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ABSTRACT

We examine the life cycles of gasoline, diesel, compressed natural gas (CNG), and ethanol (C_2H_5OH)-fueled internal combustion engine (ICE) automobiles. Port and direct injection and spark and compression ignition engines are examined. We investigate diesel fuel from both petroleum and biosources as well as C_2H_5OH from corn, herbaceous bio-mass, and woody biomass. The baseline vehicle is a gasoline-fueled 1998 Ford Taurus. We optimize the other fuel/powertrain combinations for each specific fuel as a part of making the vehicles comparable to the baseline in terms of range, emissions level, and vehicle lifetime. Life-cycle calculations are done using the economic input-output life-cycle analysis (EIO-LCA) software; fuel cycles and vehicle end-of-life stages are based on published model results.

We find that recent advances in gasoline vehicles, the low petroleum price, and the extensive gasoline infrastructure make it difficult for any alternative fuel to become commercially viable. The most attractive alternative fuel is compressed natural gas because it is less expensive than gasoline, has lower regulated pollutant and toxics emissions, produces less greenhouse gas (GHG) emissions, and is available in North America in large quantities. However, the bulk and weight of gas storage cylinders required for the vehicle to attain a range comparable to that of gasoline vehicles necessitates a redesign of the engine and chassis. Additional natural gas transportation and distribution infrastructure is required for large-scale use of natural gas for transportation. Diesel engines are extremely attractive in terms of energy efficiency, but expert judgment is divided on whether these engines will be able to meet strict emissions standards, even with reformulated fuel. The attractiveness of direct injection engines depends on their being able to meet strict emissions standards without losing their greater efficiency. Biofuels offer lower GHG emissions, are sustainable, and reduce the demand for imported fuels. Fuels from food sources, such as biodiesel from soybeans and C_2H_5OH from corn, can be attractive only if the co-products are in high demand and if the fuel production does not diminish the food supply. C_2H_5OH from herbaceous or woody biomass could replace the gasoline burned in the light-duty fleet while supplying electricity as a co-product. While it costs more than gasoline, bioethanol would be attractive if the price of gasoline doubled, if significant reductions in GHG emissions were required, or if fuel economy regulations for gasoline vehicles were tightened.

IMPLICATIONS

Advances in reformulated gasoline-fueled automobiles, low petroleum prices, and the extensive gasoline infrastructure hamper alternative fuels in competing with gasoline. However, no fuel dominates for all economic, environmental, and sustainability attributes. CNG is less expensive than gasoline, has lower pollutant and GHG emissions, and has large North American reserves. However, onboard storage penalties and the lack of fuel infrastructure lower its attractiveness. Biofuels offer lower GHG emissions, are sustainable, and reduce the demand for imported fuels. Bioethanol would be attractive if the price of gasoline doubled or if significant reductions in GHG emissions were required.

INTRODUCTION

The environmental quality and sustainability costs of U.S. cars and light-duty trucks are high. However, these vehicles also offer significant benefits related to personal freedom, mobility, and consumer affordability. The social costs can be lowered at the same time that automakers improve vehicle safety, performance, and affordability, and, more generally, consumer acceptance. One approach to achieving these goals is to substitute alternative fuels for gasoline and diesel, the focus of our work. However, continuing low fuel prices and the recent rapid improvement in performance and emissions control of gasoline-fueled automobiles make it ever more difficult for the alternative fuels to compete.

The potential of each fuel and powertrain combination can be assessed only through an economy-wide examination of the material inputs and environmental discharges associated with the "life cycle" of each combination.[1] For example, in 1996, light-duty vehicles in the United States consumed over 4.5 billion barrels of crude oil equivalent (a weighted average of the energy in all crude oil products used in light-duty vehicles).[2] To understand the implications of this fuel use, society needs to quantify the amount of nonrenewable resource use and environmental discharges that result from producing and using this fuel. We employ a systems approach, life-cycle assessment (LCA), to assess the potential of near-term fossil and biofuels used in internal combustion engine (ICE) automobiles. We also include lifetime consumer expenditure on fuel and discuss infrastructure issues for each of the options. The life-cycle approach has identified important examples in which nonsystems methods lead to recommending options that move away from the goal due to secondary impacts. For example, drawing a narrow boundary around vehicle-regulated exhaust and evaporative emissions would indicate that a hybrid electric vehicle would be preferred over a conventional gasoline automobile. However, a broader systems approach identifies the implications of the significantly higher production cost for the hybrid, which is greater than the valuation of the relatively minor emissions benefits and lower lifetime expenditure on fuel.[3]

To make a fair comparison of alternative fuel/powertrain combinations, we assume that the volume produced is sufficient so that each powertrain is optimized for the fuel, and a large infrastructure supports refueling, repair, and so on. Based on 19% of vehicles requiring premium gasoline and this fuel having a 20% market share,[4] we assume the alternative fuels have at least 20% market share and so would be transported and retailed comparably to current premium gasoline. We analyze the energy, yield, farmland requirements, and co-products of the biofuels, assuming both near-term and sustainable production. "Sustainable" production of the biofuels refers to production of these fuels when no fossil fuel is used to produce them or any required inputs (e.g., fertilizer).

Although significant research and development is being devoted to non-ICE automobile options, there are large remaining potential improvements in the ICE alternatives. Currently, only gasoline and diesel ICE vehicles are optimized for fuel economy, emissions, and consumer attributes (e.g., vehicle range, ease of refueling). Although manufacturers are producing small numbers of vehicles that are able to run on alternative fuels, these vehicles are not optimized for these fuels (taking advantage of the specific fuel properties, such as octane). In addition, the current infrastructure is designed for the petroleum fuels.

