Environ. Sci. Technol. **2003**, *37,* 5445−5452

Life Cycle Assessment of Automobile/Fuel Options

HEATHER L. MACLEAN*,† AND LESTER B. LAVE‡

Department of Civil Engineering, University of Toronto, 35 St. George Street, Toronto, Ontario, Canada M5S 1A4, and Graduate School of Industrial Administration, Carnegie Mellon University, Pittsburgh, Pennsylvania 15213

We examine the possibilities for a "greener" car that would use less material and fuel, be less polluting, and would have a well-managed end-of-life. Light-duty vehicles are fundamental to our economy and will continue to be for the indefinite future. Any redesign to make these vehicles greener requires consumer acceptance. Consumer desires for large, powerful vehicles have been the major stumbling block in achieving a "green car". The other major barrier is inherent contradictions among social goals such as fuel economy, safety, low emissions of pollutants, and low emissions of greenhouse gases, which has led to conflicting regulations such as emissions regulations blocking sales of direct injection diesels in California, which would save fuel. In evaluating fuel/vehicle options with the potential to improve the greenness of cars [diesel (direct injection) and ethanol in internal combustion engines, battery-powered, gasoline hybrid electric, and hydrogen fuel cells], we find no option dominates the others on all dimensions. The principles of green design developed by Anastas and Zimmerman (*Environ. Sci. Technol.* **2003**, *37*, 94A−101A) and the use of a life cycle approach provide insights on the key sustainability issues associated with the various options.

Introduction

Almost every facet of modern society depends on personal transportation vehicles. Light-duty vehicles (LDV, cars and light trucks) offer many benefits to society. However, LDV also have large costs in terms of safety, air pollution, and consumption of gasoline and other resources. Significant progress has been made in improving safety, lowering emissions, and lowering some production inputs and discharges, but overall, limited advances have occurred in making vehicles sustainable. Since the world has almost 600 million LDV (*2*) and this number may double by 2020 (*3*), radical changes in automobile design, components, and fuels are required for them to become sustainable.

We draw on Anastas and Zimmerman's (*1*) 12 green design principles in examining the sustainability (environmental, economic, and social components) of LDV. However, these design principles do not address the two primary challenges that automakers face with respect to green design of vehicles. First, the company must produce vehicles that customers want to buy. Second, the elaborate array of regulations they face are not entirely consistent with green design. For example, a small, lightweight vehicle could better satisfy the 12 principles than the average new vehicle sold. However, few consumers would buy this vehicle, and it would be difficult to manufacture it so that it satisfied the safety and other regulations. We elaborate several of the principles to account for customer demand and meeting regulations.

Customer preferences and regulations have led automakers to utilize many of the Anastas and Zimmerman (*1*) principles. The result has been modest improvements in sustainability through the choice of materials, improvements in fuel economy, etc. However, consumer preferences for large, powerful vehicles and the array of sometimes contradictory regulations have inhibited greater progress. Unless new car buyers change their preferences, green design principles will be able to achieve only modest gains.

To assess the gains that have been made and to set priorities for future changes, we introduce a model for examining sustainability through the entire life cycle (LC) of a LDV. The LC begins with materials extraction and moves on to vehicle manufacture, use (comprised of driving the vehicle including the LC of the fuel used, requirements for maintenance, repair, insurance, license fees, and other costs), and end-of-life.

Assessing the LC implications of design changes for LDV is particularly difficult. In producing and using the vehicle, the LC of an automobile reaches into almost every sector of the economy; design changes affect other social goals and problems, including highway safety, pollution emissions, greenhouse gas (GHG) emissions, and congestion.

The goals of the paper are to review the LC of LDV, discuss progress and challenges in improving the "greenness" of LDV, assess some differences in greenness among alternative fuel/vehicle options for the near and midterm using various LC-based methods, and discuss steps that are needed to produce a more sustainable vehicle.

Get Rid of the Problem: Eliminate Cars. In the United States, LDV result in 42 000 annual highway deaths, make a major contribution to urban ozone, cause vast congestion, and use tremendous amounts of land for roads and parking lots. Some people simply propose to eliminate cars. This vision would require completely restructuring the geography of North American cities. The current urban structure requires personal transportation vehicles in order for the vast majority of people to live and work efficiently. Thus, while a vision of a world without LDV may have nostalgic appeal, the automobile is such an integral part of U.S., Canadian, and other societies that we will almost certainly have personal transportation vehicles throughout the 21st Century. In the United States and Canada, public transportation ridership has declined from the level of the early 1990s, and the proportion of trips on public transport is small even in urban centers (*4*).

We could provide personal transportation vehicles with much less drain on petroleum, metals, land, and other resources. There is no miracle of engineering or even elaborate green design principles needed to substitute basic small, light, fuel-efficient vehicles for the current vehicles. We do not because our cars are status symbols and projections of how we see ourselves. For example, using a 3200-kg sport utility vehicle (SUV) with an acceleration time from 0 to 100 kmh of 7.9 s to get one person to his office is going far beyond basic mobility.

Making Vehicles Greener. Amory Lovins of the Rocky Mountain Institute (*5*) points out that only about 5% of a vehicle's weight is payload (passenger). Although much of

* Corresponding author e-mail: hmaclean@ecf.utoronto.ca; phone: (416)946-5056; fax: (416)978-3674.

† University of Toronto.

‡ Carnegie Mellon University.

