Transportation Fuels and the Greenhouse Effect

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Continued emissions of CO₂ and other “greenhouse” gases are expected to cause substantial global warming with adverse consequences for agriculture and coastal cities, yet emission of greenhouse gases has not been a criterion in evaluation of alternative transportation fuels. In this paper are evaluated emissions of CO₂, CH₄, N₂O, and other greenhouse gases from the use of gasoline and diesel fuel, electricity, methanol, natural gas, and hydrogen in highway vehicles. Emissions from initial resource extraction to end use are estimated. It is found that the use of coal to make any highway fuel would substantially accelerate greenhouse warming relative to the base-case use of petroleum. The use of natural gas as a feedstock would result in a small reduction. Significant reductions in emissions of greenhouse gases can be achieved only by greatly increasing vehicle efficiency or by using biofuels, electrolytic hydrogen, or nonfossil-fuel-based electricity as the fuel feedstock. Emissions of gases other than CO₂ are likely to contribute appreciably to the warming, but better data are needed. Full social-cost pricing of fuels and increased research and development on sustainable, environmentally sound fuels are recommended.

Long-term, global environmental concerns will play an increasingly important role in energy policy. Foremost among these concerns is the global warming caused in part by carbon dioxide (CO₂) emissions from the conversion of fossil fuels. In recent years there has been considerable interdisciplinary research on the changing atmospheric concentration of CO₂ and other greenhouse gases, the effects of anthropogenic releases of these gases on steady-state atmospheric concentrations, the climatic effects of increasing concentrations of the gases, and the consequences of a changing climate on human affairs. As documented herein, many scientists and energy analysts conclude that significant climatic change is likely and that actions should be taken to reduce the use of fossil fuels.

However, these concerns have not yet influenced actual policy formation. Few, if any, national or local energy plans explicitly recognize mitigation of the greenhouse effect as a development criterion. [In the late 1970s and early 1980s, when “synfuels” were being assessed, there was some concern about the CO₂ impact of synfuels from coal (1–4).] This oversight is particularly glaring in the transportation energy field, where there is a rapidly developing interest in alternatives to gasoline and diesel fuel but no systematic analyses of emissions of greenhouse gases. Indeed, policy statements and research documents on future highway transportation fuel choices, issuing from government energy organizations, automobile manufacturers, and fuel producers, totally ignore the greenhouse problem (5–11). Given the potential seriousness of the greenhouse effect, and the significantly different contributions of alternative fuels to climatic change, it would be unwise to make a commitment to an alternative transportation fuel without an evaluation of the greenhouse gases emitted by the production, distribution, and end use of the fuel.

In this paper are examined emissions of greenhouse gases (CO₂, CFCs, O₃, N₂O, CH₄, and H₂O) from the most prominent highway transportation energy options: petroleum, methanol, natural gas, electric vehicles, and hydrogen. It is shown that the alternatives vary widely with respect to their potential contribution to the greenhouse effect, and policy implications are briefly discussed. [An expanded version of this paper was published by the University Energy Research Group at the University of California–Berkeley (12). That paper should be consulted for details not provided here. For a comprehensive evaluation of alternative transportation fuels in general, including their costs and technical problems, and for support for the analytical assumptions used here, see Deluchi et al. (13).]

GREENHOUSE GASES AND THE GREENHOUSE EFFECT

Carbon Dioxide

Although deforestation and other land use changes may contribute to the greenhouse effect, energy use is clearly the primary anthropogenic source of CO₂. Globally, fossil fuel burning now accounts for 56 to 94 percent of the total net CO₂ release (14–16)—values above 75 percent are more likely (16)—and will contribute an even greater share in the future. There are many unknowns and uncertainties, which leave much room for differences of opinion about the causes and consequences of a greenhouse warming (17–22), but researchers are in almost unanimous agreement that if the concentration of CO₂ doubled, a substantial warming would occur. Recent data from ice-core studies appear to establish “irrefutable evidence for a fundamental link between the global climate system and the carbon cycle,” and indicate that “CO₂ is a dominant climate forcing factor” (23). Major studies by the U.S. Department of Energy (DOE) (18, 19), the international Scientific Committee on Problems of the Environment (SCOPE) (21), the National Research Council (24), the Environmental Protection Agency (EPA) (17), the National Science Foundation [in Nature (25)], and the World Resources Institute (26) conclude that there is a firm basis for believing that increasing emissions of CO₂ and other trace gases will

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upset the earth’s radiation balance and cause a global warming of from 1°C to 5°C in the 21st century. This warming could shift global precipitation patterns, disrupt established crop-growing regions, raise sea level by approximately a meter, and eventually melt portions of the polar ice caps and threaten coastal cities worldwide with inundation.

Other Trace Gases

Several other trace gases—methane (CH₄), nitrous oxide (N₂O), ozone (O₃), and chlorofluorocarbons (CFCs)—have a lesser, but potentially important, role in contributing to the greenhouse effect [discussions of trace gas cycles and climate can be found elsewhere (15, 26, 27–32)]. Current research indicates that they could be responsible for about 50 percent of the total greenhouse temperature increase 50 years from now. In this paper the greenhouse effect of emissions of CH₄ resulting from the use of transportation fuels and of N₂O from power plants is examined. The effects of O₃ and CFCs, and of other sources of N₂O, are discussed briefly later, and in more detail elsewhere (12).

ANALYSIS OF EMISSIONS OF GREENHOUSE GASES FROM HIGHWAY TRANSPORTATION FUELS

At present, the most commonly proposed alternatives to petroleum transportation fuels are electricity, methanol, compressed and liquefied natural gas (CNG and LNG), and hydrogen (LH₂ and hydride). In this paper is estimated the percentage change in CO₂ emissions that would result from the substitution of a mile of travel by a single-fuel, optimized alternative vehicle for a mile of travel by a heavy truck or catalyst-equipped gasoline vehicle, with concomitant substitutions along the fuel-use-to-resource-extraction chain.

Basis of Comparison

Emissions of greenhouse gases are compared on an equal work-provided basis. The petroleum fuel reference case is 1985 aggregate energy consumption (15 quads of gasoline and diesel fuel) and vehicle miles traveled (VMT) (1.78 trillion) for the entire U.S. highway fleet (33, 34). For methanol, natural gas, and hydrogen vehicles this 15-quad baseline is adjusted to account for the greater fuel efficiency of these vehicles, and for an increase (with methanol) or decrease (with NG and hydrogen) in energy consumption by trucks delivering highway fuels, relative to the reference case. Both aggregate CO₂ equivalent emissions, based on a complete substitution of the alternative fuel for gasoline and diesel fuel, and the percentage change in CO₂ equivalent emissions, with respect to the reference case, are presented.

