Environmental Implications of Alternative-Fueled Automobiles: Air Quality and Greenhouse Gas Tradeoffs

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We analyze alternative fuel-powertrain options for internal combustion engine automobiles. Fuel/engine efficiency, energy use, pollutant discharges, and greenhouse gas emissions are estimated for spark and compression ignited, direct injected (DI), and indirect injected (II) engines fueled by conventional and reformulated gasoline, reformulated diesel, compressed natural gas (CNG), and alcohols. Since comparisons of fuels and technologies in dissimilar vehicles are misleading, we hold emissions level, range (160 and 595 km), vehicle size class, and style (a 1998 Ford Taurus sedan) constant. At present, CNG vehicles have the best exhaust emissions performance while DI diesels have the worst. Compared to a conventional gasoline fueled II automobile, greenhouse gases could be reduced by 40% by a DI CNG automobile and by 25% by a DI diesel. Gasoline- and diesel-fueled automobiles are able to attain long ranges with little weight or fuel economy penalty. CNG vehicles have the highest penalty for increasing range, due to their heavy fuel storage systems, but are the most attractive for a 160-km range. DI engines, particularly diesels, may not be able to meet strict emissions standards, at least not without lowering efficiency.

Introduction

Personal transportation vehicles provide mobility and freedom. However, their costs to society are a major concern: current cars use large amounts of petroleum, metal, rubber, and other resources; they also discharge large quantities of pollutants. Annual U.S. health costs due to exposure to conventional gasoline vehicle emissions are estimated to be $20–50 billion (1). Additionally, there are impacts of carbon dioxide (CO2) on global climate, environmental effects of the fuel cycle, and costs of security in oil-producing regions. The transportation sector remains over 97% dependent on petroleum fuels and accounts for two-thirds of petroleum demand (2) and one-fourth of total U.S. greenhouse gas (GHG) emissions (3).

We explore potential modifications to personal transportation vehicles to lower their environmental cost and to make them more sustainable. Several powertrain technolo-

gies and fuels hold promise for improving performance in the near-term. Unfortunately, the most fuel-efficient technologies may not be the least expensive or score best on environmental discharges. We cannot predict the future; however, we can explore an array of fuels and powertrains to isolate the most promising candidates.

Over 90% of automobiles worldwide have internal combustion engines (ICE). A small number of non-ICE alternatives are currently being sold in the United States (e.g., battery-powered vehicles, hybrids), and others are in the development process (e.g., fuel cell vehicles). However, in the near-term, these vehicles cannot compete on performance or economic bases with ICE options.

In the last two decades, technology development of conventional gasoline-fueled spark ignition indirect injection (SIII) vehicles and direct injection (DI) diesel engines has progressed rapidly. For example, the amount of fuel required to move 1000 lb 100 mi for the average gasoline automobile dropped by 36% from 1968 to 1993 (4); some light-duty gasoline vehicles have been certified to the California Ultra-Low Emission Vehicle (ULEV) standard. These improvements have significantly raised the baseline to which alternatives have to be compared.

Only 20–25% of the energy in the gasoline is used to propel the automobile. If the Partnership for a New Generation of Vehicles (PNGV) is to attain its fuel economy target of 80 mpg, then the efficiency of the engine will have to reach approximately 40% thermal efficiency (5). At present, efficiency generates more exhaust pollutants, especially nitrogen oxides (NOx). For example, a DI diesel vehicle has the highest efficiency of ICE options but produces relatively high emissions of NOx and particulate matter (PM).

Experience with alternative fuels and engines other than gasoline SIII and diesel indirect injection (II) and DI is limited. Only about 1% of the world’s motor vehicles use fuels other than gasoline and diesel (6). Available data are primarily from controlled laboratory experiments, prototype vehicles, and limited in-use fleet experience. Currently produced alternative-fueled vehicles provide a poor indicator of the potential of the alternatives. Flexibly fueled vehicles are not optimized for either fuel or efficient control of emissions. Large-scale production of a fuel/engine combination is required to learn its efficiency and emissions characteristics.

Vehicle Comparability. Analyses of alternative-fueled automobiles must distinguish among three goals. The first is to determine, relative to a base case, how much fuel economy could be increased or GHG or conventional pollutant emissions decreased as a result of producing and using the vehicle. Smaller, lighter cars use less fuel per kilometer and can emit less GHG. A compressed natural gas (CNG) fueled car can lower both GHG and conventional pollutant emissions. The second goal is to satisfy regulations regarding other attributes of a vehicle. For example, the PNGV proposes a DI diesel that will improve fuel economy but not satisfy regulations for PM and NOx emissions. The third goal is to have consumers purchase the new vehicles voluntarily. Consumers do not regard an EV-1 as equivalent to a Chevrolet Suburban. If regulations banned the sale of Suburbans, consumers might buy the EV-1, but short of that, consumers seeking a large SUV are unlikely to buy an EV-1. The current market for cars is segmented into many niche markets.