10.1021/es034574q CCC: $25.00
Published on Web 10/22/2003

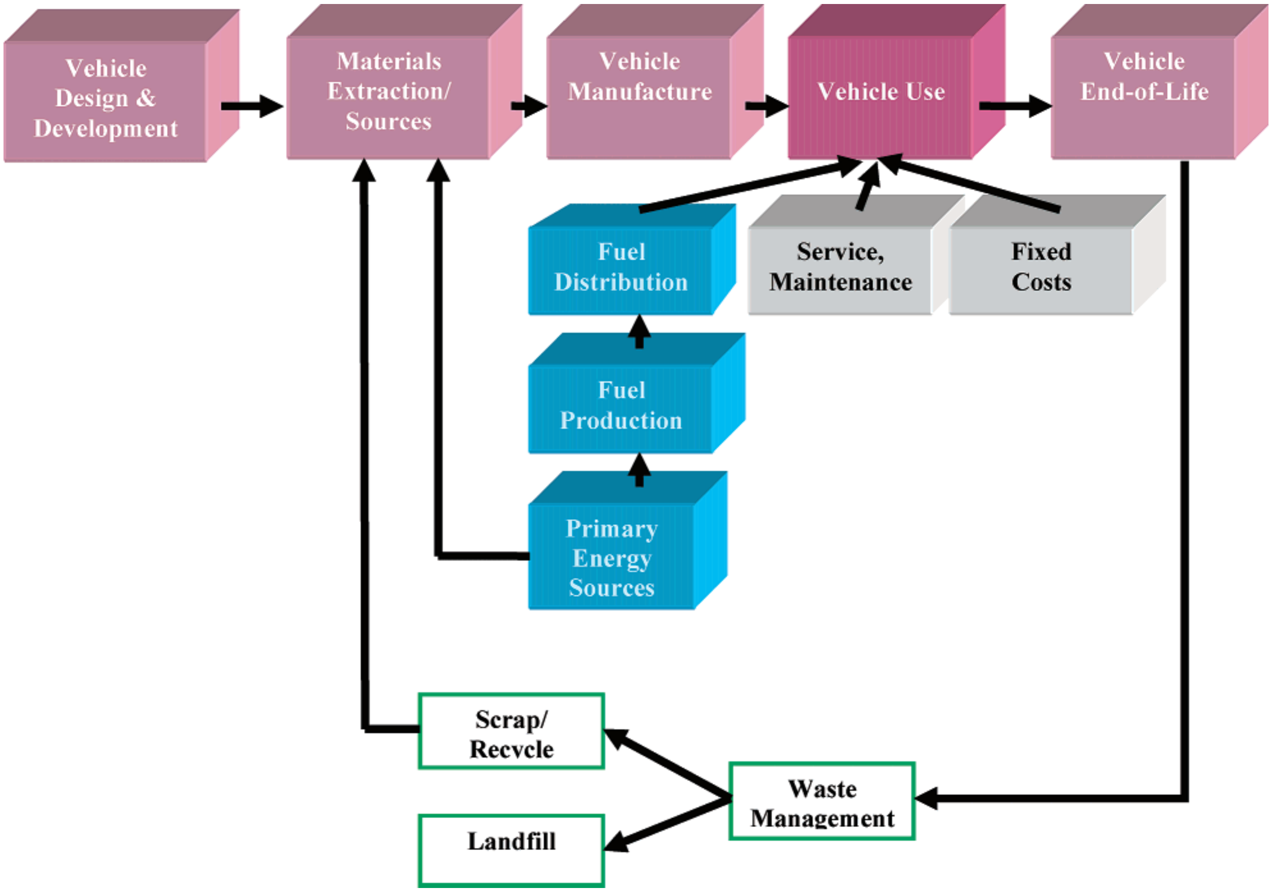

FIGURE 1. Simplified diagram of automobile life cycle.

this additional weight is necessary for meeting vehicle performance (including safety) design goals, it is sobering to recognize this limit in examining alternative design options. How do we make progress in moving toward greener vehicle designs? Referring to Figure 1, we briefly describe the stages of the vehicle LC since the performance of the entire LC must be considered when determining a vehicle's greenness.

Vehicle design and development is the most important stage since it determines the materials composition of the vehicle, fuel economy, safety, and emissions, essentially the "life cycle performance" throughout the vehicle lifetime. **Material extraction/sources** consider the materials that make up the automobile and that they must be extracted and processed. **Vehicle manufacture** involves the processing of materials into components and their assembly into the final vehicle. **Vehicle use** is the most complicated LC stage, comprising (a) the fuel cycle (often termed "well-to-tank" in LC studies), and includes producing the fuel from recovery or production of the feedstock, its transportation, conversion of the feedstock to the final fuel and subsequent storage, distribution, and delivery to the vehicle fuel tank; (b) the vehicle operation (often termed "tank-to-wheel" in LC studies) [the well-to-tank and tank-to-wheel portion together comprise the well-to-wheel] consists of the energy required to drive the vehicle, exhaust and evaporative emissions from the vehicle over its lifetime, and facilities and infrastructure to support vehicles over their lifetimes (e.g.. parking, roads); (c) the vehicle service comprises maintenance, repair, and collision repair over the vehicle lifetime; and (d) the fixed costs include insurance, license fee, depreciation, and finance charges. **End-of-Life** is the final stage of a vehicle's life and comprises transportation of the vehicle to a dismantling facility, dismantling, fluids and metals recovery, shredding, and disposal of the shredder residue (*6*).

Auto and Fuel Sector Progress. Since 1970, the automotive and fuel sectors of the economy have considerably improved their environmental performance (*7*, *8*). These improvements have been driven by increasingly strict environmental and energy/fuel regulations and to a lesser extent by a growing awareness of consumers and the industries involved of the need for improving the sustainability of vehicles and their associated fuels. The industry has taken steps itself to lower environmental burdens (e.g., refs *8*−*11*). Overall, the industry has implemented measures that fall into the majority of the 12 principles of Anastas and Zimmerman (*1*), but much work remains. The major issues of the vehicle LC that have characterized its "unsustainability" have not been solved.

Major Issues Impacting the Sustainability of the Automobile LC

Categorizing the automobile LC issues into the three facets of sustainability; environmental, economic, and social, we highlight major current issues that should be targeted for improving vehicle LC sustainability.

Environmental Issues. (a) Raw Materials/and Vehicle Manufacture. Material/resource use issues include the quantities of nonrenewable resources required (resource depletion), the environmental impacts due to materials extraction and production, the diversity in ability of materials to be recycled (or otherwise managed for end-of-life), the inherent toxicity of some materials or releases, and the increasing use of specialized materials to achieve performance goals (e.g., platinum group metals to improve catalyst efficiency and lightweight materials to lessen fuel consumption). Choosing smaller vehicles and driving these fewer kilometers are the most straightforward steps to reduce resource use, but the trends have been the opposite.

(b) Vehicle Use. *Exhaust and Evaporative Emissions.* Air pollutant concentrations in U.S. urban areas have improved during the past two decades. Improvements in emissions of conventional gasoline LDV (and associated improvements in fuel quality) have been a major factor, despite significant increases in the number of vehicle registrations and vehicle kilometers traveled per year (*12*). However, vehicles are still a major concern for emissions of regulated pollutants and air toxics. Ross et al. (*13*) and Pickrell (*12*) stress the lessening, but still of concern, gap between new car emissions certification and actual on-road emissions. Pickrell (*12*) suggests less focus on further reducing new car emissions and instead more focus on keeping vehicles up to the standard over their lifetimes.