For electric vehicles (EVs) only the percentage change in CO₂ equivalent emissions per mile, with respect to the petroleum fuel reference case, is presented. Because EVs do not yet perform well enough to be used in all applications, a calculation based on complete substitution of EVs for internal combustion engine vehicles (ICEVs), even if meant to show only the relative emissions of EVs in those niches in which they could compete, would be misleading. The ultimate aggregate CO₂ reduction available from the use of EVs depends on the extent to which EVs prove feasible in high-power-demand, long-range applications.

Sources of CO₂ and Trace Gases

Working backward from end use to resource extraction, five general sources of CO₂ resulting from the use of highway fuels are examined: (a) combustion of transportation fuels on the highway, including fuels used by trucks delivering liquid transportation fuels to retail outlets; (b) combustion of fuel in pipeline compressors or pumps, and in barges and trains during the wholesale transmission of fuels to the distributor; (c) CO₂ formed by the chemical reactions of fuel synthesis; (d) CO₂ formed by the use of process energy in fuel production plants; and (e) combustion of fuel in the initial extraction, preparation, and transport of the raw feedstock. CO₂ emissions are measured in gigatons (GT) (10⁹ tons).

Emissions of methane from vehicles using organic fuels, and from pipeline compressors and electric power plants burning natural gas; leaks from natural gas pipelines and field recovery operations; releases from coal mining; and venting of gas associated with oil recovery are estimated. Emissions of methane from coal-fired power plants are ignored. N₂O emissions from coal and NG combustion are estimated for all of the fuel options.

Other Conventions of Analysis

For ICEVs it is assumed that 97 percent of the carbon in the fuel used in Steps a, b, d, and e is completely oxidized to CO₂. This value is representative of the carbon oxidation efficiency of vehicles, which are the largest combustion source of CO₂ in this analysis. For EVs, estimates of CO₂ emitted per quad of energy are used (Table 1).

CH₄ emissions have been converted to “equivalent” CO₂ emissions. The authors have calculated that 75 years of 1 mass unit per year of CH₄ emissions has the same overall temperature effect (temperature increment per year multiplied by the number of years to atmospheric steady state, given 75 years of emissions) as 11.6 mass units of CO₂ emissions per year for 75 years (12, Appendix B). Plausible high and low CH₄/CO₂ conversion factors of 30 and 5 have been considered in the natural gas vehicle (NGV) analysis. The mass conversion factor for N₂O to CO₂ emissions is 175. N₂O emissions generally are reported in megatons (MT) (10⁶ tons). All heating values are “gross” or “higher,” and are consistent with values used by the U.S. Energy Information Administration (EIA).

GREENHOUSE GASES FROM PETROLEUM TRANSPORTATION FUELS (BASE CASE)

Situation in 1985

As the data in Table 1 indicate, the United States contributed nearly one-quarter of the total world production of CO₂ from fossil fuels in 1985. Fuel burned on the highways contributed almost one-quarter of the U.S. production of CO₂. When production and distribution of transportation fuels are included,
<table>
<thead>
<tr>
<th>Carbon-releasing energy sources</th>
<th>Carbon-releasing use, quads&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Fossil fuel energy use, 10&lt;sup&gt;9&lt;/sup&gt; tons (GT)&lt;sup&gt;b&lt;/sup&gt;</th>
<th>% Mass&lt;sup&gt;c&lt;/sup&gt;</th>
<th>% Burn&lt;sup&gt;d&lt;/sup&gt;</th>
<th>GT of Carbon burned/yr</th>
<th>GT of CO&lt;sub&gt;2&lt;/sub&gt; formed/quad</th>
<th>GT CO&lt;sub&gt;2&lt;/sub&gt; per fuel-only transportation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Petroleum</td>
<td>27.4</td>
<td>108.2</td>
<td>0.70</td>
<td>2.75</td>
<td>85.0</td>
<td>95</td>
<td>0.57</td>
</tr>
<tr>
<td>Natural gas</td>
<td>17.2</td>
<td>63.6</td>
<td>0.37</td>
<td>1.37</td>
<td>74.5</td>
<td>98</td>
<td>0.27</td>
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<tr>
<td>Coal</td>
<td>17.4</td>
<td>86.2</td>
<td>0.80</td>
<td>4.8</td>
<td>50.61&lt;sup&gt;g&lt;/sup&gt;</td>
<td>98</td>
<td>0.48</td>
</tr>
<tr>
<td><strong>TOTALS</strong></td>
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<td>258.0</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Highway Trans.</td>
<td>15.0</td>
<td>37.2&lt;sup&gt;i&lt;/sup&gt;</td>
<td>0.37</td>
<td>0.93</td>
<td>86.5</td>
<td>94.96</td>
<td>0.31</td>
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<tr>
<td>% TRANSPORTATION</td>
<td>24.2</td>
<td>14.4</td>
<td></td>
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</tr>
</tbody>
</table>

Note: Figures are rounded. GT/quad factors are adjusted to be the same for the world and the United States where input parameters are the same. Products and sums may not derive exactly from shown values. See DeLuchi et al. (12) for more detailed notes.

<sup>a</sup>Excludes nonfuel uses of resources such as oil for tar.

<sup>b</sup>Data used in converting quads to tons are as follows: petroleum: 45.7 kJ/g (energy/mass by fuel type weighted by world consumption figures (35-37)); highway fuels: 46.7 kJ/g (35, 36, 38-40); gasoline weighted 75 percent (38); natural gas: 54 kJ/g, just under the gross heating value of pure methane; coal: tonnage data from EIA (35, 37), with nonfuel use tonnage subtracted.

<sup>c</sup>The mass percentage of carbon was estimated from the following data: petroleum: 80 to 89 percent C (39, 41); highway fuels: British gasoline, 85 to 88.5 percent C; diesel fuel, 86.5 percent C (39); natural gas: 90 percent CH<sub>4</sub>, 4.5 percent C<sub>2</sub>H<sub>6</sub>, 0.3 percent C<sub>3</sub>H<sub>8</sub>, 1 percent C<sub>4</sub>H<sub>10</sub>, 1 percent N<sub>2</sub>, and 0.5 percent CO<sub>2</sub> (as supplied by the British Gas Board (41)). Additional information is available elsewhere (40, 42); coal: based on EIA data for coal consumption by rank, energy content of coal by country (37), and data from the American Society for Testing and Materials on carbon and energy content by rank (41, 43).

<sup>d</sup>Roxby and Masters (45) give 91.8 percent for petroleum, 98 percent for natural gas, and 98 percent for coal. Here petroleum was adjusted to 95 percent to account for use of oxidation catalysts in automobiles. Conversion efficiency of highway fuels for new 1987 cars estimated to be 99 percent on the basis of EPA emission data (44) [see DeLuchi et al. (12) for details]. Lifetime average of catalyst-equipped cars assumed to be 97 percent. U.S. fleet assumed to average 96 percent in 1985; world fleet, with a larger percentage of uncontrolled cars, assumed to average 94 percent.