However, it makes no sense to assume that all niches have the same number of buyers or that each niche is large enough to attain the economies of scale needed to justify production

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of the type of vehicle. Attention to vehicle comparability makes the analyses in refs 7–10 and that of Wang in ref 2 easier to interpret than those of refs 11 and 12.

Methods

Fuel and Engine Options. The feasible near-term fuel and engine alternatives we consider are shown in Table 1. Automotive manufacturers predict that only two alternative engines not currently in large-scale use have the potential for significant market entry in a 15–20-year time frame: the DI stratified charge gasoline engine and the DI diesel engine (13). These engines are equivalent to the spark ignition DI (SIDI) gasoline and compression ignition DI (CIDI) diesel, respectively, in Table 1.

Fuel/Engine Efficiencies. An important property of each fuel/engine combination is its potential efficiency in converting the energy in the fuel into vehicle movement. DI engines are inherently more efficient than II engines. However, operating at maximum efficiency (and therefore maximum fuel economy) does not result in low vehicle emissions. To achieve their maximum efficiencies, these engines must operate lean. In contrast, conventional catalyst technology is most efficient at stoichiometric conditions. Thus, emissions control results in lower efficiency (and resulting CO2 cost). Additionally, lean NOx catalyst technologies for emissions control with DI engines require low sulfur fuel and more complex emissions technologies require energy, reducing the operational efficiency.

We construct two matrices, Table 1 and S1 (see Supporting Information), that compare the potential thermal efficiencies of the various combinations with a baseline 1998 Ford Taurus sedan. The baseline vehicle has a SIII engine fueled with conventional federal gasoline. Table S1 was developed without an emissions constraint for the combinations, since we have been unable to locate published values in the literature that specify that level of detail. However, the importance of meeting strict emissions standards led us to elicit judgments from automobile industry experts (Table 1) of the efficiencies with the constraint of meeting the California ULEV standard. This standard requires emissions reductions of 85% for hydrocarbons and 50% each for carbon monoxide and NOx, as compared to the basic standard for new vehicles sold in California. Table 1 indicates that EBS used in a SIDI engine is 10–28% more efficient per MJ of fuel than the baseline fuel/engine combination. However, since EBS has a lower energy density, this car would require more fuel to travel a fixed distance. Table 1 assumes that the quality of fuel necessary for each combination to meet the ULEV emissions constraint is available, e.g., CaRFG2, EC diesel.

Experts are confident that the fuel/engine options can attain higher efficiencies than the baseline combination while meeting ULEV standards. There is more uncertainty in the estimates for the DI engines due to the lack of experience with this engine design, the lean operation required for high efficiency, and the current state of catalyst development for these vehicles.

We model a set of `comparable cars' having the various fuel/engine combinations. The comparable cars are assumed to be dedicated vehicles, produced in sufficient volume so that the vehicles are optimized. We model two sets of cars, one with conventional automobile range (defined as the product of the Taurus fuel tank capacity and combined city/highway fuel economy), 595 km, and the other, a set of niche “urban cars”, with 160-km range. Although consumers have rejected the EV-1 in part because of its limited range, the majority of household vehicle trips in California are less than 10 km in length, and the average trip time is 10 min (14). We calculate the vehicle lifetime as 225 300 km based on data in ref 15.

To model the comparable cars, we modify the baseline Taurus, employing the efficiency estimates from Table 1. For additional method details refer to ref 16. As the estimates are in close agreement, we use the lower and upper bound for the ranges and complete a sensitivity analysis to determine the impact of the efficiency ranges on the results. We do not include the outliers (low estimates) for the CNG options in the ranges we select. We adjust for energy content differences in the fuels using fuel properties taken from refs 17–19. We use attributes of the baseline vehicle and modify its efficiency, fuel storage system, curb weight, and fuel economy based on the properties of the alternative options. We replace the fuel storage system weight and fuel weight with those required for the alternative fuel/engine combination to have the specified range. We use the baseline Taurus fuel tank weight of 11.3 kg and assume that the liquid fuel tank weights are proportional to the required fuel tank capacity. CNG cylinder weights are calculated based on data in ref 20. We consider both type 2 (currently used by North American automobile manufacturers) and lighter weight type 3 designs (currently used by Japanese manufacturers). We modify the vehicle weight to account for the changes in the fuel storage system and fuel weight from the baseline vehicle by assuming a resulting change in the vehicle structural and component weight (termed secondary weight) using a manufacturer's estimate of 1.05 (21). That is, we assume than an additional kilogram of fuel or tank weight above that of the baseline vehicle requires an additional 0.5 kg of secondary weight.