GHG Emissions. Potential climate risks have been associated with increases in levels of GHG emissions. The global transportation sector is responsible for almost one-quarter of worldwide anthropogenic carbon dioxide (CO_2) emissions (*3*); the U.S. transportation sector accounts for about 5%. Canada has ratified the Kyoto Protocol, which requires the country to reduce its emissions by 6% below 1990 baseline emissions by 2012. However, since Canada's current emissions are 20% above 1990 levels (11% in the passenger transport sector; *14*), meeting this goal will require radical changes.

Economic Issues. Entire Life Cycle. The relatively low costs of current vehicles and fuels over their lifetimes set a difficult benchmark for alternative designs to meet. In addition, increasing the price of vehicles to lower environmental impacts (e.g., emissions, fuel use) or to improve social issues (e.g., safety) negatively impacts the social aspect of sustainability related to equity/affordability concerns. A key economic issue associated with sustainability is the importance of distinguishing between private and social costs. Automobile manufacturers are motivated to minimize their private costs in producing a vehicle of a particular size and quality in order to increase their profit. Consumers are motivated to minimize their private costs in owning the vehicle they desire. Ordinarily both of these parties pay little or no attention to the social costs (e.g., those associated with sustainability, air and other pollution, safety, and congestion).

Other Social Issues. Raw Materials/and Vehicle Manufacture, Vehicle Use. The other major social issues associated with the vehicle LC include safety, congestion, land use (also could be considered an environmental issue), and in the United States, energy independence.

Challenges for Green Design

The three principal challenges in designing greener vehicles are as follows:

Challenge 1. Inherent contradictions among social goals. For almost four decades, the United States has regulated automobiles, improving safety, emissions, and fuel economy; unfortunately, the regulation has produced unintended consequences. Smaller, lighter vehicles consume less fuel but protect their occupants less well in a crash as compared to larger, heavier vehicles (*15*). Fuel economy interacts with exhaust emissions since energy is required (negatively impacting fuel economy) to lower pollutant emissions. In addition, emissions standards have so far prevented key fuel economy technologies (e.g., lean burn gasoline engines and diesel engines) from achieving significant market shares in North America (*15*). By spending more money, most of the attributes can be improved without harming others. For example, spending more money can lighten the vehicles (as with an aluminum frame with greater energy-absorbing capacity), improving performance and safety. However, the increase in vehicle cost impacts economic and social aspects of sustainability since low price is an important vehicle attribute to consumers; increasing vehicle prices would hurt the poor.

Challenge 2. Advancements in sustainability can be made through technological progress, human actions, and institutional actions. Unfortunately, advances are unlikely to be made through convincing vehicle buyers to purchase small, fuel-economic vehicles: The 10 most fuel-economic models were less than 2% of new U.S. vehicles sales. Many consumers are willing to pay significant premiums for fuel-guzzling SUVs, making these the most profitable vehicles for automakers (in the mid to late 1990s, the average profit on light trucks (including SUV) was three to four times as great as that on a passenger sedan; *15*). Although a recent Canadian consumer survey showed that the average respondent would be willing to pay a premium of $1820 (Canadian) [All dollar values are in U.S. dollars unless indicated otherwise.] for a greener vehicle (*16*), in practice the auto industry has found that few consumers would be willing to pay anywhere close to this amount.

Challenge 3. Difficulties in identifying and quantifying "benefits" and "costs" to the environment and human health that stem from our inability to recognize some effects, our inability to quantify those that we can recognize, and finally, difficulties in valuation. The uncertainty is evident in studies evaluating the greenness of products (*17*−*19*). A key issue is that toxicology has produced little understanding of the impacts of the vast majority of chemicals. Published LC studies have rarely gone beyond the inventory stage, which reports quantities of inputs and outputs over the lifetime of the automobile, and studies generally do not include either economic or social issues (other than environmental issues) (*19*, *20*). As noted earlier, LC studies have received attention in the auto industry, but there have been barriers preventing their effective use in the design of greener vehicles (see ref *20* for additional discussion). Differences in the results of analyses of even simple products such as paper versus plastic cups, let alone complex products such as automobiles, indicate some of the shortcomings generally with LC assessment application (e.g., ref *20*).

Making Progress in Green Design. Almost all LC studies have been inventory studies that compare vehicle options in terms of their array of environmental discharges, material, and energy use. Analysts hope that one option will have better results than the other options in every category. If a vector-dominant alternative can be identified, then that option would be preferred. However, as is obvious from challenge 1, the principles of Anastas and Zimmerman (*1*), and the results of previous LC studies (refs *10* and *20* review large sets of these studies), there is unlikely to be any vector-dominant alternative since there are inherent differences in technologies and contradictions among social goals. To compare options that are better on some attributes and worse on others, we need to find a way to make the attributes comparable.

One way to slice through this complexity is to rely on markets to internalize the social externalities by having the price of each material, fuel, and design reflect its full social cost. If drivers had to pay for their GHG and tailpipe emissions, fuel use would have declined without regulation. If the full social costs were embodied in the price of each automotive-related good and service, automakers and consumers would be making socially informed decisions. Unfortunately, scientists cannot estimate the full social effects of choosing one fuel or one material over another. Even if that could be done, there would still be the problem of placing a dollar value on premature deaths, a decline in ecological diversity, and other effects.

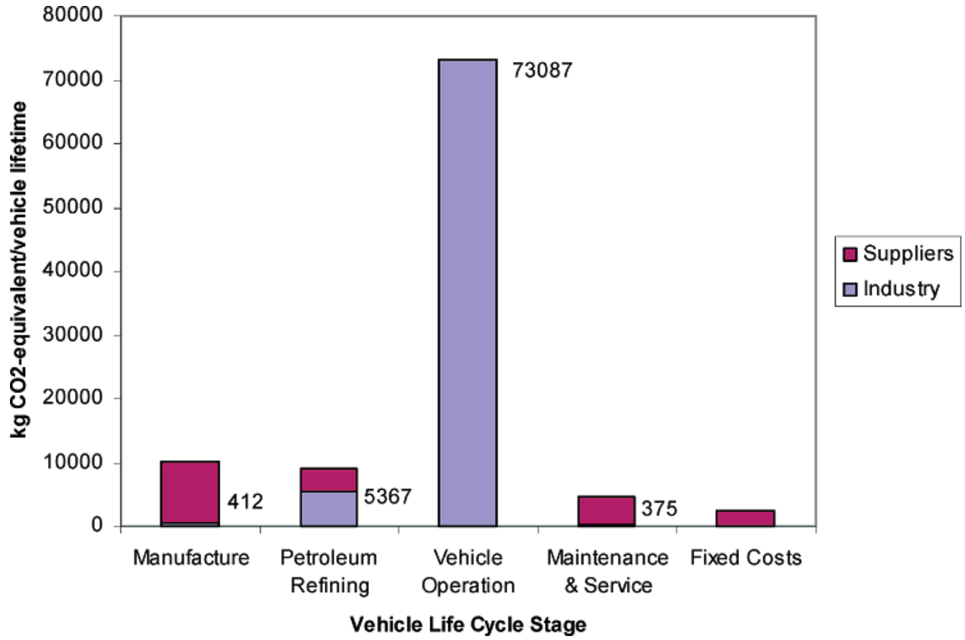

FIGURE 2. Greenhouse gas emissions from the stages of the automobile life cycle. Written values next to bars refer to emissions from industry (or vehicle in case of vehicle operation).