Researchers, including those at University of California at Davis, Ford Motor Company, and Argonne National Laboratory, have developed spreadsheet-based life-cycle models that consider a large number of fossil and biofuel/engine combinations for automobiles.[5-10] The studies are based on process modeling of the life-cycle components and include varying proportions of the economy-wide interactions resulting from the life cycles. These models focus on efficiency, energy use, emissions of criteria pollutants, and greenhouse gas (GHG) emissions of the fuel cycles and vehicle operation, and do not include economic data. Generally, the studies place less emphasis on the other life-cycle components and on vehicle optimization. Major studies on specific biofuel issues (e.g., process cost estimates, process requirements, and source yields) are ongoing at the U.S. Department of Energy (National Renewable Energy Laboratory), Argonne, and Oakridge National Laboratories.

The most comprehensive life-cycle study of a gasoline-fueled ICE automobile is a study by the U.S. Council for Automobile Research.[11] Other conventional automobile life-cycle studies include refs 1 and 12–15. Kreucher's study includes life-cycle inventories of alternative-fueled automobiles as well as the baseline conventional gasoline-fueled automobile.[12] Sullivan et al. report a life-cycle inventory of diesel and electric vehicles, comparing these to a baseline gasoline-fueled vehicle.[14] Our present work emphasizes the fuel cycles, but also includes results from the remainder of the life cycles of conventional and alternative fuel/powertrain ICE automobiles. We include economic data for the fuel options.

METHODS

We model automobiles with the fuel/powertrain options in Table 1. The fossil fuels are gasoline, reformulated gasoline (RFG), reformulated diesel, CH_3OH, and compressed natural gas (CNG). The biofuels include biodiesel from soybeans and ethanol (C_2H_5OH) from corn (corn C_2H_5OH), woody biomass, and herbaceous biomass. We analyze California Phase 2 reformulated gasoline (CaRFG2) and a low-sulfur test fuel currently marketed in California, ARCO

Table 1. Fuel/powertrain combinations.

Fuel	Powertrain
Gasoline[a]–Baseline	SIII
CaRFG2	SIII, SIDI
Diesel, EC Diesel,[b] Biodiesel (soybeans)	CIDI
CH_3OH	SIDI
C_2H_5OH[c]	SIDI
CNG (3000 psig)	SIII/SIDI

[a]Conventional federal unleaded, nonreformulated gasoline; [b]ARCO's emission control diesel, low-sulfur (~10 ppm S) test fuel; [c]Bioethanol from corn, woody biomass, and herbaceous biomass sources.

Emissions Control (EC) Diesel.[16] The fuels are burned in conventional port fuel injection [referred to as spark ignition indirect injection (SIII)] and spark ignition direct injection (SIDI) engines. The EC diesel fuel is used in a compression ignition direct injection (CIDI) engine. Direct injection allows leaner, more efficient operation but produces increased NO_x.

Efficiency estimates (with respect to a baseline conventional gasoline automobile) for each of the combinations were elicited from experts in the field and employed along with fuel and vehicle properties to model "comparable" automobiles based on a 1998 Ford Taurus sedan.[17] Our comparable automobiles have a constant vehicle lifetime (225,300 km), range (595 km), vehicle emissions level [California ultra-low emission vehicle (ULEV) standard], and vehicle size class (e.g., midsize sedan). Based on some currently produced gasoline and CNG vehicles attaining ULEV certification, this is a realistic assumption for SIII engines burning these fuels. There remains uncertainty as to whether ULEV standards can be met with the direct injection options while attaining high efficiency levels. Experts do not expect conventional diesel-fueled automobiles to be able to meet ULEV (this option is not included in this work for this reason); many question whether vehicles with diesel engines can attain the standard, even with "clean" fuels.

We report life-cycle results based on outputs of an economic input-output life-cycle analysis (EIO-LCA) model[18-20] and full fuel-cycle analysis models.[5-9,21,22] The EIO-LCA model includes economy-wide interactions and associated environmental burdens resulting from a life-cycle component. The life cycle is divided among vehicle manufacture, use (consisting of fuel production, vehicle operation, service, and fixed costs), and end-of-life stages. The fuel/vehicle options are evaluated with respect to economics, fuel properties/vehicle performance, environmental discharges [criteria pollutants, global warming potential (GWP)], energy use, resource use (renewable and nonrenewable), fuel availability, and feasibility. GWP is calculated based on 100-year GWPs of the GHG.[23] We report all life-cycle results on the basis of the vehicle lifetime.

The EIO-LCA model is employed, except for the examination of the fuel cycles, vehicle operation, and end of life. Fuel cycles include the processes of extracting raw materials, refining/processing, transporting, and retailing the fuel. The EIO-LCA sectors are too aggregate for the currently produced fuels (e.g., conventional gasoline, CaRFG2, and diesel are aggregated into the "petroleum refining" sector; allocating burdens to these specific products would be arbitrary).

Fuel production is too small for any alternative fuel to be a sector in the model (e.g., corn C_2H_5OH). Vehicle operation includes operational energy and exhaust and evaporative emissions over the vehicle lifetime. Operational energy is calculated from lifetime fuel use (total mi divided by mpg) and the combustion energy in the fuel. Exhaust emissions are based on the certification standard and include an allowance for off-cycle emissions. We calculate the off-cycle emissions based on results presented in ref 24 of the impact of high-speed, high-load off-cycle driving on exhaust emissions from CaRFG2 and alternative-fueled automobiles. Vehicle operation GWP is calculated based on a carbon balance method for CO_2 and also includes estimates of CH_4 and N_2O for the options where available. See ref 17 for additional details on the vehicle operation life-cycle component. End of life of automobiles is not included in the EIO-LCA model; we employ results from ref 11.

