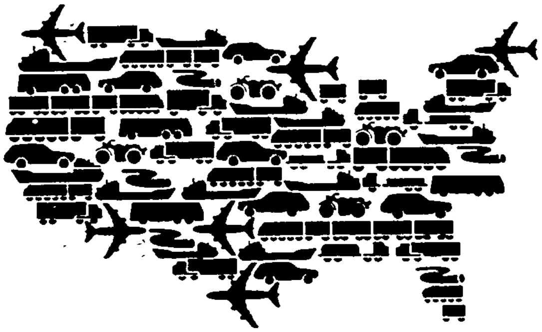
12/2-7-94 JS ①

ANL/ESD/TM-22, Vol. 2

Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity

Volume 2: Appendixes A-S



Center for Transportation Research

Argonne National Laboratory

Operated by The University of Chicago,
under Contract W-31-109-Eng-38, for the
United States Department of Energy

Argonne National Laboratory

Argonne National Laboratory, with facilities in the states of Illinois and Idaho, is owned by the United States Government, and operated by the University of Chicago under the provisions of a contract with the Department of Energy.

This technical memo is a product of Argonne's Energy Systems (ES) Division. For information on the division's scientific and engineering activities, contact:

Director, Energy Systems Division
Argonne National Laboratory
Argonne, Illinois 60439-4815
Telephone (708) 252-3724

Presented in this technical memo are preliminary results of ongoing work or work that is more limited in scope and depth than that described in formal reports issued by the ES Division.

Disclaimer

Reproduced directly from the best available copy.

Available to DOE and DOE contractors from the Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, TN 37831; prices available from (615) 576-8401.

Available to the public from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161.

ANL/ESD/TM-22, Vol. 2

Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity

Volume 2: Appendixes A-S

by M.A. DeLuchi*

Center for Transportation Research, Energy Systems Division,
Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Illinois 60439

November 1993

Work sponsored by
United States Department of Energy,
Assistant Secretary for Energy Efficiency and Renewable Energy,
Office of Transportation Technologies,
Assistant Secretary for Policy, Planning and Program Evaluation,
Office of Environmental Analysis,
United States Department of Transportation and California Department of Transportation,
University of California Transportation Center

**DeLuchi is affiliated with the Institute of Transportation Studies, University of California, Davis.*

Contents

Contents (Cont.)

Acknowledgments

This report has benefited from reviews by (in alphabetical order): Frank Black, U.S. Environmental Protection Agency; Gene Ecklund, U.S. Department of Energy; Diane Fisher, Environmental Defense Fund; David Hall, Kings College, London; Tom MacDonald, California Energy Commission; Terry Renner, Amoco Oil Corporation; Dan Santini, Argonne National Laboratory (ANL); Mai Nguyen-Misra, U.S. Environmental Protection Agency; and Stefan Unnasch, Acurex Corporation. I am grateful to Carol Wouters, Florence Henning, and Marita Moniger at ANL for editing this document, and I especially thank Dan Santini for his management skills in overseeing the publication of this report.

Most of the research for this report was supported by a dissertation grant from the University of California Transportation Center, which is funded through the U.S. Department of Transportation and the California Department of Transportation. The U.S. Department of Energy provided funds for the research, review, editing, and publication process, through its Office of Transportation Technologies, which is in the Office of Energy Efficiency and Renewable Energy, and the Office of Environmental Analysis, which is in the Office of Policy, Planning and Program Evaluation.

The estimates made within this report are my own and do not necessarily represent values that are endorsed by any of the reviewers or sponsoring organizations.

Appendix A:

Review of General Methods

Appendix A:

Review of General Methods

A.1 The General Method: What Should and What Can Be Done

The point of comparing greenhouse gas emissions from different fuels is to determine the difference in emissions that would result from choosing one fuel over another and to compare the emissions from the chosen fuel with those representing the status quo. To estimate the greenhouse effect from using an alternative fuel instead of gasoline, one must define a baseline scenario in which gasoline is used and no alternative fuels are used, and compare it with a scenario in which alternative fuels and less gasoline are used. In principle, this process is not quite as straightforward as it sounds because choosing an alternative fuel would not necessarily result in a one-for-one substitution of the alternative fuel for gasoline, with no other changes occurring.