Fuel Vehicle Options with the Potential To Make Progress in Green Design

Improved Conventional Gasoline Internal Combustion Engine Vehicles. The most obvious ways to improve the sustainability of conventional internal combustion engine (ICE) gasoline vehicles would be for consumers to buy fewer vehicles, choose smaller vehicles, drive them less, and maintain them better. Few consumers choose this option as recent studies show (*4*, *14*, *15*).

The first method we use to evaluate where improvements can be made in the sustainability of LDV takes a LC perspective but focuses on a narrow set of sustainability attributes that are determined to be the primary goals; in this case, lowering fossil fuel use and GHG emissions. In an earlier study, we used our Economic Input-Output, Life Cycle Analysis (EIOLCA) tool to inventory resource use, environmental discharges, and economic impacts throughout the entire U.S. economy resulting from each stage of the LC of a LDV (*21*). The current EIO-LCA model utilizes the 1997 U.S. Department of Commerce Input−Output technical coefficient matrix, which disaggregates the U.S. economy into 480 sectors (1997 is the most recent year matrix available). The use of the Economic Input−Output method (a linear general equilibrium model of an economy) allows us to examine quantitatively the economy-wide implications of a change in final demand for a good or service represented by a sector of the economy. In our model, the economic matrix is augmented with a matrix of sectoral environmental discharge and resource consumption data obtained from U.S. government publicly available databases [the sector coefficients in the environmental matrix are unit resource use (or environmental discharge) per dollar of sector output]. Therefore, it is possible to determine the economy-wide economic and environmental implications (e.g., energy use, GHG emissions) resulting from production of additional automobiles, gasoline, servicing of vehicles, etc. The model has been developed by researchers in the Carnegie Mellon University Green Design Institute. The model, description, and data sources can be found at www.eiolca.net.

The current analysis is for a 2002 Ford Taurus and calculates the energy/fuel use and GHG emissions [Since generally the fuels used during the vehicle LC have similarly high carbon contents, and therefore GHG emissions and fuel use are roughly proportional, we illustrate our points with GHG.] resulting from the manufacture of the vehicle (including all suppliers), the production of the gasoline, the maintenance and service, and the fixed costs. End-of-life is not included in the EIO-LCA model (analyses show that energy use, emissions, and economic impacts due to this LC stage are small; *20*). The vehicle fuel economy assumed in the analysis is the 2002 Taurus combined U.S. EPA rated city/highway fuel economy of 10 L/100 km. For further details about specific EIO-LCA model sectors used and method employed, see ref *21*. Results are shown in Figure 2 for GHG emissions. All values are reported in CO_2 equivalents [Since the different GHG have different atmospheric lifetimes and contributions to radiative forcing, the different gases are weighted by their 100-yr Intergovernmental Panel on Climate Change Global Warming Potentials (GWP) to determine an equivalent mass of CO_2 (e.g., kg of CO_2-equiv) (*22*).] and are for an assumed vehicle lifetime of 312 000 km. Figure 2 shows the quantity of total emissions for each LC stage from the "industry" itself (e.g., automobile manufacturers/assemblers, petroleum refineries) or "vehicle" (in the case of vehicle operation) as well as from all of the suppliers to these industries throughout the economy. For the case of vehicle operation, since this LC stage consists of driving the vehicle during its lifetime, there is no supplier component.

The GHG emissions from the manufacture of the automobile are 10 000 kg of CO_2 equiv. Of this amount, only 412 kg result from the automobile industry (primarily assemblers) sector. The suppliers to the sector, transportation, and other supporting activities are responsible for the much larger portion of emissions resulting from vehicle manufacture. Vehicle operation is the source of the majority of GHG emissions, about 73% of the total of 100 230 kg of CO_2 equiv resulting from the LC of a Ford Taurus. This is in agreement with results reported in ref *10*. Carbon dioxide is the GHG emitted in the largest quantity and is very dominant even after weighting the other gases by their higher global warming potentials. Therefore, we concentrate on dealing with the largest source of the problem, CO_2 resulting from the operation of the vehicle.

Looking more closely at the factors contributing to the magnitude of these emissions, we examine the factors in the equation used to estimate the emissions produced during the operation of the vehicle each year, E_{CO_2}:

$$E_{CO_2} = \mathrm{VKT} \times \mathrm{FC} \times C_{content} \times 44/12 \qquad (1)$$

where E_{CO_2} is the emissions of CO_2 per year in grams, VKT is the vehicle kilometers traveled per year, FC is the fuel consumption (L/100 km), and $C_{content}$ is the grams of carbon per liter of fuel.

To achieve reductions in CO_2 emissions:

• Vehicle kilometers traveled can be reduced, requiring behavioral but not design changes (lack of progress to date results primarily from challenge 2).

• Fuel consumption of vehicles can be lowered through vehicle design changes [some of which impact vehicle performance, economics, consumer attractiveness (negative and positive)], and consumers choosing smaller, lighter vehicles (challenges 1−3).

• The carbon content of the fuel can be lowered by moving to compressed natural gas (CNG), a renewable fuel such as ethanol, potentially electricity or hydrogen, or adopting carbon sequestration measures (*23*) (may be sustainability tradeoffs) (challenges 1−3).

None of the above cases represent current trends in the LDV sector. As noted earlier, GHG emissions from the LDV fleet in Canada are 11% above 1990 levels. So, where do we look to lower fuel consumption and GHG emissions from the LDV fleet?

A recent U.S. National Academy of Sciences (*15*) study concluded that fuel economy could be improved by 55% by a series of small improvements in gasoline vehicles, without changing vehicle size or performance; the increased manufacturing costs would be offset by the fuel savings over the lifetime of the vehicle. While these improvements were being phased in, the study found that these more fuel-efficient vehicles would be counterbalanced by consumer choices of more vehicles and the shift toward larger, more powerful vehicles (challenges 1 and 2).