<sup>e</sup>From EIA (35).

<sup>f</sup>World fuel-only consumption estimated by assuming that the ratio of U.S. use of fuel F to U.S. total consumption of F = world fuel use of F to world total consumption of F, using EIA data (35).

<sup>g</sup>61 percent U.S. coal; 50 percent worldwide. Fixed carbon percentages.

<sup>h</sup>Other estimates in the literature are 18.86 GT in 1980 (45), 18.2 to 23.9 GT in 1980 (44); 18.3 GT in 1983 (cited by Keepin et al. (46)); and 19.76 GT for 1982 (43). See also estimates of GT CO<sub>2</sub>/quad of fuel in Bentz and Salmon (2) and Marland (4).

<sup>i</sup>Excludes fuel use by off-highway and military vehicles. U.S. data from Holcomb et al. (33).

<sup>j</sup>Includes fuel use by automobiles to total highway fuel use for the world in 1985 equals the ratio of motor gasoline use to total highway fuel use for OECD countries in 1984 (0.773)(38).

CO<sub>2</sub> from Oil Production and Nonhighway Product Distribution

For every unit of fuel energy delivered to a vehicle (including gasoline delivery trucks), about 0.16 unit is consumed in the production, processing, refining, and pipeline or barge transport of the highway fuel, for an overall efficiency of about 86 percent (42). It is assumed that 0.13 of the 0.16 unit of lost energy for every energy unit delivered to the vehicle is in combusted process fuel or material otherwise converted to CO<sub>2</sub>, not in lost product, which does not contribute CO<sub>2</sub>. Thus CO<sub>2</sub> emissions from the use of process energy in petroleum production, refining, and transmission would be 13 percent of the 1.138 GT/year produced by end use, or 0.148 GT/year (assuming that the process fuel produces CO<sub>2</sub> at the same GT/quad rate as do gasoline and diesel fuel).

CO<sub>2</sub> from Flared Natural Gas Coproduced with Petroleum

The quantity of associated gas vented or flared worldwide declined from about 4 quads in 1983 to 3.6 quads in 1984 and 3.1 quads in 1985 (36, 37, 47). In 1985 this energy waste was about 2.6 percent of the energy content of world production of crude oil, and 0.5 percent of the energy value of U.S. domestic oil production. In countries supplying the United States with imports, the energy value of flared gas was more than 5 percent of oil production.
Worldwide, venting and flaring will continue to decline as natural gas increases in value and is reinjected, used domestically, or exported. It is assumed that the near-term U.S. domestic production of 21 quads of oil will be associated with venting and flaring of 0.080 quad of NG (0.4 percent), and that importing 11 quads of oil will be associated with venting and flaring of 0.55 quad of gas (5 percent). The total is 0.020 quad NG/quad oil produced for U.S. consumption, on average. Thus the 17.4 quads of oil needed for the highway use chain will result in the venting or flaring of 0.3354 quad NG (assuming that highway fuels come from domestic and foreign sources in the proportion of total domestic production to total imports). Assuming that 75 percent of this is burned, the result is 0.015 GT CO₂/year, at 0.058 GT CO₂/quad NG.

**CH₄ Emissions**

*From Vehicles*

Available data on methane emissions from highway vehicles indicate a lifetime average of 0.08 g/mi for diesel vehicles and gasoline passenger cars, and 1.0 g/mi for gasoline trucks (12, Table 2). Multiplying these rates by the 1.78 trillion miles traveled in 1985 results in 0.000241 GT CH₄, or 0.003 GT CO₂ equivalent.

**Vented Associated Natural Gas**

From the preceding, 0.089 quad of associated NG is assumed to be flared in the production of oil used by the highway transportation sector. This is 0.0019 GT NG, or 0.022 GT CO₂ equivalent.

**N₂O Emissions from Oil Refineries**

About 0.03 MT N₂O is emitted per quad of oil burned (48–50). Assuming 1.95 quads of oil burned in refineries and in transport, and given a N₂O:CO₂ conversion factor of 175, 0.010 GT CO₂ equivalent of N₂O would be emitted.

**Total CO₂-Equivalent Emissions from Gasoline and Diesel Vehicles**

The total is calculated as follows:

1.138 (CO₂ from vehicles) + 0.003 (CH₄ from vehicles) + 0.148 (CO₂ from fuel production and transmission) + 0.015 (CO₂ from flaring of associated CH₄) + 0.022 (CH₄ from venting of associated CH₄) + 0.010 (N₂O from use of process fuel) = 1.336 GT/year

**GREENHOUSE GASES FROM ELECTRIC VEHICLES**

In this section the CO₂ emissions of power plants supplying EVs are estimated for two scenarios. In the base case it is assumed that no new capacity is required and that the electricity demand by EVs is sufficiently widespread that, nationally, fuel inputs, including nonfossil sources such as nuclear and hydropower, are used in the proportion that they are being used currently by electricity producers. In the second scenario it is assumed that new generating capacity is required, and emissions from new coal and NG power plants are estimated.

**CO₂ Emissions from Power Plants, No New Capacity Required (Scenario 1)**

Assume that X quads per year are consumed by petroleum-fueled vehicles in those applications suited for EVs. Considering the entire fuel-production and end-use chain, this would have resulted in 0.0891X GT of CO₂-equivalent emissions (recall that 15 quads resulted in 1.336 GT CO₂).

On the basis of vehicle tests and other efficiency estimates discussed in Appendix A of DeLuchi et al. (12) it is assumed that an optimally efficient (from an economic standpoint) electric car, van, or light truck is three times more efficient, including recharging, than an optimally efficient ICE version of the same vehicle. Given this, and the EIA's estimate (51) that in 1985 power plants were 30.2 percent efficient on average in converting input energy to electricity available at the outlet, including transmission losses and energy used internally by electricity plants, 1.104X quads would have to burned in power plants to supply the energy needed for EVs to displace the X quads of gasoline and diesel fuel. The percentage shares of each fuel input to U.S. power plants in 1985 were as follows: coal, 56.0 percent; nuclear, 16.0 percent; NG, 12.0 percent; hydro and other, 11.9 percent; and oil, 4.1 percent. The 1.10X quads would therefore comprise 0.618X quad of coal, 0.132X quad of natural gas, and 0.045X quad of oil. The remainder of the total input would be from the non-CO₂-producing sources, mainly nuclear and hydro.

Multiplying the estimate of CO₂/quad of fuel in Table 1 by the corresponding amount of each fuel input to electricity production (and, of course, assuming 0 GT CO₂/quad of nuclear, hydro, and other power) and summing yield 0.0735 GT of CO₂/year. It is assumed that 4 percent more CO₂, or 0.00294X GT/year, would be produced by the initial mining, processing, and distribution of the input fuels.