We assume the opposite for any reduction in weight. We calculate the fuel economy change associated with a change in vehicle weight (applicable to a midsize sedan) based on expert judgment (21) and our previous work (16, 22) using the following relationship:
Improvement Research Program, ref emissions. There has not been a set of FTP and off-cycle from an off-cycle driving cycle to determine rates for these details of the method, see ref linear deterioration over the vehicle lifetime. For additional and California ULEV for the comparable cars) and assume emissions are higher during the off-cycle mode (15% of the time does not correspond to 15% of the lifetime driving time is in the off-cycle mode (of those from all vehicles (have emissions from 10 to 1000 times higher than the average (approximately 5\%)). Un-

\[
\text{w}_1 / \text{w}_2 = (\text{mpg} / \text{mpg})^{0.72}
\]  

where \(\text{w}_1\) and \(\text{w}_2\) are the existing and new vehicle curb weights, respectively, in pounds; and \text{mpg} and \text{mpg} are the existing and new vehicle fuel economy, in miles per gallon. Although this relationship has been developed for gasoline-fueled vehicles, we assume that it applies to all of the combinations. The relationship assumes that a vehicle weight change is accompanied by a powertrain modification so that performance of the vehicles is equivalent; however, for large weight increases, performance will decrease. We calculate the operational energy of each of the vehicles using the following equation:

\[
E_{\text{op}} = (D\text{E}_{\text{cgb}}) / E\text{HFE}
\]  

where \(E_{\text{op}}\) is the operational energy of the vehicle, \(D\) is the lifetime distance traveled, and \(E\text{E}_{\text{cgb}}\) is the combustion energy (higher heating value) of the applicable fuel used in each comparable car. \(E\text{HFE}\) is the U.S. Environmental Protection Agency combined city/highway fuel economy for the baseline vehicle. For the comparable cars, \(E\text{HFE}\) is a calculated combined city/highway fuel economy based on the applicable fuel (e.g., mpg of E85).

**Greenhouse Gases.** The primary GHG resulting from motor vehicle use are \(\text{CO}_2\), methane, nitrous oxide, and ozone. The amounts of methane and nitrous oxide resulting from low emission gasoline and diesel vehicles are very small (3). Even for CNG vehicles, which emit approximately 10 times the amount of methane of gasoline automobiles, the quantity is very small as compared to \(\text{CO}_2\) even when weighted by its global warming potential. Therefore, we only report results for \(\text{CO}_2\).

**Exhaust and Evaporative Emissions.** Average real-world emissions over the vehicle lifetime from the baseline and comparable cars are the values of concern to determine whether any of the options are likely to lessen the impact on local air quality. Real-world emissions are comprised of emissions that occur during three general driving conditions; on-cycle driving (conditions covered in the Federal Test Procedure (FTP)), off-cycle driving (conditions other than those in the FTP, e.g., high speed, high load), and as a result of malfunctioning emissions control systems. The largest source of emissions continues to be a small number (approximately 5–10%) of vehicles (primarily older) with malfunctioning emissions control systems. These vehicles have emissions from 10 to 1000 times higher than the average of those from all vehicles (23). Approximately 15% of vehicle driving time is in the off-cycle mode (24). The impact of off-cycle operation on emissions is difficult to determine since not all vehicles experience this off-cycle driving, and 15% of the time does not correspond to 15% of the lifetime driving distance. Finally, not all of the regulated exhaust emissions are higher during the off-cycle mode (24). Unfortunately, there are many barriers to determining real-world emissions even for conventional vehicles (14, 25, 26); therefore, we use a simplified method to calculate exhaust emissions.