Other options for increasing fuel economy would be to make the fuel economy standards stricter (particularly for light trucks) and/or increase gasoline prices. These have a history of not being politically popular options primarily due to contradictions in social goals and consumer preference (challenges 1 and 2). Gasoline prices could be increased to induce consumers to drive less and choose more fuel-economic vehicles. However, comparing European and U.S. fuel prices and average fuel economy, it appears that roughly tripling the price of fuel is associated with about a 30% improvement in fuel economy. Assuming that the demand response is proportional to price, this experience suggests that a further tripling of price would be required to induce drivers to choose a vehicle mix that averaged 4.7 L/100 km (50 mpg). We doubt that the U.S. or Canadian governments would be able to increase the price of gasoline to \$3.5−4.0/L by raising fuel taxes.

Based on our evaluation of a large number (12) of published well-to-wheel (include fuel cycle and vehicle operation LC stages) studies of conventional and alternative fueled automobiles, we found that only a switch to vehicles that use renewable or low carbon fuels is likely to achieve the goals of significantly lowering fossil fuel use and GHG emissions (for additional details of the evaluation, see ref *20*). We discuss these results with respect to the different vehicle options in the next sections. Figures 3 and 4 show the mean and ranges of results of the studies for the well-to-tank (fuel cycle) efficiencies and GHG emissions for the fuel/vehicle options. Figure 5 shows well-to-wheel GHG emissions results. Keith (*24*) reports, however, that there are few fuel

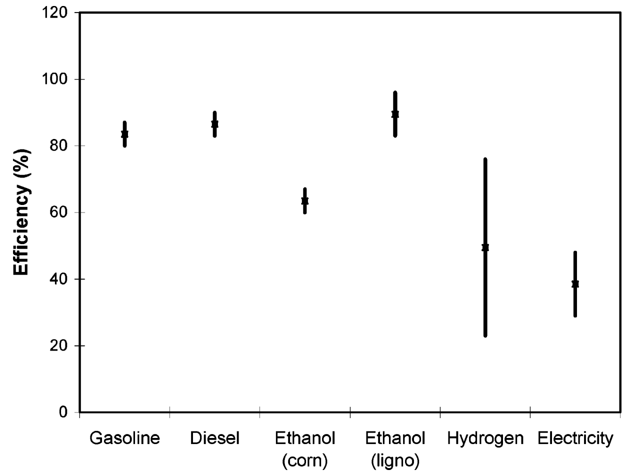

FIGURE 3. Well-to-tank (fuel cycle) efficiency for fuel options. Graph shows mean and range of estimates from set of well-to-wheel studies examined. Efficiency (%) is defined as follows: (energy in the fuel delivered to consumers/energy inputs to produce and deliver the fuel) × 100. Ethanol (corn) is ethanol produced from corn. Ethanol (ligno) is ethanol produced from lignocellulosic feedstocks. For ethanol, efficiencies are calculated based only on fossil (not renewable) fuel inputs.

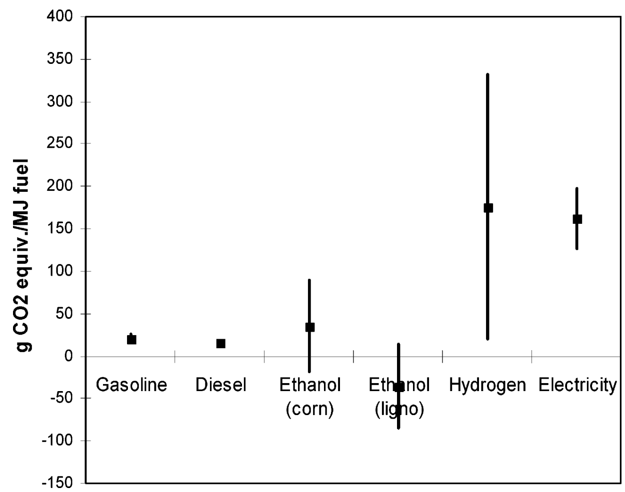

FIGURE 4. Well-to-tank (fuel cycle) greenhouse gas emissions. Graph shows mean and range of estimates from set of well-to-wheel studies examined. Ethanol (corn) is ethanol produced from corn. Ethanol (ligno) is ethanol produced from lignocellulosic feedstocks.

options for providing *substantial* supplies of energy with low CO_2 emissions. As well, the options that have this potential may not be "overall green design winners" when evaluated over their entire LC. Therefore, we look in more detail at the greenness of several alternatives that have the potential to improve these aspects (and others) of the sustainability of LDV.

Battery-Powered Vehicles. Automakers invested large amounts of resources into R&D of battery-powered vehicles (BPV). BPV have been marketed as "zero emission vehicles" (or ZEV) since they have no tailpipe and no vehicle emissions. California regulators neglected other environmental, economic, and social aspects of sustainability in mandating BPV. In addition, these vehicles would do little to reduce vehicle exhaust and evaporative emissions as compared to conventional ICE or hybrid vehicles meeting the most stringent emissions standards for new LDV (*25*).

We highlight a few of the aspects of the LC of BPV with respect to sustainability issues. Producing and recycling

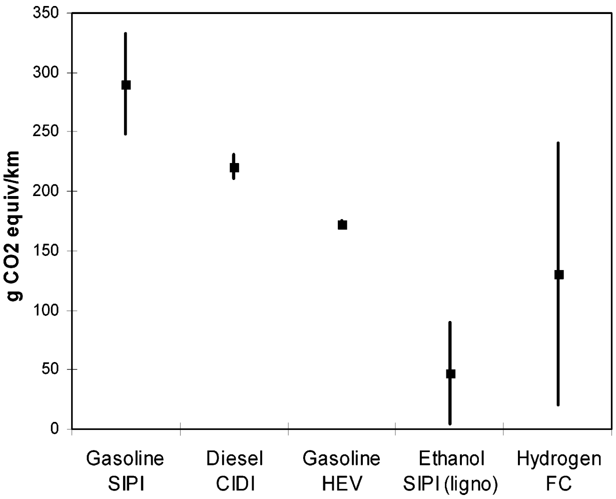

FIGURE 5. Well-to-wheel (fuel cycle and vehicle operation) greenhouse gas emissions. Graph shows mean and range of estimates from set of well-to-wheel studies examined. Gasoline SIPI is gasoline spark ignition port injection internal combustion engine vehicle (ICE). Diesel CIDI is diesel compression ignition direct injection ICE vehicle. Gasoline HEV is gasoline hybrid electric vehicle (with ICE). Ethanol SIPI (ligno) is ethanol from lignocellulosic feedstocks-fueled SIPI ICE vehicle. Hydrogen FC is a hydrogen-fueled fuel cell vehicle.