**CH₄ and N₂O Emissions**

*CH₄ from NG Use*

Assuming that 3 percent of the 0.132X quad of NG used in electricity plants is not burnt, and is released as methane, and that an additional 3 percent of the delivered gas is lost through pipelines and in field operations (see later section on Natural Gas Fuels), 0.00792X quad of CH₄, or 0.000167X GT CH₄ would be emitted (1 GT contains about 47.5 quads), the equivalent of 0.00193X GT of CO₂.

*CH₄ from Coal Use*

One source (30) cites five estimates of emissions of CH₄ from coal mining, ranging from 30 tg/year to 100 tg/year, with most around 35 tg/year (0.038 GT/year). This indicates an emission rate of about 0.0005 GT CH₄/quad of coal produced. Given the estimate of 0.618X quad of coal required, 0.00358X GT CO₂ equivalent would be emitted.
**$N_2O$ Emissions from Coal Use**

Estimates of $N_2O$ production from worldwide coal combustion range from 0.03 MT $N_2O$/quad of coal to 0.10 (48–50, 52). Here it was assumed to be 0.055 MT/quad. Total CO$_2$-equivalent emissions would be 0.00595X GT.

**Total CO$_2$-Equivalent Emissions from EVs**

The total is calculated as follows:

$$0.07350X \text{ (CO}_2\text{ from power plants)} + 0.00294X \text{ (CO}_2\text{ from feedstock recovery)} + 0.00193X \text{ (CH}_4\text{ from leaks and stacks)} + 0.00358X \text{ (CH}_4\text{ from coal mining)} + 0.00595X \text{ (N}_2\text{O from coal combustion)} = 0.0879X \text{ GT/year}$$

This is a 1 percent decrease from the 0.0891X GT/year emitted by gasoline and diesel fuel use in applications in which EVs are feasible.

**New Power Plant Capacity Required (Scenario 2)**

**New Coal Plants**

Assuming that new coal plants will have a conversion efficiency of 38 percent (53, 54), and that electricity distribution losses are 6 percent (51), and given 0.101 GT CO$_2$/quad coal, CO$_2$ production would be $(X/3)/0.36(0.101 \text{ GT CO}_2/\text{quad}) = 0.0935X \text{ GT CO}_2$. The authors increase this by 4 percent to account for CO$_2$ released by the energy used in coal mining and delivery.

CH$_4$ and $N_2O$ emissions associated with the mining and burning of 0.926X quad of coal would be responsible for 0.00891X ($N_2O$) and 0.00537 (CH$_4$) GT CO$_2$-equivalent emissions, applying the emission rates and conversion factors discussed previously. The grand total would be 0.112X GT, 26 percent more than the amount emitted by petroleum-fueled vehicles in the base case.

**New Natural Gas Plants**

Assuming an electricity generation and distribution efficiency of 36 percent, the CO$_2$ production by an EV fleet using power generated from natural gas would be (0.926X quad) (0.058 GT/quad) = 0.0537 GT CO$_2$. On the basis of data cited hereafter in the natural gas vehicle analysis, it was assumed that an additional 0.08 unit of CO$_2$ is produced by pipeline compressors and field recovery equipment for each unit produced by the power plant. This amounts to 0.00429X GT CO$_2$. The CO$_2$ equivalent of the 3 percent unburned methane from utilities and 3 percent methane leaks from pipelines would be about 0.0136 GT. $N_2O$ emissions, at 0.007 MT/quad of NG (see natural gas vehicle analysis), would amount to 0.00113 GT CO$_2$ equivalent. The total would be 0.0727X GT CO$_2$-equivalent emissions per year, an 18 percent reduction from the petroleum-fueled base case.

**GREENHOUSE GASES FROM METHANOL FUELS**

Methanol can be made from many feedstocks including coal, natural gas, organic wastes, crops, and wood products. In this section the authors first estimate greenhouse emissions from end use and fuel transportation, because these do not depend on the feedstock. Then the emissions attributable to coal- and natural gas–based production methods are examined in turn. Biomass, which can be made into other fuels besides methanol, is treated in a separate section.

**CO$_2$ Emissions from End Use**

Assuming that methanol vehicles are 13 percent more efficient than gasoline vehicles, and just as efficient as diesel fuel vehicles, the 13 quads of gasoline and 2 quads of diesel fuel consumed annually on the highways would be replaced by 13.5 quads of methanol. The authors increase this to 13.6 quads to account for the greater energy use of methanol delivery trucks (13). It is assumed that delivery of fuel from the fuel station to the vehicle is 100 percent efficient.

At 22.5 kj/g, this would be 0.702 GT/year of methanol. Methanol is 37.5 percent carbon by weight, so the methanol used in a year for the highway fleet would contain 0.263 GT carbon. With 97 percent oxidation the result is 0.935 GT of CO$_2$ per year. This reduction in CO$_2$ output relative to gasoline and diesel fuel use (1.138 GT/year) is primarily due to the lower carbon-to-hydrogen ratio of methanol.

**CH$_4$ Emissions from Methanol Vehicles**

The few data available on methane emissions from methanol vehicles [0.06 g/mi by a prototype Ford Escort wagon (55)] indicate that they emit about as much as do available gasoline vehicles. A total of 0.003 GT CO$_2$-equivalent emissions were therefore assumed.

**CO$_2$ from Nonhighway Transportation of Methanol**

Because methanol is twice as bulky and heavy as gasoline per energy unit, the shipment of an energy unit of methanol would require more fuel and thus produce more CO$_2$—in most cases almost twice as much—as the movement of gasoline or diesel fuel. Assuming that methanol transport is 98 percent efficient (42), an additional 0.02 unit of fuel would be needed for the transport of each unit consumed in end use. CO$_2$ production thus would be 0.019 GT/year.

**Methanol from Coal**

**CO$_2$ from Fuel Used in Coal Mining and Delivery**

0.014 unit of process energy is required for each energy unit of coal mined (42). This results in about 0.03 unit for each unit of methanol burned on the highways. It is assumed that the energy used in delivering coal to the conversion plant is included in this estimate and that the process fuel would be methanol. The CO$_2$ production would therefore be $0.03 \times 0.935 \text{ GT/year} = 0.028 \text{ GT/year}$. 

CO₂ from Conversion of Coal to Methanol

Gasification The total amount of carbon that must be made available for methanol manufacture would be 0.263 GT/year for end use, plus 5 percent of this for transmission and feedstock recovery, equaling 0.276 GT carbon/year.

The initial gasification of coal in methanol conversion produces gas with an H₂:CO:CO₂ ratio of about 0.68:1.00:0.205 (56, 57). In the next stage, the H₂:CO ratio is shifted to 2:1 by adding H₂ and removing CO at a 1:1 ratio. With these relationships it can be calculated that the 0.276 GT of carbon needed per year for methanol fuel would result in 1.166 GT CO₂/year being released from coal conversion (12).

