corolla-AT			
gasoline price ($/gal)	2.12	1.38	0.71
emissions cost multiplier	5		
carbon dioxide ($/ton)	76		
Breakeven Vehicle Price Difference[f]			
price ($)	−340	+98	+1116
no battery replacement	+1140	+1578	+2596

[a] AHEV is advanced HEV. The AHEV is assumed to have 50% higher fuel economy than the currently manufactured Prius. Fuel economy is 48.6 mpg for the Prius, 42.7 mpg for the performance Prius (Perf-Prius), and 72.9mpg for the AHEV. [b] The additional initial price (not including batteries) of the HEV as compared to the Corolla-AT. One battery replacement is required over the lifetime of the HEV; three battery replacements are assumed for the Corolla-AT. [c] The gasoline price required under the assumption that the HEV costs $4000 more than the Corolla-AT. They each have a lifetime of 200 000 km. The lifetime maintenance is the same. The batteries are replaced, and the discount rate is 6%. The median social costs of emissions are used: nitrogen oxides, $1060/ton; hydrocarbons, $1400/ton; carbon monoxide, $1050/ton; and carbon dioxide, $14/ton. [d] Table entries are the gasoline price, emissions multiplier, or carbon dioxide social valuation required to equate the lifetime cost of a hybrid electric vehicle (HEV) with those of a Toyota Corolla with automatic transmission (Corolla-AT) under the stated assumptions. [e] The factor by which the median social cost valuations of hydrocarbons, nitrogen oxides, and carbon monoxide emissions would have to be multiplied to equate the HEV and Corolla-AT lifetime costs. [f] The breakeven vehicle price difference is the difference in the vehicle price that equates the lifetime costs of the HEV and Corolla-AT. A negative value for the difference indicates that the HEV price would have to be this amount lower than that of the Corolla for equal lifetime costs. For these cases we assume $1.50/gal gasoline, median valuations of emissions, battery replacements, and a 6% discount rate.

improvements in fuel economy, emissions, and acceleration; the battery lasts the life of the vehicle and the car is priced $3,500 more than a comparable Corolla. While the new Prius is more attractive, it still is not cost-effective in saving fuel and lowering emissions.

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. Since it is difficult to store sufficient hydrogen to give the vehicle the range of current cars, 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 liquid fuels require 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. Figure 3 shows GHG emissions for a gasoline fuel cell vehicle.

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 (*43*). An analysis similar to that done for the hybrid indicates that in the near term the vehicle would not be cost-effective 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/Propulsion Technology 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 ICE automobile as the baseline (∗). There is no dominant alternative, although a range of feasible and attractive fuel/propulsion combinations exists for personal transportation vehicles. However, all would have trouble displacing gasoline because of the low price of petroleum, the immense investment in current infrastructure, and the rapid progress that has been made in improving efficiency and environmental performance of reformulated gasoline-fueled ICE vehicles.

Each fuel technology scores reasonably well in terms of lowering emissions of ozone precursors, particulate matter, and air toxics. Direct injection engines are likely to dominate the market only if they are able to meet emissions standards without losing their efficiency advantage and without having to use significantly more expensive fuels. CNG and the electric vehicles do well on ozone and air toxics; the diesel does badly on air toxics.

CNG offers lower fuel prices while biomass ethanol is much more expensive. Battery-powered cars, and to a lesser extent CNG, have a penalty for range. The electric vehicles, especially the fuel cell, are more expensive to make.

The largest differences among the options occur for social issues. Biomass ethanol is better for energy independence, global warming, and fuel depletion but worse for infrastructure cost. CNG also has high infrastructure costs but shares advantages for energy independence and global warming. The preferred fuel/engine option that is best depends on the attributes of greatest concern. However, in our judgment, two fuels offer a significant challenge to gasoline/diesel. CNG in optimized engines is cheaper and cleaner, in greater supply, and offers energy independence and lower GHG emissions. However, to realize these advantages, automakers and fuel suppliers would have to make large investments to design and construct the plants to build engines and chassis required for these cars and to make these cars attractive to consumers. Additionally, investment would be required in new wells, pipelines, and retailing structure. If strict reductions in GHG are required, petroleum prices double, or we are willing to invest in making our energy system more sustainable, ethanol from biomass is the attractive alternative. However, in addition to the infrastructure investments required for CNG, large investments would be required for the facilities that convert biomass into ethanol.