batteries is expensive, leading to large increases in the cost of driving (negatively impacting economic sustainability). In addition, the heavy metals utilized in the batteries are discharged into the environment in processing (negatively impacting the environmental aspect of sustainability). This goes against one of Anastas and Zimmerman's (*1*) central green design principles of using inherently nontoxic materials in vehicles. If the U.S. fleet of 210 million vehicles were run on current lead acid, nickel cadmium, or nickel metal hydride batteries, the amount of these metals discharged to the environment would increase by a factor of 20−1000, raising vast public health concern (*26*). The recent well-to-wheel studies we examined considered average U.S., Western Europe, World, and California electricity generation mixes as well as a North America natural gas combined cycle option. For these cases, generating the electricity to charge the batteries of a BPV has a low efficiency (Figure 3 shows a range of 30−50%) and produces pollution and GHG (Figure 4 shows 130−200 g of CO_2 equiv/MJ of electricity (*20*). [It is important to remember that it is not useful to directly compare emissions per MJ of fuel since the efficiencies of the propulsion systems in which the fuels are used vary greatly. One MJ of electricity is not equal to 1 MJ of gasoline.] If the electricity is produced from renewable sources or nuclear, these issues are likely of lesser concern, but there are other environmental and social concerns associated with these options. These issues are beyond the scope of this paper, but Bergerson et al. (*27*) provide additional information on the environmental impacts of a wide range of electricity generation options.

Since BPV have overwhelming negative impacts on sustainability as compared to the benefit of no vehicle emissions, there is no need to confront the issue of how we deal with the challenges. However, other fuel/vehicle options present more complicated cases.

Hybrid Electric Vehicles. Hybrid electric vehicles (HEV) combine an energy transformation system with one or more energy storage systems. The most common option is an ICE (gasoline) and battery. HEV that are currently on the road, such as Toyota's Prius, have a smaller gasoline ICE than conventional vehicles but a much larger battery pack. Improvements in fuel economy and emissions result from (i) the smaller engine, (ii) the engine does not have to follow the driving cycle closely, (iii) the engine is shut off when the vehicle is stopped, and (iv) regenerative braking. However, HEV are inherently more complicated and expensive than conventional ICE due to their two or more sources of power and since they incorporate advances not currently utilized on conventional vehicles. For example, the Honda Civic HEV has a special aluminum lightweight engine block, other lightweight components, and an advanced nitrogen oxides (NO_x) absorptive catalytic converter allowing the engine to run lean and the vehicle to meet California's Ultra Low Emission Vehicle standards (*28*).

To evaluate the desirability of today's HEV, we take a step beyond quantifying selected LC discharges, material, and energy use by including private and social costs in the analysis. Lave and MacLean (*29*) compare the second generation of the Toyota Prius HEV [We took measures to make an "apples to apples" comparison by adjusting the acceleration of the Prius to be approximately equal to that of the Corolla (for consumer comparability issues). This resulted in somewhat worse fuel economy for the Prius. For additional details, see ref *28*.] with Toyota's similar-sized conventional ICE Corolla with respect to pollutant [carbon monoxide (CO), NO_x, non-methane organic gases (NMOG)] and GHG (CO_2) emissions and costs (initial vehicle price and expenditure on fuel) over a 250 000-km vehicle lifetime. At a gasoline price of $0.40/L ($1.50/gal), the Prius would use $1364 less fuel than the Corolla over its lifetime ($932 at a 6% discount rate), while the Prius was priced at $3495 more than the Corolla.

Using social values for abating pollution emissions from Matthews and Lave (*30*), the social cost of the lower pollutant and CO_2 emissions of the Prius are worth $409 ($328 at 6% discount) at the median valuation and $818 ($639 at 6% discount) at the high valuation. The higher sales price of the Prius is not justified by fuel savings, emissions reductions, or a combination of the two. Technological innovation that improves HEV fuel economy, lowers emissions, and/or lowers the price premium as well as an increased gasoline price or increased social valuations of pollutants or CO_2 could result in an HEV being more attractive than the conventional ICE.

The analysis presented above is an attempt to enlighten tradeoffs between diverse benefits and costs by quantifying and monetizing the costs and environmental benefits. Critics of analyses such as these have said that the value of cleaning up the air is priceless and that placing dollar values on environmental costs and benefits is not sound. These are not practical criticisms. Resources are limited and should be allocated taking into account cost-effectiveness in order to move toward the goal of sustainability. By attaching dollar values to emissions or other aspects of sustainability, it is possible to compare HEV with other options that have the potential to improve greenness. However, this is clearly a simplification; dollars do not tell the entire story. We are well aware of the limitations of putting dollar values on the environmental and social components of sustainability and the more formal Benefit Cost Analysis.

Alternative Fuel Internal Combustion Engine Vehicles. Other alternatives that offer the potential of greener LDV include ICE vehicles fueled with alternative fuels and fuel cell vehicles (which we discuss in the next section). None of these options are inherently more sustainable than conventional gasoline ICE vehicles. This results from challenges 1−3. We discuss for each of the options some of the important issues that need to be considered in determining their potential greenness.

(a) Diesel. Diesel vehicles illustrate well the tradeoffs among social goals (challenge 1). Compression ignition, direct injection engines using diesel fuel are about 24% efficient as compared to about 20% efficiency of gasoline ICE (*20*). The well-to-tank efficiency of diesel is slightly higher than that of gasoline (as shown in Figure 3). Therefore, the use of these vehicles could result in substantial fossil fuel savings. Although diesel has a higher carbon content than gasoline, due to the higher fuel production efficiency and vehicle efficiency, diesels can make some progress on lowering GHG emissions. Figure 5 shows well-to-wheel diesel vehicles' GHG emissions of 210−230 g of CO_2 equiv/km as compared to 250−330 for gasoline vehicles. [The larger range for the gasoline vehicle emissions than the diesel results in part due to a larger number of the studies that we investigated including results for gasoline vehicles.] However, diesel vehicles have barely penetrated the North American markets. There are several reasons for this, but one central barrier with respect to contradictions in social goals is the higher NO_x and particulate matter (PM) emissions from diesel vehicles. Although PM traps have been developed for diesel vehicles and there has been progress on NO_x reduction, tiny particles and NO_x still are of concern. These pollutants have been related to premature death and morbidity.