CH₄ from Coal Mining

Because about 25 quads of coal are required in this methanol scenario, 0.0125 GT methane would be released, using the 0.0005 GT CH₄/quad rate from the EV section. This is a substantial release, the equivalent of 0.145 GT CO₂.

N₂O from Coal Used to Generate Steam

Given an emission rate of 0.055 MT N₂O/quad of coal (see EV analysis), and assuming that this applies to all the 3.1 quads of coal used to generate process energy, 0.030 quad CO₂ equivalent would be produced.

Total CO₂-Equivalent Emissions from Methanol Vehicles, Coal Feedstock

The grand total is calculated as follows:

0.935 (CO₂ from vehicles) +
0.003 (CH₄ from vehicles) +
0.047 (CO₂ from fuel transport and coal recovery) +
1.479 (CO₂ from conversion of coal to methanol) +
0.145 (CH₄ from coal mining) +
0.030 (N₂O from coal combustion) =
2.639 GT/year

This would be a 98 percent increase over the 1.336 GT/year released in the petroleum fuel base case. It has been calculated elsewhere (12) that even if the efficiency of conversion of coal carbon to methanol were increased 30 percent, and greenhouse gas emissions from all processes were reduced accordingly, the net result would still be a 51 percent increase in emissions of CO₂-equivalent gases.

Methanol from Natural Gas

Manufacture and Transport of Methanol

Conversion of Natural Gas to Methanol The initial reforming of natural gas (CH₄ + H₂O → CO + 3H₂O) produces a gas with a 3:1 hydrogen (as H₂)-to-carbon ratio (59, 60). Because methanol synthesis requires a 2:1 ratio, the reformed gas is actually carbon deficient, and so carbon conversion efficiency is relatively high: about 91 percent is converted to carbon in methanol (Jerome Trumbley, Celanese Corp., 1987, unpublished data). This indicates that only 0.10 carbon unit of CO₂ is emitted for each unit of methanol produced.

Process Energy and Other Considerations More process energy is required to run a methanol plant than is provided by combustion of purge gas and recycling of waste heat. It is assumed that this additional process fuel is methanol and is 10 percent of the energy content of the methanol produced by the plant. The total CO₂ from process energy and purge gas would be 0.20 x 0.935 = 0.187 GT CO₂.

As a check on their assumptions about process energy and carbon conversion, the authors have estimated that the overall thermal efficiency implied is 70.5 percent, which is consistent with values in the literature (12).

CO₂ from Recovery and Initial Shipping of Natural Gas

Because methanol plants would be located close to gas fields, gas would not be transported far, and so the energy used in gas transmission probably would amount to no more than 1 percent of the output. Gas recovery and processing require about 5 percent of the energy withdrawn from the reservoir (see data in the section on natural gas fuel). Combining these figures, about 0.06 unit of gas would be consumed for each unit delivered to the plant. Thus 0.06 × 19.7 (from the preceding discussion) = 1.18 quads of CH₄ burned in field plant equipment and in pipeline compressors, and about 0.069 GT CO₂ produced per year.

CH₄ Leaks

Data cited hereafter indicate that the amount of gas lost in recovery and transmission is 3 to 4 percent of the amount delivered. It is assumed that transmission losses are negligible for the short distances from field to methanol plant. Losses during recovery are assumed to be 1.5 percent of the amount delivered to the plant, or 0.0175 × 19.7 = 0.34 quad. This is equivalent to 0.084 GT CO₂.

N₂O emissions from methane conversion appear to be negligible (12).

Total CO₂-Equivalent Emissions from Methanol Vehicles, Natural Gas Feedstock

The total is calculated as follows:

0.935 (CO₂ from vehicles) +
0.003 (CH₄ from vehicles) +
0.018 (CO₂ from methanol transmission) +
0.187 (CO₂ from natural gas-to-methanol) +
0.069 (CO₂ from natural gas production and transmission) +
0.084 (CH₄ losses) =
1.296 GT/year CO₂

This would represent a 3 percent decrease from the base case of gasoline and diesel fuels.

GREENHOUSE GASES FROM NATURAL GAS FUELS

CO₂ Emissions from NGVs

Available data indicate that 13.5 quads of CNG, or 13.1 quads of LNG, could replace the 15 quads of diesel fuel and gasoline currently consumed on the highways, assuming that NG would be no more efficient than diesel fuel in compression ignition engines (13). A further 0.8 percent reduction in energy use due to the elimination of truck distribution of highway fuels (13) is assumed. Assuming that NG is pure methane, and that oxidation is 97 percent complete, if CNG vehicles replaced all gasoline and diesel fuel vehicles, a total of 0.769 GT/year of CO₂ would be produced. With an all-LNG fleet, 0.746 GT/year would be produced.

CO₂ Emissions from Compression or Liquefaction of Natural Gas

There are reasonably good data indicating that compression of natural gas to 3,000 psi requires about 0.04 mmBtu of electricity for every mmBtu of gas produced. Compressors typically use electricity. If future electricity production and distribution are 36 percent efficient, the extra energy required at the compressor would result in 0.11 unit of fuel being burned at the power plant for each unit delivered to vehicles, and thus 0.085 GT CO₂, assuming natural gas is the feedstock for electricity generation.

Liquefaction at the service station by small, self-powered, skid-mounted units requires about 0.21 mmBtu of gas for every mmBtu of LNG produced. On-site liquefiers use natural gas as the process energy.

It is assumed that delivery from the compressor to the CNG vehicle is 100 percent efficient. Vaporization losses in the transfer and storage of LNG are on the order of 2 percent. It is assumed that all vaporized LNG is returned to the liquefier, the effect of which is to increase the energy requirements of liquefaction per unit of LNG energy actually delivered to the vehicle. Thus the final amount of liquefaction energy required is 0.21 unit to liquefy one unit of LNG on the first pass plus 0.02 x 0.21 = 0.004 unit of energy to reliquefy the vaporized LNG. (Only two passes were assumed, and the 2 percent of the reliquefied gas that vaporizes was ignored.) The result is 0.214 x 0.746 = 0.160 GT CO₂.

CO₂ Emissions from Distribution and Production of Gas

Additional NG is used in transporting and recovering the gas itself, and the use of this gas produces CO₂. In this section an estimate is made of the amount of gas consumed during the entire resource-recovery-to-end-use process, which may be thought of as the total amount of natural gas removed from deposits less any fuel losses. [Lost gas is not burned, and thus does not produce CO₂, although it does contribute directly to the greenhouse effect. This direct contribution of methane is estimated separately. Also, the energy used to recover and ship gas that is eventually lost does produce CO₂. This is included in the total energy consumption figures used for pipelines and field operations.]