For ICE options, our previous work finds that the use stage in the automobile life cycle has a much larger economic impact and environmental burden than vehicle manufacture, which has larger burdens than end of life.[1] The EIO-LCA model used in this work reports the impacts resulting from the industry itself (e.g., motor vehicle and passenger car bodies) and those resulting from all suppliers to the industry (e.g., from extraction of raw materials necessary to produce the components and fluids for the automobile). The supplier portion of impacts is much larger than that of the industries themselves. Primary differentiating factors among the ICE alternatives are in the fuel cycles and vehicle operation (and the related vehicle comparability) facets of the life cycles.[17,25] Vehicle manufacture and end-of-life differences among the engines and fuel storage equipment are small (most differences are less than 10%). The long-term, average maintenance costs for alternatively fueled vehicles will approach those of conventional vehicles.[26] Additionally, ref 26 reports that lifetime fixed costs for the vehicles are expected to be similar.

Fuel Cycles

The magnitudes of fuel production energy use and process emissions for fossil fuels are reported based on an assessment of published studies.[5-10] In selecting the full fuel-cycle studies we utilize for the energy and emissions estimates, we consider the study method, comprehensiveness, and year of the study, as well as publications that cite the study results. The studies are generally in close agreement. For the fossil fuels, we take averages where possible of the values for energy use and the various process emissions from the studies.

For the biofuels, particularly those that are not produced commercially or are produced as byproducts, the data on feedstock yields, energy use, and especially process emissions are more uncertain. We develop insights for the biofuels based on fuel cycle data for biodiesel and C_2H_5OH from biomass sources using near-term technologies.[10,22,27-29] For the biofuel energy use and process emissions, we utilize ref 10, and based on refs 28 and 29, we update the biomass yields and electricity credits to correspond to the latest available estimates. Additional details of the biofuel method are in the Biofuels section.

Fossil Fuels

Fossil fuels are nonrenewable; their production and use result in large amounts of GHG emissions. However, gasoline is attractive with respect to price, availability, ease of use, fuel properties (e.g., relatively high-energy density), continuing vehicle performance and emissions improvements (with RFG), and is supported by the current infrastructure. We examine the potential of gasoline-powered SIII vehicles to lower environmental costs by considering CaRFG2 (the "cleanest" high-volume gasoline in the United States). Additionally, we consider the potential of direct injection engines with CaRFG2, as these engines are capable of higher efficiency operation. However, the more efficient direct injection engines produce more particulate matter and NO_x. Much of the success of direct injection engines will depend on the level of efficiency they are able to attain while meeting strict emissions standards. We examine a low-sulfur diesel fuel, since it could be used in the most efficient, proven ICE; while uncertain, this fuel/engine combination may have the potential to meet ULEV standards.

Although CNG is a fossil fuel, it has several benefits over other fossil fuels. It is an inherently "cleaner" fuel resulting in lower engine emissions, is in abundant supply in North America, currently has a low price, and results in lower GWP. A primary impact of the vehicle comparability issue is the additional fuel and fuel storage required for CNG vehicles to attain the 595-km range. For example, the CNG vehicle becomes considerably heavier (average 1720 kg compared to the 1510-kg Taurus) and less efficient than the baseline gasoline vehicle when sufficient heavy storage cylinders are added to attain this km range.[17] Holding cylinder type constant, 3000-psig options are slightly more attractive than 3600-psig options due to the lower storage cylinder wall thickness and resulting lower-weight cylinders. However, there is a small penalty for onboard fuel storage volume at the lower pressure. Since the results are similar for both pressures[17] and fuel-cycle differences are small,[30] we limit the scope of this work to the 3000-psig options.

Due to safety issues associated with CH_3OH as a result of its toxicity and to its relative unattractiveness (lower energy density, no significant efficiency or emissions benefits) compared with C_2H_5OH, we do not analyze it further.

Biofuels

Concern over fossil fuel consumption, GHG emissions, and U.S. dependence on foreign fuel sources has led to the investigation of renewable fuel sources for automobiles. Currently, only a small percentage of energy is produced from renewable resources (3% of the U.S. energy supply is provided by biomass sources, and a recent executive order calls for a tripling of that level by 2010).[31] In the United States, biofuels are produced from several sources, including C_2H_5OH from corn and biodiesel from soybeans. Approximately 1.5 billion gal of C_2H_5OH are produced from corn annually, consuming ~6% of domestic corn production.[27] Aside from being derived from renewable sources and, therefore, supporting sustainability, biofuels address issues of global warming, energy independence (if the farming and fuel production are domestic), and support for a farm economy. If the fuels and inputs into the fuel production were to be produced using no fossil fuels, production and combustion of these fuels would result in no net CO_2. The carbon released as CO_2 from burning the fuel would be incorporated into the regrowth of the plant.

Both C_2H_5OH and biodiesel are primary candidates for renewable automobile fuels. Biodiesel used in high-efficiency CIDI engines has the potential to be sustainable, has low sulfur content, and has resulting emissions benefits. Attaining very low sulfur content in conventional diesel fuel is expensive. C_2H_5OH has good vehicle fuel properties, the potential to be sustainable, low sulfur content (which benefits emissions), and can be produced from several biomass sources. Currently, corn is the primary source, but herbaceous biomass crops (e.g., switch grass) and short rotation woody biomass crops (e.g., hybrid poplars) are being developed for C_2H_5OH production. Unfortunately, biofuels are more expensive than gasoline (we include details in the Fuel Expenditure section).