(b) Ethanol. Ethanol can be used in low level blends with gasoline (10% ethanol, E10) in all of today's gasoline ICE vehicles or in high level blends (up to 85% ethanol, E85) in flexible-fueled vehicles produced by several vehicle manufacturers (there are currently about 3 million of these on the road in the United States and Canada). A key issue with respect to the sustainability of these vehicles is the well-to-tank portion of their LC. Ethanol from cellulosic material (grasses and trees) could have a high production efficiency as shown in Figure 3 [on the order of 80−95% when only fossil fuel inputs are considered (rather than considering fossil and renewable inputs in calculating the efficiency)] and be a more sustainable fuel (Figure 4 shows GHG emissions of a maximum of only 15 g of CO_2 equiv/MJ of ethanol according to the studies evaluated), although the current cost is estimated to be twice that of gasoline (without taxes) on an energy basis (*31*). Another important issue is that there are no large-scale cellulosic ethanol production facilities; therefore, additional uncertainty in the life cycle results. Ethanol from corn or fossil fuels would be cheaper but far from sustainable (*32*) and would have high GHG emissions if produced using current methods (up to 90 g of CO_2 equiv/MJ of ethanol; Figure 4) (*31*, *20*). Results for ethanol for the well-to-wheel range from almost zero for some cellulosic options to over 160 g of CO_2 equiv/km for E85 produced from corn based on our review of the well-to-wheel studies (*20*). Figure 5 shows only results from ligno-cellulosic options (4−90 g of CO_2 equiv/km). In all of the above cases, results are dependent on the fuel production pathway and, most importantly, the amounts of fossil fuel inputs into the ethanol production. The sustainability promise of cellulosic ethanol must be weighed against the greater cost and other potential issues in the fuel cycle (e.g., sustainability of large-scale land use for growing biomass).

(c) Fuel Cell Vehicles. Hydrogen-fueled fuel cell vehicles are considered by many to be the most promising alternative technology for LDV. The potential of zero vehicle emissions (only water vapor and some heat) and high efficiency (on the order of 40% for a proton exchange membrane (PEM) fuel cell, according to the National Fuel Cell Research Center ascompared to 15−20% for a spark ignition ICE) are two of the benefits most often cited. Much R&D is occurring on fuel cells, but we are 20 yr away from having large numbers of these vehicles on the road. Breakthroughs in fuel cell and hydrogen storage technologies and associated economics and the required transition to a different fuel infrastructure result in significant challenges to commercialization of these vehicles. Again, only by considering the entire LC are we able to determine whether fuel cell vehicles have the potential to be greener than other vehicle options. Any LC analyses done today would be speculative due to the infancy of the field (materials, production methods, etc.) and breakthroughs that must occur for even moderate scale use; therefore, we discuss some key LC issues with respect to Anastas and Zimmerman's (*1*) principles.

The potential of fuel cell vehicles to move us toward sustainability depends greatly on four sustainability issues: (i) the impacts on the environment and economy of the materials used in the vehicles, (ii) the energy source and methods used for hydrogen production, (ii) their life cycle costs, and (iv) consumer acceptance (challenges 1−3).

(1) Considerable progress must be made in reducing the amounts of specialized materials utilized in the production of fuel cell vehicles. For example, the high precious metals requirements including platinum result in resource availability and cost issues. These material requirements must be lowered, and high-volume processes for manufacturing fuel cell components are required. These issues have implications for end-of-life management as well.

(2) Onboard re-forming of hydrocarbon fuels such as gasoline and methanol to produce hydrogen is being considered; however, this would continue our dependence on fossil fuels (and resulting GHG emissions) in the transport sector. Therefore, we focus on hydrogen, the ultimate fuel that designers are looking to power fuel cell vehicles. Hydrogen can be produced through many pathways. A recent well-to-wheel study by General Motors and Argonne National Laboratory (*33*) considers six options for the production of each of gaseous and liquid hydrogen. The options include those from natural gas, electrolysis, and central versus station choices. The efficiencies of hydrogen production range from 23% to 57% (the full set of studies in Figure 3 show a range of results up to 76%). However, the fuel cell is expected to be much more efficient than an ICE, and what is important is the efficiency of the fuel production and the vehicle as a system. GHG emissions from the hydrogen production reported in GM/Argonne (*33*) vary widely from 100 g of CO_2 equiv./MJ of fuel (gaseous H_2 from natural gas) to 330 g of CO_2 equiv/MJ of fuel (liquid H_2, electrolysis, U.S. electricity mix). No hydrogen pathways from renewable options such as hydropower, wind, solar, or biomass were considered by GM/Argonne (*33*). The well-to-wheel emissions from the full set of studies [GM/Argonne (*33*) was one of the studies included in the larger set of studies] (Figure 5) show that hydrogen fuel cell options had a very wide range, from 20 to 240 g of CO_2 equiv/km (compared to on average 300 g of CO_2 equiv/km for a conventional gasoline vehicle) (*20*). Renewable options (with little fossil fuel inputs) such as the option resulting in a value of 20 g of CO_2 equiv/km (gaseous H_2 from electrolysis, 100% hydro power) could make significant progress with respect to this aspect of sustainability but may have other sustainability costs. This result reinforces the need for the LC approach in evaluating vehicle options. Fuel cell vehicles are not inherently greener than conventional vehicles.

(3) Assuming fuel cell vehicles could be shown to significantly lower environmental impacts and to achieve other social goals, the remaining sustainability hurdle is cost. Unfortunately, the current reality is that they are extremely expensive (a fuel cell automobile would cost about $1 million). Toyota and Honda have started leasing prototype-style vehicles in Japan and California for about $8500−10 000/month for 30 months (*34*). These vehicles use gaseous hydrogen stored onboard the vehicle and have a range about half that of a conventional vehicle.

(4) Clearly, large scale cost reductions (3) are required for these vehicles to meet the economic criteria of sustainability and to achieve large scale consumer acceptance. Other consumer acceptance issues will also be important such as

vehicle performance, range, available infrastructure for refueling and servicing, etc.