Transmission

In 1985, 0.53 trillion cubic feet (TCF) of gas was consumed in compressors and 17.79 TCF of gas was consumed by all end users, including the gas used in the compressors but excluding losses (51). Thus the ratio of ultimately combusted energy into the pipeline to useful energy out (i.e., energy that could reach the CNG or LNG station inlet, where it would be compressed or liquefied), excluding losses, is [17.79/(17.79 - 0.53)] = 1.03. This indicates a 97 percent efficiency.

Production

In 1985, 0.87 TCF was used by field-gathering and processing-plant equipment to produce 16.95 TCF of gas, including process fuel and lost gas (51). Data cited hereafter indicate that this loss is as high as 2 percent of produced gas. Therefore the ratio of gas withdrawn from the reservoir to gas put into the pipeline, excluding losses, is [16.95 - (0.02 x 16.95)]/[16.95 - 0.87 - (0.02 x 16.95)] = 1.055.

Total

The product of the production and transmission factors is 1.03 x 1.055 = 1.0867, which indicates 0.0867 unit of CO₂ produced by field operation and pipeline compressor for every unit produced by end use (including service stations). The result is thus 0.0867 x 1.11 x 0.769 = 0.074 GT CO₂/year for CNG, and 0.078 GT/year for LNG.

CH₄ Emissions

Vehicles, Pipeline, and Field Equipment

Light-duty natural gas vehicles emit 0.08 to 2.5 g/mi methane (61-64); a value of 1.2 g/mi was used. Proceeding as was done earlier in the calculation for petroleum-fueled vehicles gives 0.00235 GT/year CH₄, or 0.027 GT/year CO₂-equivalent emissions.

Emissions of unburnt methane from pipeline compressors and plant machinery would be about 8.5 percent of the 0.027 GT figure, because gas use in these applications is only about 8.5 percent of end use [(0.53 + 0.87)/(17.79 - 0.53 - 0.87)], or 0.002 GT CO₂ equivalent.

Leaks

Available data indicate that about 3 percent of the amount of gas delivered to users is lost during recovery and transportation (30, 51). Using the multiplicative factors derived earlier, 16.3 quads (1.035 x 1.03 x 1.11 x 13.5) of NG would have to be produced to fuel the CNG fleet, and 17.3 quads for LNG.
vehicles. Three percent of 16.3 and 17.3 is 0.49 and 0.52 quad, respectively, or about 0.0105 GT (using 0.50 quad). The CO₂ equivalent would be 11.6 times this, or 0.122 GT. (It is assumed that this is methane that would not have leaked from natural formations had it not been withdrawn and transported.) A negligible amount of methane would be lost from venting LNG tanks (12).

**N₂O Emissions from Electricity Production**

N₂O production from natural gas combustion is on the order of from 0.0055 to 0.01 MT/quad of NG, an order of magnitude lower than production from coal (49, 52). About 1.5 quads of gas would be burned to produce the electricity needed to compress the gas for the highway fleet, resulting in about 0.002 GT CO₂-equivalent emissions of N₂O.

**Total CO₂-Equivalent Emissions from Natural Gas Vehicles**

The grand total is calculated as follows:

<table>
<thead>
<tr>
<th>CNG</th>
<th>LNG</th>
</tr>
</thead>
<tbody>
<tr>
<td>(CO₂ from vehicles) +</td>
<td>0.746</td>
</tr>
<tr>
<td>0.027 (CH₄ emissions from vehicles) +</td>
<td>0.027</td>
</tr>
<tr>
<td>0.085 (CO₂ from compression liquefaction) +</td>
<td>0.160</td>
</tr>
<tr>
<td>0.074 (CO₂ from NG production and transmission) +</td>
<td>0.078</td>
</tr>
<tr>
<td>0.002 (CH₄ from pipeline and field equipment) +</td>
<td>0.002</td>
</tr>
<tr>
<td>0.122 (CH₄ losses) +</td>
<td>0.122</td>
</tr>
<tr>
<td>0.002 (N₂O from NG power plants) =</td>
<td></td>
</tr>
<tr>
<td>1.081 GT/year</td>
<td>1.135 GT/quad</td>
</tr>
<tr>
<td>CO₂/year</td>
<td></td>
</tr>
</tbody>
</table>

CNG vehicles would offer a reduction of 19 percent in emissions of greenhouse gases relative to gasoline and diesel fuels. The reduction with LNG vehicles would be 15 percent.

This estimate is moderately sensitive to the value of the CH₄-to-CO₂ conversion factor, which could range plausibly between 5 and 30. If 5 is used, rather than 11.6, the result is more substantial reductions of 25 and 21 percent. On the other hand, if a conversion factor of 30 is used, there will be a 4 percent decrease with CNG, and no change with LNGVs, relative to the (modified) base case (12).

**GREENHOUSE GASES FROM USE OF BIOFUELS**

In general, the carbon released by the combustion of a biofuel was removed from the atmosphere earlier by a plant, and thus the CO₂ formed by combustion about equals the CO₂ removed. However, as shown hereafter, it is still possible that the production and use of a biofuel would release net CO₂, relative to what would have occurred had the biofuel not been made.

Bioenergy Crops Replace a Forest

The difference between the amount of forest carbon released as a result of clearing a forest and the order-of-magnitude-smaller amount of carbon fixed in crops (65) constitutes a one-time net emission of CO₂. In addition, there would be a release of CO₂ from the soil as a result of the clearing (40, 65) and a large release of N₂O (66).

**Biofuels from Waste**

There is some support for the hypothesis that the long-term, steady-state rate of accumulation of carbon in organic waste material substantially exceeds the rate of its oxidation, resulting in the net removal of carbon from the atmosphere (67, 68). If this is the case, the production of biofuels would reduce the net withdrawal of CO₂ from the global cycle by humans and so cause an increase in the concentration of CO₂.

In conclusion, the use of biofuels would not contribute to the greenhouse effect, unless forest land were cleared to plant biomass feedstock, or waste products were used that otherwise would not have oxidized.

**GREENHOUSE GASES FROM HYDROGEN FUELS**

Hydrogen can be made by splitting water (electrolysis), steam-gasifying coal, steam-reforming natural gas, or partially oxidizing oil. It is likely that electrolytic hydrogen will not be produced commercially from fossil-fuel-based electricity because it is generally cheaper and more efficient to make hydrogen directly from fossil fuels than to use fossil fuels to make electricity to split water. Thus electrolytic hydrogen probably will be made from nonfossil electricity sources and will not contribute to the greenhouse effect.