Current and near-term biofuel production assumes the use of fossil fuels for the production of fertilizers, as fuel for farm equipment and transportation, and in varying proportions for the fuel conversion process. The majority of fuel conversion energy for corn C_2H_5OH and biodiesel is currently from fossil fuel sources. In contrast, the near-term assumption for the herbaceous and woody biomass-derived fuels is that the combustion of the lignin (a nonfermentable biomass component) can be used to generate the steam and electricity required for C_2H_5OH production, resulting in little fossil fuel use.[27]

To make a significant contribution, bioalcohols need not replace all the gasoline used in light-duty vehicles. However, an interesting statistic for biofuels is how much land would have to be used for biomass growth in order for the biofuel to replace the ~100 billion gal of gasoline currently fueling the light-duty fleet.[32] Approximately 120 billion gal of C_2H_5OH or 75 billion gal of biodiesel are required, taking into account the differences in the heating values and fuel-engine efficiencies of the fuels (SIDI with the bioethanol and CIDI with the biodiesel). Based on current and near-term yields from refs 27 and 29, we calculate the required corn, soybean, woody, and herbaceous biomass quantities. Farmland requirements are estimated based on the average U.S. corn, soybean, woody, and herbaceous biomass yields.[27,33] For these calculations, the baseline case is conventional gasoline in an SIII engine. To provide an additional reference point, we calculate the amount of gasoline that would be required to fuel the light-duty fleet assuming the fleet comprised SIDI gasoline vehicles.

The attractiveness of sustainable production of the biofuels is evaluated using a simplified approach. We assume that we are able to substitute the current or near-term fuel-cycle fossil fuel use on a MJ basis with the produced biofuel; that is, we assume that C_2H_5OH or biodiesel can be used to produce fertilizer, to run farm equipment, and provide process heat. We do not assume any other process changes.

Since the co-products from using corn or soybeans can be worth more than the fuel, the cost of the resulting fuel depends on the value of the co-products. Both dry- and wet-milling corn processes are used for C_2H_5OH production. The dry-milling process is designed for C_2H_5OH production, and the only co-product is distillers' grains and solubles. However, the wet-milling process has several co-products, which are more valuable than the distillers' grains and solubles.[27] We present the dry-milling scenario in this work. Co-products of biodiesel from soybeans are soymeal and glycerin. The only near-term biomass C_2H_5OH co-product is steam from burning the lignin. The steam can be used for process heat and the excess used to generate electricity that can be sold to the grid. We calculate the amounts of co-products that are produced based on ref 10, updating co-product yields according to refs 27–29.

RESULTS

Air Pollutants

The focus for automobile-related air pollutants has been on vehicle exhaust and evaporative emissions. The focus is now shifting to other life-cycle stages due to the promise of continuing significant improvements in vehicle emissions.[17,34,35] Since we assume all vehicles meet the ULEV standard, exhaust and evaporative emissions are reported to be equal. Table 2 reports life-cycle air pollutant emissions for the fossil-fueled automobiles and the improvement for the ULEV over the baseline Tier 1 vehicle.

The emissions associated with the manufacture of the vehicle are larger in magnitude than those from the fossil fuel cycles. Some of this difference is due to the EIO-LCA model, which draws a larger boundary around the process than the models used for the fuel-cycle results. For ULEV vehicles, lifetime driving emissions are roughly equal to the fuel-cycle emissions, except for CO where fuel-cycle emissions are small. Even when vehicles attain ULEV standards, exhaust emissions of CO dominate those of the other life-cycle stages. For the various fuels, fuel-cycle emissions are similar for each pollutant. Low sulfur, reformulated fuels might require more processing and energy than the values reported here.

Fuel-cycle emissions for the biofuel options are reported in refs 7, 10, 22, and 27. We report insights based on these estimates. With current and near-term production methods, the biofuels cycles (even with the electricity credit in the case of the biomass C_2H_5OH) emit higher levels of SO_2, particles, and especially NO_2 and CO, than the fossil fuel cycles emit. The major sources of these emissions are the combustion of the fossil fuel used in producing the fertilizers and in operating farm and transportation equipment, and emissions from the fuel conversion processes. In our judgment, the current fuel-cycle production emissions for the biofuels are not a significant concern due to the potential to lower the emissions from these processes (e.g., tractors using cleaner diesel with emissions control systems). In the longer term, alcohol or biodiesel-fueled tractors can replace current diesel tractors. As expected, the electricity credit results in pollutant emissions credits, since the biomass electricity is cleaner than the primarily fossil fuel electricity it displaces. Even with the near-term technology assumption, emissions of SO_x from biomass C_2H_5OH production are smaller than for fossil fuel production, and in the cases where the electricity credit is applied, these emissions are reported as negative values.

Global Warming Potential

Figure 1 reports GWP for the vehicle alternatives. The figure assumes sustainable production (no fossil fuel use) for the biofuel options. We omit corn C_2H_5OH and

Table 2. Estimated air pollutants resulting from life cycles of fossil-fueled automobiles (kg/vehicle lifetime).