Discussion

The good news is that LDV have made progress toward sustainability but the bad news is that much work remains. There are limited options to make vehicles much greener without giving up the attributes that consumers demand. No option is inherently sustainable; however, some options have the potential to be more sustainable than others. Greener vehicles are likely to be more expensive over their lifetime, which negatively impacts the economic aspect of sustainability. In addition to expense, many of the vehicles would run into difficulties in satisfying society's desires for vehicles that are safe, are nonpolluting, have a range of 600 km, have adequate interior space, and have immense power. Green designers are unlikely to satisfy potential buyers without first finding out what the buyers want. Much progress has been made in the field of green design generally and specifically for LDV. However, many key challenges remain. Moving forward will require widescale implementation of Anastas and Zimmerman's (*1*) principles along with the recognition of the primary challenges to greening automobiles for the 21st Century.

Acknowledgments

We thank the Canadian National Science and Engineering Research Council; the National Centre of Excellence Auto-21; the Ontario Ministry of Agriculture, Food and Rural Affairs; the University of Toronto; and the U.S. National Science Foundation for support. However, the authors accept responsibility for the information and views expressed in the paper.

Literature Cited

(1) Anastas, P. T.; Zimmerman, J. B. *Environ. Sci. Technol.* **2003**, *37* (5), 94A−101A.
(2) Business Communications Company, Inc. *New transportation fuels: trends and developments*; 2001. www.the-infoshop.com/study/bc5767_transportation_fuel.html.
(3) Sperling, D. *Issues Sci. Technol.* **2002**, *19* (1), 59−66.
(4) Kohn, H. *Factors affecting urban transit ridership*; Statistics Canada. www.statcan.ca/english/IPS/Data/53F0003X1E.htm (accessed June 6, 2000).
(5) Lovins, A. Rocky Mountain Institute. www.rmi.org (accessed July 2003).
(6) Sullivan, J. L.; Costic, M. M.; Han, W. *Automotive Life Cycle Assessment: Overview, Metrics and Examples*; No. 980467 Society of Automotive Engineering: Warrendale, PA, 1998.
(7) Mildenbeger, U.; Khare, A. *Technovation* **2000**, *20*, 205−214.
(8) United Nations Environment Programme and International Automobile Industry. *Industry as a partner for sustainable development*; Automotive: United Kingdom, 2002.
(9) Keoleian, G. A.; Spatari, S.; Beal, R. T.; Stephens, R. D.; Williams, R. L. *Int. J. Life Cycle Assess.* **1998**, *3* (1), 18−28.
(10) Sullivan, J. L.; Cobas-Flores, E. *Full Vehicle LCAs: A Review*; Proceedings of the 2002 Environmental Sustainability Conference and Exhibition, Graz, Austria; Society of Automotive Engineers, Inc.: Warrendale, PA, 2002; SAE 2001-01-3725.
(11) Stephens, R. D.; Wheeler, C. S.; Pryor, M. *Life cycle assessment of aluminum casting processes*; Proceedings of the 2002 Environmental Sustainability Conference and Exhibition, Graz, Austria; Society of Automotive Engineers, Inc.: Warrendale, PA, 2002; SAE 2001-01-3726.
(12) Pickrell, D. *Transport. Res. Part A* **1999**, *33*, 527−547.
(13) Ross, M, Goodwin, R.; Watkins, R.; Wenzel, T.; Wang, M. Q. *J. Air Waste Manage. Assoc.* **1998**, *48*, 502−515.
(14) Natural Resources Canada. Canada's Natural Resources Now and for the Future. *End Use Energy Data Handbook 1990−2000*; July 2002; oee/nrcan/gc/ca/neud/dpa/data_e/Data_handbook.pdf (accessed October 12, 2002).
(15) National Research Council. *Effectiveness and impact of corporate average fuel economy (CAFE) standards*; Committee on Effectiveness and Impact of CAFE Standards, Board of Energy and Environmental Systems, National Academy of Sciences. Washington, DC, 2001.
(16) Maritz Automotive Research Group. *Green At What Cost?* 2001; http://www.ca.cgey.com/knowledge_centre/insights/GreenAtWhatCost-2001.pdf.
(17) Portney, P. R. *Issues Sci. Technol.* **1993**, *10* (2), 69−75.
(18) Arnold, F. *Environmental Forum*, Sept/Oct 19th−23rd, 1993.
(19) Matthews, H. S.; Lave, L. B.; MacLean, H. L. *Risk Anal.* **2002**, *22* (5), 853−860.
(20) MacLean, H. L.; Lave, L. B. *J. Prog. Energy Combust. Sci*. **2003**, *29*, 1−69.
(21) MacLean, H. L.; Lave, L. B. *Environ. Sci. Technol.* **1998**, *32*, 322A−33A.
(22) Intergovernmental Panel on Climate Change. *Climate Change 2001*; Houghton, J. T., Ding, Y., Griggs, D. J., Nogner, M., van der Linden, P. J., Dai, X., Maskell, K., Johnson, C. A., Eds.; Cambridge University Press: Cambridge, UK, 2001.
(23) Herzog, H. *Environ. Sci. Technol.* **2001**, *35*, 148A−153A.
(24) Keith, D. W. *Clim. Change* **2001**, *49*, 1−10.
(25) Lave, L. B.; Russel, A. G.; Hendrickson, C. T.; McMichael, F. C. *Environ. Sci. Technol.* **1996**, *30*, 402A.
(26) Lankey, R. L.; McMichael, F. C. L. *Environ. Sci. Technol.* **2000,** *34*, 2299−2304.
(27) Bergerson; Lave, L. B.; MacLean, H. L. *Environ. Sci. Technol.* (submitted for publication).
(28) Argonne National Laboratory. www.transportation.anl.gov/pdfs/HV/257.pdf (accessed January 22, 2003).
(29) Lave, L. B.; MacLean, H. L. *Transport. Res. Part D* **2002**, *7*, 155−62.
(30) Matthews, H. S.; Lave, L. B. *Environ. Sci. Technol.* **2000**, *34*, 1390−95.
(31) Lave, L. B.; Griffin, W. M.; MacLean, H. L. *Issues Sci. Technol.* **2002**, *18* (2), 73−78.
(32) DiPardo, J. *Outlook for Biomass Ethanol Production and Demand*; Energy Information Administration, U.S. Department of Energy; www.eia.doe.gov/oiaf/analysispaper/biomass.html (accessed September 4, 2002).
(33) General Motors Corporation; Argonne National Laboratory; BP; Exxon Mobil; and Shell. *Well-to-Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems—North American Analysis*; April 2001.
(34) Yamaguchi, J. *Automot Eng. Int. Soc. Automot. Eng.* **2003**, *March*, 54−58.

Received for review June 9, 2003. Revised manuscript received August 7, 2003. Accepted August 20, 2003.

ES034574Q