In our judgment, the hybrid and fuel cell vehicles are not attractive in the near term as compared to the other technologies; battery-powered cars are attractive only for highly specialized circumstances.

Acknowledgments

We thank the U.S. Environmental Protection Agency, General Motors, U.S. National Science Foundation (through the Center for Integrated Study of the Human Dimensions of Global Change under cooperative agreement number SBR-9521914), The Sloan Foundation, and Texaco for support.

Literature Cited

(1) Lankey, R.; McMichael, F. C. *Alternative Fuel Vehicle Batteries*; Working Paper, Green Design Initiative; Carnegie Mellon University: Pittsburgh, PA, 1999.
(2) Lave, L. B.; MacLean, H. L. *An Environmental Economic Evaluation of Hybrid Electric Vehicles Based on the Toyota Prius*; Working Paper, Green Design Initiative; Carnegie Mellon University: Pittsburgh, PA, 1999.
(3) MacLean, H. L.; Lave, L. B. *Environ. Sci. Technol.* **2000**, *34*, 225.
(4) MacLean, H. L.; Lave, L. B.; Lankey, R.; Joshi, S. *J. Air Waste Manage. Assoc.* In press.
(5) MacLean, H. L.; Lave, L. B. *Environ. Sci. Technol.* **1998**, *32*, 322A–330A.
(6) MacLean, H. L. Ph.D. Dissertation, Carnegie Mellon University, Pittsburgh, PA, 1998.
(7) Carnegie Mellon University, Green Design Initiative. Website software http://www.eiolca.net.
(8) Lave, L. B.; Joshi, S.; MacLean, H. L.; Horvath, A.; Hendrickson, C. T.; McMichael, F. C. *Proceedings of the 1998 SAE Total Life Cycle Conference*, Graz, Austria, December 1998.
(9) Lave, L. B.; Cobas, E.; Hendrickson, C. T.; McMichael, F. C. *Environ. Sci. Technol.* **1995**, *29*, 420A–426A.
(10) Hendrickson, C. T.; Horvath, A.; Joshi, S.; Lave, L. B. *Environ. Sci. Technol.* **1998**, *32*, 184A–191A.
(11) *Transportation Energy Data Book*, 18th ed.; Davis, S., Ed.; U.S. Department of Energy, Office of Transportation Technologies; Prepared by Oak Ridge National Laboratory: Oak Ridge, TN, 1998; ORNL-6941.
(12) Greene, D. L. *Transportation and Energy*; Eno Transportation Foundation, Inc.: Landsdowne, VA, 1996.
(13) *New ARCO Diesel Fuel Could Lead to Cleaner Bus, Truck, and Car Emissions*; Press Release, ARCO, 1999.
(14) Brinkman, N. General Motors, Warren, MI, personal communication. 1999.
(15) Lave, L. B. *Science* **1981**, *212*, 893.
(16) *Consumer Reports New Car Price Report, 1998 Ford Crown Victoria, 1998 Ford Taurus*; Consumers Union of U.S., Inc.: Los Gatos, CA, 1998.
(17) *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990–1997*. Office of Policy, U.S. Environmental Protection Agency: Washington, DC, 1999.
(18) Cadle, S. H.; Groblicki, P. J.; Gorse, R. A.; Hood, J.; Korduba-Sawicky, D.; Sherman, M. *Dynamometer Study of Off-Cycle Exhaust Emissions – The Auto/Oil Air Quality Improvement Research Program*; Society of Automotive Engineers: Warrendale, PA, 1997; SAE 971655.
(19) *Dynamometer Study of Off-Cycle Exhaust Emissions*; Auto/Oil Air Quality Improvement Research Program, Technical Bulletin 19; Coordinating Research Council: Atlanta, GA, 1996.
(20) Vachon, T. *Proceedings of the 1997 Diesel Engine Emissions Reduction Workshop*, University of California, San Diego, La Jolla, CA, July 28–31, 1997; p 207.
(21) *Evaluation of Fuel-Cycle Emissions on a Reactivity Basis: Volume 1-Main Report, Acurex Environmental Final Report*; Acurex Environmental Corporation; Prepared for California Air Resources Board: Mountain View, CA, 1996; FR-96-114.
(22) *Evaluation of Fuel-Cycle Emissions on a Reactivity Basis: Volume 2-Appendices, Acurex Environmental Final Report*; Acurex Environmental Corporation; Prepared for California Air Resources Board: Mountain View, CA, 1996; FR-96-114.