The problem is that using X gallons of any alternative fuel would do more than just displace the production and consumption of X gallons of gasoline. First, there would be price effects: the use of an alternative fuel would reduce the demand for gasoline, which would reduce the price of gasoline, which would thereby increase demand for gasoline by inducing more travel. (Of course, if the alternative fuel were to displace all gasoline and were to be the same price as gasoline, this situation would not occur.) Technically, the extra greenhouse gas emissions from the induced travel should be assigned to the alternative-fuel policy since these emissions would hypothetically not have occurred had the alternative-fuel policy not been adopted. On the other hand, the use of an alternative fuel could have countervailing price effects. For example, the use of domestic gas to make compressed natural gas (CNG) would raise the price of gasoline; higher prices should induce conservation and therefore reduce greenhouse gas emissions in other gas-using sectors.

Second, a change in gasoline demand will change refinery operations, and because all products (including gasoline) come from a single input (crude oil), a change in the output of one product would affect the price and quantity of other products. These changes in price and output of other refinery products (diesel fuel, jet fuel, residual fuel, etc.) would affect the use of these products and thus change greenhouse gas emissions. Again, these changes in greenhouse gas emissions should be assigned to the alternative-fuel policy.

Third, the alternative fuel would have different performance and range characteristics than gasoline, and these differences would probably affect how and how much people would travel. This change in travel would, in turn, affect emissions of greenhouse gases, and these changes in emissions should be assigned to the use of the alternative fuel, in comparison with the gasoline "business-as-usual" scenario.

One could find more indirect effects. Because petroleum is such an important part of the U. S. economy, a change in the price and availability of petroleum would have repercussions throughout the economy: it would affect fuel choice, energy conservation, the substitution of capital for labor, and so on.

Modeling the macroeconomic effects of fuel substitution is beyond the scope of this analysis. I have limited my effort to an engineering-type analysis, which assumes, in effect, that using X-miles-worth of alternative fuel B means not using, distributing, refining, transporting, and recovering X-miles-worth of gasoline and crude. This simplification should not be viewed as a poor attempt at macroeconomic projection, but rather as an answer to the question, "What would be the effect of a net elimination (after all the macroeconomic and consumer adjustments) of X-miles-worth of gasoline production and use and a net increase in X-miles-worth of production and use of alternative fuel B?" I think it is useful to have an answer to this question, even if the conditions that will make it realistic are not specified. The answer is useful because at very large levels of alternative fuel use, the dominant effect on energy use and emissions is likely to be first-order displacement of gasoline.

A.2 Structure of the Greenhouse Gas Emissions Model

I use a detailed energy use and emissions model to calculate emissions of carbon monoxide (CO), methane (CH_4), nitrous oxide (N_2O), nonmethane organic compounds (NMOCs), nitrogen oxides (NO_x), and carbon dioxide (CO_2) from the use of gasoline, diesel, methanol, natural gas (CNG and liquefied natural gas [LNG]), ethanol, electric, liquefied petroleum gas (LPG), and hydrogen (liquid hydrogen [LH_2] and hydride) vehicles. The basic output of the model is given in grams of CO_2-equivalent emissions per mile of travel by the vehicle. "CO_2-equivalence" refers to the combining of emissions of all the different gases into a single index, a procedure which is explained in Appendix O. The result for electricity is given in grams of CO_2-equivalent emissions per kilowatt-hour (kWh) of electricity delivered to end users and is embedded in the result for transportation fuels.

In virtually all cases, the model calculates grams of CO_2-equivalent emissions from stage s (e.g., oil recovery) of the fuel-production-and-use cycle from use of fuel f (e.g., diesel fuel), per mile of travel, as follows:

$$G_{s,f} = En_{s,f} \times Em_{s,f} \times M \tag{A.1}$$

where:

$G_{s,f}$ = CO_2-equivalent emissions from stage s of the cycle for fuel f, in grams per mile of travel;

$En_{s,f}$ = energy use efficiency measure, in 10^6 Btu of process energy used at stage s of the cycle for fuel f, per 10^6 Btu of fuel f available to end-users;

$Em_{s,f}$ = CO_2-equivalent emissions, in grams per 10^6 Btu of process energy used at stage s of the cycle for fuel f; and

M = fuel available to the transportation sector, in 10^6 Btu per mile of travel.

Total greenhouse gas emissions per mile for the cycle for fuel f are simply the sum of the $G_{s,f}$ for all s, plus emissions from material manufacture and assembly. I discuss materials further in Appendix P.