	SO_x	CO	NO_x	NMOG/ VOCs[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]Nonmethane organic gases (NMOG) for vehicles and volatile organic compounds (VOCs) for fuel production; [b]Vehicle exhaust emissions refers to estimates of both on- and off-cycle exhaust emissions discharged over the vehicle lifetime. These amounts do not include an allowance for malfunction emissions. 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.

biodiesel since, as shown below, a vast amount of land is required for large-scale production. For any fossil-fueled automobile option, the amount of CO_2 equivalent generated from its life cycle is between 77,000 kg for the CNG SIDI combination and 99,000 kg for the CaRFG2 SIII option. Multiplying this life-cycle amount by the large number of vehicles being produced in the United States gives at least a partial indication of the magnitude of the impact of these vehicles on GWP. Even with a range of 595 km, the direct-injection CNG vehicles have the potential to lower GHG emissions by 30% compared with the baseline vehicle. The EC diesel lowers GHG emissions by 25% compared with the baseline gasoline vehicle. RFG has local air quality benefits but results in an increase in GWP, even though the fuel has a lower carbon content than

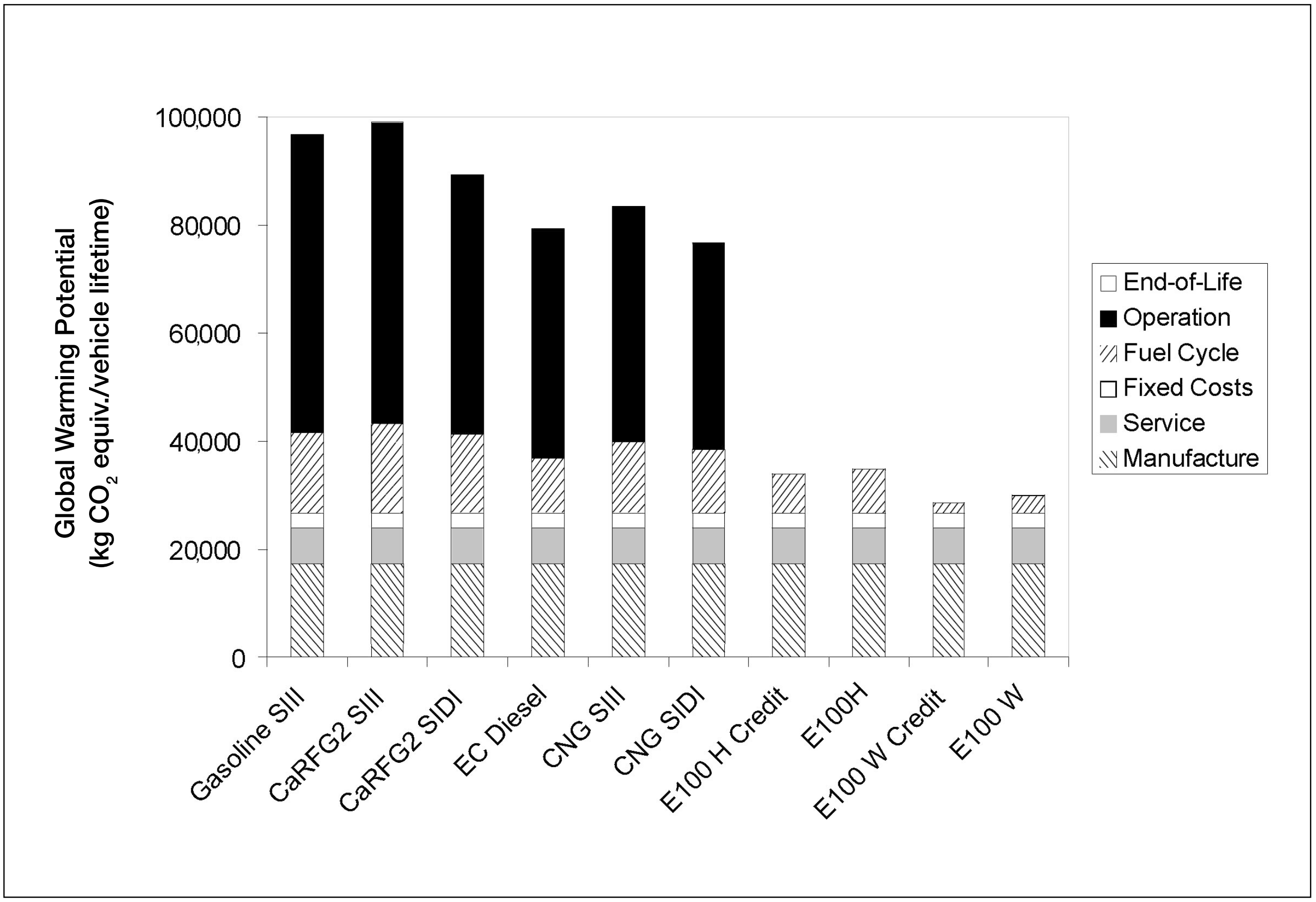

Figure 1. Life cycle GWP of automobile alternatives (assumes sustainable production of biofuels).

conventional gasoline. This is due to the slightly lower vehicle fuel economy with CaRFG2 (because of lower energy density of the fuel) and the additional energy required during the fuel production. The potential for GHG benefits from the direct injection engines is dependent on their attaining a high efficiency while meeting strict emissions standards.

For fossil fuels, the GWP from lifetime vehicle operation dwarfs the emissions from the other life-cycle components. For the baseline automobile, the sum of GWP emissions across all the life-cycle stages, except vehicle operation, is 42,000-kg CO_2 equivalent, compared with 55,000 kg for vehicle operation. The GWP resulting from the fossil fuel production is similar to that for vehicle manufacture, about 20–30% of the GWP resulting from vehicle operation.