Of the three fossil fuel feedstocks for hydrogen, only coal would be available in the long term in the United States. Elsewhere, the authors have estimated emissions of greenhouse gases from the mining of coal and its conversion to hydrogen (for use in transporting hydrogen and by hydrate and LH₂ vehicles) and from the use of coal-based electricity for hydrogen liquefaction and compression (12). Because hydrogen is the least promising near-term alternative fuel, the calculations are omitted here. The results of the analysis follow:

<table>
<thead>
<tr>
<th>Hydride Vehicles</th>
<th>LH₂ Vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.419 (CO₂ from coal gasification) +</td>
<td>1.155</td>
</tr>
<tr>
<td>0.946 (CO₂ from process energy) +</td>
<td>0.770</td>
</tr>
<tr>
<td>0.074 (CO₂ from coal-power for compression liquefaction) +</td>
<td>0.981</td>
</tr>
<tr>
<td>0.141 (CH₄ from coal mining) +</td>
<td>0.167</td>
</tr>
<tr>
<td>0.097 (N₂O from coal combustion) =</td>
<td>0.167</td>
</tr>
<tr>
<td>2.677 GT</td>
<td>3.240 GT</td>
</tr>
</tbody>
</table>

These represent increases of 100 percent (hydride vehicles) and 143 percent (LH₂ vehicles) with respect to current emissions from petroleum use.

**EFFECT OF TRACE GAS EMISSIONS NOT ESTIMATED**

Emissions of CFCs and ozone precursors, and N₂O emissions from vehicles, may contribute to the greenhouse effect of transportation fuels. At present, though, there are not enough data to quantify these effects for all of the alternatives. The possible greenhouse role of gases and sources not treated in the quantitative analysis is discussed here.

**CFCs**

The various CFC compounds are among the most potent of the greenhouse gases. However, the only significant source of
CFCs from highway vehicles is the air conditioning systems of scrapped automobiles. Because this contribution is independent of the fuel used, accounting for CFC emissions here would increase the total emission of greenhouse gases by the same amount for all of the alternatives, and thus would not affect absolute differences in emissions of greenhouse gases or the ranking of the alternatives.

Ozone

Ozone formation in the boundary layer due to vehicular emissions depends in large part on the quantity and reactivity of hydrocarbon emissions. [The boundary layer, sometimes called the mixed layer, is generally the first 2 km of the atmosphere. It is separated from the overlying free troposphere by a temperature inversion that prevents mixing of the contents of the boundary layer with those of the free troposphere.] Current indications are that emissions from gasoline and diesel vehicles have the greatest ozone-formation potential of the fuels considered here, followed by methanol, natural gas, electricity (assuming nighttime battery recharging), and hydrogen vehicles.

Unfortunately, differences in the ozone-formation potentials of the fuels have not yet been satisfactorily quantified. Furthermore, there is disagreement in the literature about the extent to which ground-level sources of ozone precursors ultimately affect ozone concentration above the boundary layer in the free troposphere, where ozone has the greatest impact on climate (27, 29, 69). Finally, the effect on climate of changes in the concentration of ozone is not well characterized (27, 29–31, 69). These uncertainties make it difficult to infer the climatic effect of changes in emissions of ozone precursors in the boundary layer.

N₂O

From Vehicles

Data on N₂O emissions from gasoline-burning vehicles are available, but there are no data for N₂O emissions from alternative-fueled vehicles. N₂O emissions from gasoline-fueled automobiles depend significantly on the type of catalyst, rather than on total NOx emissions or fuel nitrogen content. Cars without catalytic converters produce essentially no net N₂O.

Data on N₂O emissions from highway vehicles have been tabulated elsewhere (12, Table 3). Those data showed that N₂O emissions from cars with three-way catalysts are much higher than emissions from cars without catalysts but still relatively low—on the order of 0.02 GT CO₂ equivalent for the whole fleet in 1985 assuming replacement of uncontrolled passenger cars. It thus appears that N₂O from petroleum-fueled vehicles is relatively unimportant. N₂O emissions from alternative fuels will depend primarily on the composition of catalysts optimized for particular fuels. Such catalysts have not been developed. However, given the likelihood that N₂O emissions from petroleum vehicles are small (less than 2 percent of total CO₂-equivalent emissions calculated here), and that N₂O emissions from alternative-fueled vehicles would be of the same order of magnitude, quantification of N₂O emissions from alternative-fueled vehicles is not likely to change the findings.

From Other Sources

See DeLuchi et al. (12) for a discussion of N₂O emissions from coal gasification, NG reforming, and the corona discharge from power lines.

FINDINGS

The fuels reviewed in this paper are ranked in Table 2 by CO₂-equivalent emissions. The major findings follow.

Table 2. SUMMARY OF EMISSIONS OF GREENHOUSE GASES FROM ALTERNATIVE VEHICULAR FUELS, INCLUDING PRODUCTION, DISTRIBUTION, AND END USE OF FUEL

<table>
<thead>
<tr>
<th>Fuel/Feedstock</th>
<th>Total CO₂-Equivalent Emissions (GT/yr)</th>
<th>Change per Equivalent Mile, Relative to Petroleum (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EVs from nonfossil electric</td>
<td>0</td>
<td>-100</td>
</tr>
<tr>
<td>Hydrogen from nonfossil electric</td>
<td>0</td>
<td>-100</td>
</tr>
<tr>
<td>CNG/LNG/methanol from biomass</td>
<td>0</td>
<td>-100</td>
</tr>
<tr>
<td>2 × fleet efficiency, to 29 mpg,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>petroleum</td>
<td>0.668</td>
<td>-50</td>
</tr>
<tr>
<td>CNG from natural gas</td>
<td>1.081</td>
<td>-19</td>
</tr>
<tr>
<td>EVs from new natural gas plants</td>
<td>-d</td>
<td>-18</td>
</tr>
<tr>
<td>LNG from natural gas</td>
<td>1.135</td>
<td>-15</td>
</tr>
<tr>
<td>Methanol from natural gas</td>
<td>1.293</td>
<td>-3</td>
</tr>
<tr>
<td>EVs from current power mix</td>
<td>-d</td>
<td>-1</td>
</tr>
<tr>
<td>Gasoline and diesel from crude oil</td>
<td>1.336</td>
<td>-1</td>
</tr>
<tr>
<td>EVs from new coal plants</td>
<td>-d</td>
<td>+26</td>
</tr>
<tr>
<td>Methanol from coal, 30 percent</td>
<td></td>
<td></td>
</tr>
<tr>
<td>increased efficiency</td>
<td>2.013</td>
<td>+51</td>
</tr>
<tr>
<td>Methanol from coal, baseline</td>
<td>2.639</td>
<td>+98</td>
</tr>
<tr>
<td>Hydride from coal</td>
<td>2.677</td>
<td>+100</td>
</tr>
<tr>
<td>LH₂ from coal</td>
<td>3.240</td>
<td>+143</td>
</tr>
</tbody>
</table>

*Excludes CFCs, O₃, and vehicular N₂O. CH₄ and N₂O multiplied by 11.6 and 175, respectively, to convert to CO₂ with same temperature effect, on a mass basis.