(23) Wang, M.; Saricks, C.; Santini, D. *Effects of Fuel Ethanol Use on Fuel-Cycle Energy and Greenhouse Gas Emissions*; Center for Transportation Research, Argonne National Laboratory: Argonne, IL, 1999; ANL/ESD-38.
(24) Wang, M. Q. Argonne National Laboratory, Argonne, IL, personal communication, 1999.
(25) Wang, M. Q. *GREET 1.4 Transportation Fuel-Cycle Model*; Center for Transportation Research, Argonne National Laboratory: Argonne, IL, 1998.
(26) Wang, M. Q. *Development and Use of the GREET Model to Estimate Fuel-Cycle Energy Use and Emissions of Various Transportation Technologies and Fuels*; Center for Transportation Research, Argonne National Laboratory: Argonne, IL, 1996; ANL/ESD-31.
(27) Wooley, R.; Ruth, M.; Sheehan, J.; Ibsen, K.; Majdeski, H.; Galvez, A. *Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis Current and Futuristic Scenarios;* National Renewable Energy Laboratory: Golden, CO, July 1999; NREL/TP-580-26157.
(28) Delucchi, M. A. *A Revised Model of Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity*; Institute of Transportation Studies, University of California–Davis: Davis, CA, 1997; UCD-ITS-RR-97-8.
(29) Delucchi, M. A. *Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity. Volume 1: Main Text*; Center for Transportation Research, Argonne National Laboratory: Argonne, IL, 1991; ANL/ESD/TM-22,Vol. 1.
(30) Kreucher, W. M. *Soc. Automot. Eng.* [*Spec. Pub.*] **1998**, *No. 982218*.
(31) Sheehan, J.; Camobreco, V.; Duffield, J.; Graboski, M.; Shapouri, H. *Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus*; Final Report; National Renewable Energy Laboratory: Golden, CO,1998; NREL/SR-580-24089.
(32) *Federal Alternative Motor Fuels Programs Fifth Annual Report to Congress*; U.S. Department of Energy, Department of Transportation Technologies, National Renewable Energy Laboratory: Golden, CO, 1996; DOE/GO-10096-240.
(33) Liss, W. Natural Gas Research Institute, Chicago, IL, personal communication, 1998.
(34) Robinson, G. State Farm Insurance, Pittsburgh, PA, personal communication. 1998.
(35) Sullivan, J. L.; Williams, R. L.; Yester, S.; Cobas-Flores, E.; Chubbs, S. T.; Hentges, S. G.; Pomper, S. D. *Soc. Automot. Eng.* [*Spec. Pub.*] **1998**, *No. 982160*.
(36) *Fact Sheet OMS-2 Air Toxics from Motor Vehicles*; U.S. Environmental Protection Agency: Washington, DC, 1994; EPA 400-F-92-004.
(37) Priestley, E. Exxon Research and Engineering Company, Annandale, NJ, personal communication, 1999.
(38) U.S. Department of Energy. Energy Information Administration Website. Table 6. U.S. Refiner Motor Gasoline Prices by Grade and Sales Type/Table 4. Selected National Average Natural Gas Prices, 1993–1999. www.eia.doe.gov/price.html (accessed March 20, 2000).
(39) McMichael, F. C.; Hendrickson, C. T. *IEEE Spectrum* **1998**, February.
(40) *1997 Recycling Rate Study;* Battery Council International: Chicago, IL, 1998.
(41) *Evaluation of a Toyota Prius Hybrid System* (*THS*); U.S. Environmental Protection Agency: Washington, DC, 1998; EPA420-R-98-006.
(42) Matthews, H. S. Ph.D. Dissertation, Carnegie Mellon University, Pittsburgh, PA, 1999.
(43) Hanisch, C. *Environ. Sci. Technol.* **1999**, *33*, 458A–462A.
(44) Baker, R.; Barker, T.; Greenfield, N. Ford Motor Company, Detroit, MI, personal communication, 1999.
(45) Brinkman, N.; Hilden, D.; Krieger, R.; Monroe, D.; Oh, S. General Motors, Warren, MI, personal communication with Brinkman, N., 1999.
(46) Makino, E. Nissan Motor Co., Ltd., Alsugi-City, Kanagawa, Japan, fax communication, 1999.

Received for review November 30, 1999. Revised manuscript received June 8, 2000. Accepted June 19, 2000.

ES991322+