To calculate on-cycle emissions, we use a method based on the certification standards (Tier 1 for the baseline vehicle and California ULEV for the comparable cars) and assume linear deterioration over the vehicle lifetime. For additional details of the method, see ref 16. We examine test results from an off-cycle driving cycle to determine rates for these emissions. There has not been a set of FTP and off-cycle driving vehicle emissions results published for all of the options we consider. However, as part of the Auto/Oil Air Quality Improvement Research Program, ref 24 provides an examination of FTP as well as the impact of high-speed, high load off-cycle driving on exhaust emissions from CaRF2 and alternative fuels. Unfortunately, Cadle (24) only tests SIII vehicles, the vehicles do not satisfy ULEV standards, and some of them are flexibly fueled. Nonetheless, in our judgment some useful insights can be gained from this work. The hydrocarbon emission rates from the off-cycle driving cycle exceed those from the FTP for less than half of the fleet/fuel combinations. The carbon monoxide emission rate is 2–5 times higher during the off-cycle. NO\(_x\) emissions are about 40% higher during the off-cycle than the FTP across all fuel/fleet combinations. Overall, Cadle (24) concludes that the benefit of the CaRF2 and the alternative fuels are similar for the FTP and the off-cycle driving cycles. Since the vehicles in the study do not meet ULEV standards, we do not use the emissions factors from the study but employ the relative percentage changes in emissions for the off-cycle driving cycle as compared to the FTP. We do not report the emissions from the fraction of the ULEV fleet that are expected to become "high emitters" but consider this issue in the Results and Discussion section. Although the non-methane organic gases emissions from the alternative fuels have a lower reactivity than those from gasoline, we do not include this in our analysis. Since FTP and off-cycle driving cycle PM emissions from properly functioning gasoline, CNG, and M85 vehicles are reported to be low (14) and the ULEV PM standard only applies to diesel vehicles, we consider PM from these vehicles in the toxics section since diesel PM is an EPA-designated air toxic. Since emissions levels of a vehicle are not correlated with fuel economy (23, 27), we assume identical emissions factors for the 160- and 575-km range vehicles.

As with the regulated pollutants, average real-world emissions of EPA-designated toxic air pollutants from vehicles are not available, and the largest sources of these toxics are vehicles with malfunctioning emissions control systems. We detail our method for calculating the toxic emissions in the Supporting Information.

**Results and Discussion**

Table 2 presents vehicle attributes for the higher range comparable cars. The lower and upper entries for the options result from using the minimum and maximum efficiency estimates in calculating the attributes. The difference in the weights for the 595-km range vehicles is 280 kg. The magnitude of this weight difference is significant because automobile designers labor to save small amounts of weight. The diesel weighs the least due to its high efficiency and the high energy density of its fuel. The CNG vehicles are the heaviest due to the heavy storage cylinders (average 160 kg) required for gas storage and the low energy density of the CNG. Due to the heavier weight of the 3600 psig CNG cylinders, the 3000 psig vehicles are slightly more attractive. However, there is a tradeoff due to the larger amount of fuel that can be stored in a given volume at 3600 as compared to 3000 psig. The amount of CNG required for the vehicle to achieve the 595-km range is substantial. For example, assuming the SIDI engine achieves its maximum efficiency, the 3600 psig SIDI with type 3 cylinders requires approximately 1500 standard ft\(^3\) of CNG. On the basis of currently produced cylinders (20), three 330 mm diameter by 900 mm long cylinders could be used to satisfy this requirement.

The lifetime fuel use of the comparable cars varies considerably. Due to the low energy density of the alcohols, even with DI technology, the number of liters of neat methanol used during the vehicle lifetime is 40% higher than the number of liters of gasoline required by the baseline vehicle. The diesel requires the least fuel, 70% of that of the baseline vehicle, due to its high efficiency and high fuel energy density.

**Impact of Vehicle Range/Vehicle Equivalency.** At the 160-km range, the magnitude of the difference between the
highest and lowest attribute values is much smaller than that for the 595-km range vehicles. For example, the average curb weights for the 160-km vehicles are between 1440 and 1510 kg (5% difference), whereas the corresponding range for the 595-km vehicles is four times that amount. As expected, all of the vehicles become heavier and less fuel economic as their range increases. The vehicle attributes are similar for both ranges for the gasoline and diesel vehicles; however, for the lower energy density fuels, there are higher weight penalties. The difference in curb weights for the baseline 595-km range vehicle and its 160-km range counterpart is 60 kg (4% of vehicle weight). The corresponding difference for 3600 psig SIII CNG vehicles is 280 kg (15%).