*bIgnores greenhouse gases from energy used to mine and transport uranium for nuclear power.

*cAssumes biofuels used for process energy. Ignores greenhouse gases from soil or from changes in land use.

*dAggregate CO₂-equivalent emissions depend on the level of penetration assumed possible for EVs.

*eIgnores greenhouse gases from energy used to mine and transport uranium, N₂O emissions from NG and petroleum power plants, and CH₄ emissions from petroleum and coal power plants.

fPetroleum fuel baseline assumes 1985 total VMT and efficiency.

1. The use of coal to produce methanol, hydrogen, or synthetic natural gas would increase CO₂-equivalent emissions from the transportation sector considerably, even if conversion efficiencies were greatly improved. If the electricity to charge battery-powered electric vehicles came from new coal plants, the net result would be a moderate increase in CO₂-equivalent emissions. In all cases, the release of methane from coal mining and the production of N₂O from coal combustion would contribute significantly to the greenhouse effect of using coal as a transportation fuel feedstock.

2. The use of natural gas to produce CNG, LNG, or electricity for EVs would result in only slight to moderate reductions in CO₂-equivalent emissions. The use of natural gas as feedstock for methanol would result in approximately the same CO₂-equivalent emissions as result from using petroleum fuels.
In general, the reduction in CO$_2$-equivalent emissions with NG is not as great as might be expected, given the low carbon-to-hydrogen ratio of methane and the high efficiency of NGVs and methanol vehicles, because the greenhouse effect of methane emissions from vehicles and pipelines is significant when expressed in CO$_2$-equivalent units. Reducing leaks of methane from pipelines, storage facilities, and production operations could significantly reduce the greenhouse effect of using natural gas.

In light of the growing enthusiasm for methanol as a replacement for petroleum in transportation (6, 8, 70, 71), an important finding of this research is that a commitment to methanol from natural gas in the near term, and from coal in the long term, would worsen the threat of climatic change. Emissions of greenhouse gases would continue unabated in the near term, and increase substantially in the long term, relative to the petroleum-fuel base case.

3. Improving average fleet efficiency would reduce CO$_2$ emissions proportionately and is a viable strategy for addressing the greenhouse effect in transportation. An improvement of the average efficiency of the whole U.S. fleet, including trucks and buses, from 14.5 (in 1985) to 29 mpg would reduce CO$_2$ emissions by 50 percent.

4. There are two fuel feedstock options that do not produce net CO$_2$: biomass and nonfossil electricity. The use of biofuels would not release net CO$_2$ unless forests were cleared to plant feedstock crops or biomass was used that otherwise would have been a carbon sink. Biomass can be converted to alcohol or synthetic natural gas and thus could be used to fuel methanol or natural gas vehicles. Electricity from nuclear, solar, hydro, or geothermal power could supply EVs or be used to split water to make hydrogen fuels.

5. N$_2$O emissions from vehicles appear to be primarily a function of the chemical composition and age of the catalytic converter. The few data available indicate that N$_2$O emissions from gasoline vehicles with three-way catalytic converters are relatively unimportant.

Lack of data on the ozone-formation potential of reactive hydrocarbon and NO$_x$ emissions from alternative fuels, on the movement of ozone and ozone precursors to the upper and middle troposphere, and on the steady-state climatic response to changes in the distribution of ozone precludes quantitative estimates of the greenhouse effect of emissions of ozone precursors from highway vehicles.

RECOMMENDATIONS AND DISCUSSION

This analysis has shown that substantial long-term reductions in CO$_2$-equivalent emissions from the transportation sector can be accomplished only through the use of high-efficiency vehicles, biofuels for NGVs and methanol vehicles, or nonfossil electricity for hydrogen and electric vehicles. From a greenhouse perspective, the policy question is thus: What is holding these options back, and what can be done to encourage their adoption?

Further improvements in vehicular efficiency are being stalled primarily by low world oil prices and consumer demand for larger cars. Biofuels are very expensive and could not supply even one-half of total demand for highway fuels, at current fleet efficiency. Solar energy is very expensive (on a private cost basis), and nuclear energy is expensive and politically unpopular. Electric vehicles do not perform well enough to be used in all highway applications; hydrogen vehicles do but are very expensive (on a private cost basis), and fuel storage is still problematic. In a nutshell, current petroleum fuels are relatively cheap, alternative non-CO$_2$-producing fuels are relatively costly, on a private cost basis, and some alternative vehicular technologies have performance drawbacks. Thus two kinds of policies are needed to address these problems.

First, fuels and technologies should be priced at their social (full economic) cost, not at their private cost. Gasoline is currently the cheapest transportation fuel on a private cost basis, but the external costs of gasoline use, from air pollution to the cost of defending oil fields in the Middle East, are large. The authors have estimated elsewhere (13) that if the external costs of gasoline and diesel fuel use are at the high end of a plausible range, and the private costs of hydrogen or electric vehicles, using solar power (with essentially no external costs), are at the low end of a plausible range, the use of hydrogen and electric vehicles, where their performance is acceptable, is more economically efficient. That analysis did not attempt dollar estimates of the effects of emissions of greenhouse gases on world climate, or of the effects of policing the Middle East in the event of large-scale conflict.

Second, research and development (R&D) should be directed at fuel and vehicle combinations with low external costs, especially those that do not produce CO$_2$ or exacerbate global tensions, because these external costs are difficult to estimate but probably very large. For electric vehicles, this means R&D aimed at increasing the energy density and power of batteries, reducing battery cost, and reducing recharging time without sacrificing battery performance and life. For hydrogen vehicles, R&D should focus on increasing the mass-energy density of hydrides, reducing the desorption temperature of hydrides, increasing the no-vent period for LH$_2$ vehicles, making the handling of LH$_2$ boil-off safe, and reducing storage costs for both hydride and LH$_2$ vehicles.

For fuels, R&D money should be spent on sustainable, clean, non-CO$_2$-producing technologies that have received comparatively little funding but are technically feasible and have the potential to supply a large portion of U.S. energy consumption. This indicates that the government should generously support solar energy R&D and stimulate production with large purchases. [Federal R&D support for nuclear fission, fusion, and breeder reactors has been at least an order of magnitude larger than support for solar alternatives (72, 73). Hydrosis is a relatively mature technology and will not contribute an appreciably larger share of energy supply in the future. Therefore long-range strategies aimed at reducing CO$_2$ from the transportation sector, and indeed from all energy sectors, should focus on reducing costs of solar and renewable technologies.]

Proper pricing of petroleum fuels will encourage efficiency improvements and reduce CO$_2$ emissions proportionately, and increase national efficiency of resource use. Proper pricing combined with increased R&D on solar energy production and hydrogen and electric vehicles will hasten the efficient adoption of sustainable, environmentally sound, non-CO$_2$-producing transportation options.
REFERENCES