Although some reductions in GHG emissions from automobiles could be realized with the use of CNG and increases in fossil-fueled vehicle efficiency, improvements necessary to satisfy the Kyoto Agreement and a sustainable transportation system require more radical measures.[36] Biofuels have the potential to offer these much greater reductions. As mentioned previously, sustainable production would result in no net CO_2 from the fuel cycle and fuel combustion. If the excess energy were used to generate electricity that reduces generation from conventional sources, there would be a net CO_2 benefit. There remains a GWP due to the non-CO_2 GHG (for the current and near-term biofuels, these amounts are less than 10,000 kg CO_2 equivalent per vehicle lifetime). The fuel cycle emissions shown in Figure 1 are due to these non-CO_2 GHG.

Wang et al. report that even with current and near-term production methods, there are potential GWP benefits for the biofuels, particularly for biomass C_2H_5OH, due to carbon sequestration, the electricity credit, and the fact that little fossil fuel energy is used in the C_2H_5OH conversion process.[27] Current production of corn C_2H_5OH and biodiesel has less benefit for GWP, due to the absence of the electricity co-product, and significantly higher process fossil energy. For a near-term scenario, ref 10 reports about a 25% decrease in fuel-cycle CO_2 equivalent emissions for E85 (85% corn C_2H_5OH, 15% conventional gasoline) flexibly fueled vehicles compared with conventional gasoline automobiles.

Table 3. Energy use of ICE options (GJ/vehicle lifetime).

Life Cycle Stage or Fuel/Powertrain	Industry[a]	Suppliers[b]	Total
	Vehicle		
Manufacture	8	233	241
Service	7	90	97
Fixed Costs	1	40	41
End of Life	2		2
Vehicle Use	**Fuel Cycle**	**Vehicle Operation**	**Total**
Gasoline SIII	154	816	970
CaRFG2 SIII	172	800	972
CaRFG2 SIDI	152	705	857
EC Diesel CIDI	89	612	701
Biodiesel CIDI	231/252[c]	612	843/864
E100 Corn SIDI	400/420	657	1057/1077
E100 H SIDI Credit[d]	73/988	657	730/1645
E100 H SIDI	125/1062	657	782/1719
E100 W SIDI Credit[d]	5/1116	657	662/1773
E100 W SIDI	108/1266	657	765/1923
CNG 3000 SIII[e]	151	803	954
CNG 3000 SIDI	134	701	835

Note: Table assumes near-term production for biofuels; [a]Refers to the primary/final industry for the life-cycle stage (e.g., for manufacture, motor vehicle, and passenger car bodies); [b]Refers to all of the industries throughout the economy who are the suppliers to the industry referred to in item a; [c]First entry is fossil energy and second figure is total energy; [d]H is herbaceous biomass, W is woody biomass, and Credit is electricity credit co-product for biofuels; [e]CNG – Type 3 cylinders, 3000-psig pressure.

Energy Use

Table 3 shows energy use for the automobile life cycles. Comparing the fossil fuel automobile options, there are not substantial differences in their life-cycle energy use. The EC diesel results in the largest saving, 20%, due to its high efficiency. However, the energy required to produce this very low sulfur diesel is uncertain, and it is not likely the same processes would be employed with large-scale production. The results for any of the other options are within 10% of the baseline's 1351 GJ. Mirroring the GWP results, the operational energy use for the fossil fuel options is much larger than the energy required for fuel production. For example, to produce the gasoline for the baseline vehicle over its lifetime requires ~150 GJ, while operating the vehicle requires over 800 GJ.

Table 3 reports near-term amounts of total and fossil energy for the biofuels. Comparing fuel cycle total energy for the biofuels with that of the fossil fuels is misleading. For bioalcohols and biodiesel, large amounts of energy are required in the conversion processes. For the fossil fuels, nature has already converted the biomass to these fuels (e.g., petroleum is formed by the decay and incomplete oxidation of biomass and animal debris buried in sedimentary rocks during geologic times); therefore, far less energy is required throughout the fossil fuel cycles. A more relevant fuel-cycle energy use comparison is to compare fossil fuel energy use, since, particularly for the biomass C_2H_5OH, the majority of the energy used in the biomass conversion plant is from the biomass itself. Just 10% of the biomass fuel cycle energy is required for biomass farming and transportation to a C_2H_5OH conversion facility; the remaining 90% is used in the conversion of biomass to C_2H_5OH and its transport, storage, and distribution.

After subtracting the fossil energy required to produce 1 gal of C_2H_5OH from the energy contained in the gallon, the net energy balance is close to 60,000 Btu/gal for biomass C_2H_5OH (even ignoring the electricity credits) and 25,000 Btu/gal for corn C_2H_5OH.

Fuel Availability/Feasibility

Experts disagree on the amount of petroleum that could be extracted at prices close to the current levels. Similarly, there is no consensus on the amount of natural gas that could be extracted at current prices. However, since the United States imports more than half of the petroleum it uses, even relatively small reductions in demand due to the use of biofuels could help to lower oil prices and increase U.S. energy security.

Table 4 reports biofuel yields and land required to substitute the gasoline currently used by SIII light-duty vehicles with the biofuels used in their relevant engines. Results for both current/near-term and sustainable production are shown. The low soybean yield per acre is a primary factor in the much larger land requirement for the biodiesel. Assuming a 5–15% efficiency advantage of SIDI gasoline engines over SIII, and taking into account the slightly lower energy content of CaRFG2 (which is the fuel we assume is used in SIDI engines), between 88 and 98 billion gal CaRFG2 would be required to fuel the current fleet if SIDI automobiles were used.[17]

Two central biofuel issues are sustainable production and co-product value. Clearly, with sustainable production (using biodiesel or C_2H_5OH to run tractors, etc.), less C_2H_5OH is available to fuel automobiles. Table 4 indicates the reduced yields and resulting larger land area required for the sustainable production.