**Energy Use.** Average lifetime operational energy for the 595-km range vehicles is lowest from the diesel, 610 GJ, or 74% of that of the baseline vehicle’s 820 GJ. The SIII CNG 3600 psig, type 2 cylinder vehicle has the highest value at 830 GJ. As expected, due to the lower efficiencies of the II engines, these vehicles have higher operational energies than the DI. In several cases the alternative fuel SIII cars have slightly higher energy use than the baseline even if they attain their maximum efficiencies. As expected, the energy use is lower when range is reduced to 160 km, due to the lighter weight of the vehicles. The diesel again has the lowest energy, less than 590 GJ. However, unlike the higher range, the baseline vehicle has the highest operational energy. The most significant savings in energy use occur with the II CNG vehicles as they are penalized most (i.e., heavier weight) to achieve higher ranges. We include additional details about energy use in our discussion of the sensitivity analysis.

**Greenhouse Gases.** Carbon dioxide, resulting from combustion of the fuel used over the vehicle lifetime, is shown in Figure 1. For the 595-km range, average CO2 from the baseline vehicle is 53 670 kg. The largest amount results from the CaRFG2 SIII combination (54 210 kg), while that resulting from the 3000 psig SIDI CNG with type 3 cylinders is lowest (36 650 kg), 68% of the baseline. Although the carbon content of the CaRFG2 is slightly lower than that of conventional gasoline due to the presence of the oxygenate, the CaRFG2’s lower energy content results in additional fuel being required.
over the vehicle lifetime, and this more than offsets the benefit of the lower carbon content. The emissions from the diesel are 41,215 kg, 77% of the baseline. Although the diesel is a more efficient vehicle than the CNG, the higher carbon content in the fuel (85.6 wt % as compared to 75 for the CNG) offsets this benefit. Due to the lower weight and therefore higher fuel economy, the use of the 160-km range vehicles results in less CO₂.

**Exhaust and Evaporative Emissions.** Table 3 presents the results for both on- and off-cycle regulated pollutant emissions from the baseline and ULEV vehicles. The reductions in the emissions from the ULEV vehicles are a result of the emission standard. If all of the fuel/powertrain combinations attain ULEV status in the near-term and at a reasonable cost, as is predicted by experts in the field ([23, 27, 28]), vehicle emissions will not affect the choice of the fuel/engine combination. Meeting the ULEV standard with the diesel and the alcohol/DI combinations result in the lowest operational energy (ranging from 590 to 620 GJ) while the DI CNG and gasoline vehicles are only slightly higher (ranging from 630 to 650 GJ). However, when we examine the possibility of the vehicles only attaining their minimum efficiencies, then the diesel is the clear winner (630 GJ) as compared to the second lowest option, the E100 SIDI (720 GJ). This is due to the range of the efficiency estimates for the SIDI combinations and resulting heavier vehicles. In the case of the M100 SIDI combination, the operational energy is approximately 75% that of the baseline for the maximum efficiency and 95% for the minimum efficiency. The CNG vehicle energy requirements are penalized the most due to the heavy fuel storage systems.

**Sensitivity Analysis.** To illustrate the sensitivity of the results to the efficiencies of the various fuel/engine combinations, Figure 2 presents the operational energy for the 595-km vehicles corresponding to both their minimum and maximum efficiencies. Assuming their maximum efficiencies are attained, the diesel and the alcohol/DI combinations result in the lowest operational energy (ranging from 590 to 620 GJ) while the DI CNG and gasoline vehicles are only slightly higher (ranging from 630 to 650 GJ). However, when we examine the possibility of the vehicles only attaining their minimum efficiencies, then the diesel is the clear winner (630 GJ) as compared to the second lowest option, the E100 SIDI (720 GJ). This is due to the range of the efficiency estimates for the SIDI combinations and resulting heavier vehicles. In the case of the M100 SIDI combination, the operational energy is approximately 75% that of the baseline for the maximum efficiency and 95% for the minimum efficiency. The CNG vehicle energy requirements are penalized the most due to the heavy fuel storage systems.

Since CO₂ is related to energy use, the results are similar and again show the importance of attaining high efficiencies with the DI options for them to significantly improve over the baseline. If the SIDI CNG vehicles attain their maximum efficiency, they have the potential to reduce CO₂ 40% from the baseline. Attaining their minimum efficiency results in a 25% reduction. For the diesel, attaining maximum efficiency results in a 25% reduction and minimum efficiency, a 20% reduction.

The results are particularly sensitive to the SIDI efficiency estimates. If the SIDI combinations are able to achieve high efficiencies, then these combinations have a significant advantage over the SIII options (e.g., improved vehicle attributes, lower fuel requirements, operational energy, and CO₂). The attainment of the maximum efficiency is less...
important for the diesel, but this is in part a function of the smaller range of its estimates. The efficiency ranges for the SIDI vehicles have little impact.