The land area of the United States is 1.94 billion acres. Ninety-two million acres are developed, 380 million acres are cropland, and 125 million acres are pastureland, yielding a total of ~600 million acres.[32] Even eliminating from consideration land that is in areas too dry or too cold to grow biomass, or on hills and mountains too high or steep to harvest, there is a great deal of land that could be used for growing woody or herbaceous biomass.

Most current biofuel processes do not take advantage of the use of waste materials in production of the fuels. For example, the current production of corn C_2H_5OH uses cornstarch as the raw material. The process might also use the corn stover as biomass to produce C_2H_5OH. If so, the biomass process would supply additional C_2H_5OH as well as steam to run both processes. Electricity credits associated with this fuel production are even possible.

Note that the co-product of the woody and herbaceous alcohol cycles is electricity, while the corn C_2H_5OH and particularly the biodiesel fuel cycles yield more valuable co-products. Based on the near-term electricity credits associated with woody and herbaceous biomass (1.73 and 0.865 kWh/gal of C_2H_5OH produced, respectively),[27] production of 120 billion gal of C_2H_5OH would result in net electricity generation of ~210 million MWh for woody biomass or 105 million MWh for herbaceous biomass. These amounts correspond to 6 and 3%, respectively, of current net U.S. generation. Based on ref 27, this electricity co-product is assumed to have the potential to displace electricity generation on the basis of the U.S. average generation mix. For additional details, see ref 27. Efficiency improvements for C_2H_5OH production would trade increased C_2H_5OH yield for decreased electricity credits. Producing C_2H_5OH from corn (dry-milling process) or biodiesel from soybeans in the above quantities yields

Table 4. Biofuel requirements to replace 100 billion gal of gasoline used to fuel SIII vehicles:[a] near-term and sustainable poduction.

Fuel	Biosource[b] Yield (bushel or dry ton/acre/yr)[c]	Fuel Yield: Near-Term[d] (gal fuel/bushel or dry ton)	Required Biosource (billions bushels or dry tons)	Land Required: Near-Term Production (billions acres)	Fuel Yield: Sustainable Production[e] (gal fuel/bushel or dry ton)	Land Required: Sustainable Production (billions acres)
Corn C_2H_5OH	125	2.6	46	0.37	0.85	1.1
Herbaceous C_2H_5OH	5.75	80	1.5	0.26	63	0.33
Woody C_2H_5OH	5.26	76	1.6	0.30	62	0.37
Soybean Biodiesel	36	1.4	55	1.5	0.81	2.6

[a]Values in the table are to produce 120 billion gal of C_2H_5OH or 75 billion gal of biodiesel; [b]Biosource refers to corn, soybeans, or biomass corresponding to that required for the fuel produced; [c]Values for corn and soybeans are reported in bushels, those for herbaceous and woody biomass in dry tons biomass; [d]Near-term refers to current corn C_2H_5OH and soybean biodiesel production and near-term C_2H_5OH from herbaceous and woody biomass; [e]Sustainable production refers to no fossil fuel use throughout the entire fuel cycle.

significant amounts of co-products. The corn C_2H_5OH production would result in 332 million dry tons of distillers' grains and solubles, and the soybean biodiesel, 55 million tons of glycerin and 1.2 billion tons of soymeal.

Unused farm land and excess production of corn and soybeans might make some production of corn C_2H_5OH or biodiesel attractive, particularly if there were high demand for the co-products and concern for reducing petroleum imports. However, using food to produce vehicle fuel in a world with more than 6 billion people raises moral concerns. In addition, corn and soybeans require more fertilizer, pesticides, and effort (e.g., irrigation, planting, harvesting) than the herbaceous and woody biomass sources. Furthermore, the amount of land suitable for corn or soybeans is much smaller than the amount of land suitable for hybrid trees or grasses. In our judgment, fuels from corn and soybeans will not have an appreciable effect on the market for light-duty vehicle fuel.

Fertilizer Use

Fertilizer use for the fossil fuel cycles is small.[7,10] The EIO-LCA model reports small amounts of fertilizer use by the supplier industries to vehicle manufacture, service, and fixed costs. Assuming near-term technology production methods, farming of all of the biofuel crops requires significant amounts of fertilizer. Corn and herbaceous biomass farming require large amounts of nitrogen fertilizer—440 g/bushel and 9300 g/dry ton biomass, respectively.[10] Woody biomass and soybeans require far less nitrogen fertilizer— about 930 g/dry ton and 130 g/bushel, respectively. Smaller amounts of phosphoric and potassium fertilizers are required. The use of the additional nitrogen fertilizer in production of the herbaceous biomass is a major source of the higher GHG emissions of N_2O from the C_2H_5OH produced from this feedstock. However, compared with corn, production of soybeans and biomass has lower N_2O and NO_x emissions from nitrification and denitrification of nitrogen fertilizer. Wang reports that ~1.5% of the nitrogen in nitrogen fertilizer applied to corn fields is released as N_2O to the atmosphere.[10]

Fuel Expenditure

We estimate the expenditure on each fuel for the conventional and alternative-fueled vehicles over their lifetimes. We assume constant annual fuel use and constant fuel price, based on current and near-term technologies. The entries in Table 5 are the estimated lifetime (225,300 km) fuel expenditure estimates net of taxes, delivery, and retail markup. Since some of the fuel/engine combinations are more efficient on an energy content basis than is gasoline in an SIII engine, the fuel prices are reported on an energy content basis. The gasoline price estimates are based on the October 1999 refinery gate price of \$0.629/gal for conventional gasoline and the additional premium for CaRFG2.[37] Since the price of EC diesel is uncertain, our estimate reflects the October 1999 refinery gate price of conventional diesel plus a small premium.