Lifetime GHG emissions resulting from the operation of any vehicle fueled by a fossil fuel are significant. Light-duty vehicles account for 18% of the U.S. total CO2 emissions (3). This implies the importance of increasing efficiency, smaller more fuel economic vehicles, and renewable energy sources. The GHG differences among the options have the potential to be significant. If the entire light-duty fleet instantaneously was replaced by vehicles whose operation resulted in an average 40% lower CO2, the GHG reduction would be close to the level required to satisfy the Kyoto requirement (30). In the near-term, efficiency improvement can lower resource use and GHG emissions; however, it is apparent that improving efficiency of vehicles fueled by nonrenewable energy sources will not achieve the reductions likely to be required to satisfy Kyoto and will not lead to sustainability. Further reductions will be necessary through the use of renewable energy sources.

Increasingly strict emissions standards can be attained only with the use of proper fuels. For gasoline and diesel, fuel formulation (particularly low sulfur levels) is important. From a life cycle perspective, we recognize that there are upstream tradeoffs associated with the production of “cleaner” fossil fuels (2). We could not find published data regarding the incremental changes in energy use or emissions from refineries that are producing these reformulated and/ or low sulfur fuels as compared to producing conventional fuels. The additional upstream emissions and energy use to produce CaRFG2 appear to add a maximum of 15% to any of the fuel cycle discharge or energy results (31). Even less is known about the EC diesel fuel cycle since current low-volume production methods are not likely representative of those to be used in large-scale production. New York and Massachusetts have adopted the California emissions standards but do not require the appropriate low sulfur gasoline during vehicle use. Unfortunately, vehicles designed for extremely low emissions are more sensitive to sulfur than earlier vehicles (12). Using high sulfur fuel will increase emissions immediately; the higher emissions might continue even after low sulfur gasoline is used due to poisoned, possibly permanently, catalysts. CNG vehicles are less dependent on specific fuel properties in meeting low emissions standards than gasoline or diesel. In addition, key issues for the future are the fraction of low emission vehicles that become high emitters (and the resulting emissions). These issues will have significant impacts on air quality. Experts suggest that the increasing redundancy in emissions control systems and other improvements in engine and emissions control are likely to lead to improvements in both these areas. However, in the absence of stringent inspection and maintenance programs and effective onboard diagnostics, these gains may be lost.

Although the amounts of the toxic air pollutants resulting from vehicle operation may appear small (see Supporting Information), even tiny amounts of very toxic substances can be a cause for concern. When these small amounts are multiplied by millions of vehicles, the issue is intensified. Vehicles fueled by CNG have the potential to be a significant benefit with respect to toxics. Although the primary focus of the ULEV standard is on lowering regulated exhaust emissions not reductions in the toxic air pollutants, the emissions control systems, engine controls, and fuel formulations that will be required to meet the standard are likely to have a favorable impact on toxic emissions. However, as with the regulated pollutants, malfunctioning emissions control systems can offset this benefit.

If the focus is on GHG and resource use, then vehicles fueled with renewable energy sources such as alcohols and diesel from biomass result in no net CO2. However, in the absence of renewables, diesel and SIDI vehicles containing high levels of efficiency improvement improvements over the baseline.

Consumer behavior through the selection of fuel economic vehicles and decreasing miles traveled also impacts these results. If local air quality is the priority, then CNG and other vehicles meeting low emission standards will be of benefit. However, consumer behavior through vehicle maintenance, effectiveness of inspection and maintenance programs, and onboard diagnostics are likely to have the most significant impact on real-world emissions. CNG fueled automobiles are an attractive option with respect to GHG, exhaust and evaporative emissions of regulated and toxic pollutants, and the more abundant domestic resource base. However, the heavy and bulky fuel storage systems and consumer acceptance of gaseous fuels for cars are barriers to their acceptance. Considerable CNG storage technology development is necessary for cars with ranges equivalent to those of gasoline-fueled automobiles to be attractive. “Urban cars” fueled by CNG are a reasonably attractive option. In the absence of renewable energy sources, it is difficult to beat a conventional reformulated gasoline-fueled ULEV automobile that is fuel economic, properly maintained, and not driven excessively.

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Supporting Information Available

Details of toxic results and the unweighted and toxicity-weighted lifetime emissions from the comparable cars (text and three tables, 6 pages). This material is available free of charge via the Internet at http://pubs.acs.org.

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