Estimates of costs of production of C_2H_5OH from biomass range from \$0.6 to \$1.9/gal, with similar average costs for production from woody and herbaceous sources.[33] Wooley et al. report a near-term production cost of C_2H_5OH from woody biomass as \$1.44/gal C_2H_5OH (with an uncertainty range of +\$0.20/–\$0.08); assuming the best industry technology, the cost is \$1.16.[29] In terms of gasoline equivalent gallons, the costs are \$1.73 and \$1.39, respectively. Wooley et al. estimate that biomass feedstock conversion costs will fall to \$0.76/gal by 2015.[29] Based on these reports, we assume identical near-term C_2H_5OH cost from herbaceous and woody biomass, resulting in a cost of \$1.44/gal.

We calculate the price for corn C_2H_5OH using two information sources. Both costs are reported in Table 5. The first value is based on C_2H_5OH industry price information; EIN Publishing Inc. reports an October 1999 selling price for C_2H_5OH FOB their plant of \$0.90/gal.[38] We calculate the second value based on the current C_2H_5OH subsidy for its use in gasohol and on the gasoline excise tax being reduced by \$0.06/gal for C_2H_5OH-blended gasoline. Therefore, this provides a \$0.60/gal C_2H_5OH subsidy, since typically one part C_2H_5OH is blended with nine parts

Table 5. Near-term fuel prices and lifetime expenditure on fuel (net of taxes, delivery, and retail markup).

Fuel	Lifetime Energy Required (GJ)	Price[a] (1999\$/GJ)	Lifetime Expenditure (1999\$)
Gasoline SIII	740	5.18	3836
CaRFG2 SIII	740	5.85	4330
CaRFG2 SIDI	650	5.85	3804
EC Diesel CIDI	570	4.40	2510
Biodiesel CIDI	570	13.88	7911
C_2H_5OH SIDI Corn	595	11.22,[b] 15.34[c]	6679,[b] 9128[c]
C_2H_5OH SIDI Herbaceous Biomass	595	17.96	10,686
C_2H_5OH SIDI Woody Biomass	595	17.96	10,686
CNG 3000-psig SIII	720	2.31	1663
CNG 3000-psig SIDI	640	2.31	1478

Note: Number of significant digits in the table is for calculation purposes and does not represent the accuracy of the figures; [a]Assumes use of current technology for fossil fuel, corn C_2H_5OH, and biodiesel production and near-term technology for herbaceous and woody biomass fuels; [b]Price calculated based on C_2H_5OH subsidy based on its use in gasohol; [c]Price calculated based on October 1999 C_2H_5OH price [EIN 00].

gasoline, resulting in a corn C_2H_5OH price of $1.23/gal. Prices of CNG are based on a wellhead price of $2.31/MCF (million standard cubic feet) for October 1999.[37]

Compared to the baseline, the only significant saving is through the use of CNG or diesel. The high efficiency of the diesel lowers fuel cost; however, the price of low sulfur, reformulated diesel, were it produced in significant volume, is very uncertain. The biofuels are considerably more expensive than the fossil fuel options. The infrastructure required and the associated cost of biofuel production is the major barrier to wider use. The refinery gate price for gasoline is less than half the production cost of bioethanol.

CONCLUSIONS

Gasoline- and diesel-fueled automobiles have made important progress in improving fuel economy and reducing emissions. Near-term improvements of gasoline vehicles, combined with low-sulfur RFG, make it difficult for any fuel to displace gasoline. A further difficulty is the need to build a new infrastructure to produce and deliver the alternative fuel. No alternative fuel is likely to be successful unless there are substantial petroleum price increases or more stringent regulations concerning emissions and fuel economy standards, along with new regulations concerning GHG emissions.

CNG is the most attractive alternative fuel, since it is currently less expensive than gasoline and diesel and has lower emissions. However, onboard storage and vehicle range issues, along with the need for new pipelines to transport the gas and new filling stations to sell it, potentially doom widespread adoption of CNG. Additionally, with a strong focus on GWP, a shift away from fossil fuels would be necessary. And although diesel vehicles are attractive due to their high efficiency and fuel availability, the ability of these vehicles to meet strict emissions standards even with low sulfur, reformulated fuel is uncertain.

Biofuels offer the benefits of lower GHG emissions, sustainability, and domestic fuel production. The herbaceous and woody biomass-based C_2H_5OH options are more attractive than producing the biofuels from food products. The latter crops require additional maintenance, and feasible fuel production requires a high demand for their co-products. The C_2H_5OH from herbaceous or woody biomass could replace much of the gasoline required for the light-duty fleet while supplying electricity as a co-product. While it is more expensive than gasoline, bioethanol would be attractive if the price of gasoline doubled, if significant reductions in GHG emissions were required, or with tightening of fuel economy regulations for gasoline vehicles.

Major uncertainties need to be resolved before firm policy conclusions can be drawn.

- What will be the efficiency of direct injection engines after modifying them to meet strict emissions standards?
- Can diesel engines meet strict emissions standards using low-sulfur reformulated fuel?
- What are near-term biomass yields, processing costs, C_2H_5OH yields, and electricity credits?
- What would be the price of CNG if there were a major increase in the demand for this fuel?
- What will happen to gasoline and diesel prices, both as a result of petroleum price changes and as a result of requiring low-sulfur, reformulated fuels?
- What will future regulations require for tailpipe emissions, fuel economy, and GHG emissions?

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