The calculation of $En_{s,f}$, $Em_{s,f}$, and M is the main work of the model. The resultant $G_{s,f}$ values are shown in Table 9 in Volume 1 of this report. Table 3 in Volume 1 shows the values for En for the various fuels, and Table 6 in Volume 1 shows Em values. Table A.1 shows energy use in 10^6 Btu/mi for the alternative fuels relative to gasoline in the base case. Each of these is discussed in more detail next.

The one exception to the general calculation method represented by Equation A.1 is the calculation of CO_2 emissions from a natural gas-to-methanol or coal-to-methanol plant. In this

TABLE A.1 Relative Mile/10^6 Btu Fuel Economy of Alternative-Fuel Vehicles, Base Case

Gasoline vehicle (arbitrarily set to 1)	1.000
Diesel fuel vehicle (arbitrarily set to 1)	1.000
Methanol *mixture* in gasoline vehicle application[a]	1.150
Methanol in diesel vehicle application	0.970
NG in gasoline vehicle application	1.068
NG in diesel vehicle application	0.835
EV in gasoline vehicle application (EV energy from outlet)	3.473
Hydrogen (hydride) in gasoline vehicle application	1.062
Hydrogen in diesel vehicle application	0.947
Ethanol in gasoline vehicle application	1.140
Ethanol in diesel vehicle application	0.940
LPG in gasoline vehicle application	1.089
LPG in diesel vehicle application	0.849

[a] I assume that the relative efficiency of the methanol vehicle is proportional to the methanol volume content of the mixture.

Note: These values are calculated from the data in Table 2 in Volume 1 of this report.

case, CO_2 emissions are calculated as the difference between carbon in the input feedstock and carbon in the output fuel rather than as the product of an emission factor and a process-energy-consumption figure. However, emissions of non-CO_2 greenhouse gases from the plant and off-site emissions from the generation of electricity consumed by the plant are calculated as per Equation A.1. This calculation is explained in more detail in Appendix J on methanol.

A.2.1 Calculation of $E_{n,s}$: Process Energy per Unit of Fuel Energy Made Available to Consumers

The use of process energy at a stage of the cycle (e.g., feedstock recovery) per unit of fuel made available to the transportation sector is calculated in one of two ways, depending on the fuel. For coal and natural gas (NG), there are enough data on supply and disposition and the use of process energy at each stage of the extraction-to-use cycle to allow one to calculate, historically, how much of what kind of process energy is used at each stage and, for a given amount of fuel produced, how much ends up being available for end use in transportation. Thus, if one knows, for example, that in the United States in 1987, (1) X energy units of coal were produced, (2) Y energy units of coal were used to produce the electricity used at coal mines, and (3) Z units of energy of any kind (including the coal) were used in coal mining operations, then one knows that $Z/(X - Y)$ units of energy were consumed per unit of coal energy available for end use.

For methanol, hydrogen, ethanol, and synthetic natural gas (SNG), there are no such aggregate historical data on energy flows because these are quite minor fuels; consequently, the calculation must be done differently. For petroleum and uranium, there are aggregate data on the amount of process energy used at some of the stages of the cycle, but the cycles and outputs are more complex than those for NG and coal, and it is not possible to simply and directly calculate the amount of energy used at a stage of the process per unit of product fuel made available for end users.

So, for all fuels other than coal and NG including natural gas liquids (NGLs), the model first calculates the amount of process energy used to produce a unit of energy from that process, which is not necessarily the same as process energy per unit of fuel energy available to the transportation sector. The two will be different (i.e., the amount of fuel produced at any stage of the fuel-extraction-and-use system will not equal the amount that comes out of the system and is available to highway users) if, at any point in the entire fuel-extraction-and-use system, the fuel is used to process or transport itself. For example, the amount of SNG available to the highway transportation sector will be less than the amount produced if the gas is shipped via pipeline, because gas-fired pipeline compressors will consume some of the gas to run themselves, and electric-motor-driven compressors will probably draw some power from gas-fired stations. This "own use" must be accounted for.

The simplest way to account for "own use" is to multiply one ratio (process energy at stage X to energy produced at stage X) by another ratio (energy produced at stage X to energy ultimately available for consumption in the transportation end-use sector). For example, if fuel system F uses $P_1 \times 10^6$ Btu of energy (none of which is from fuel F) to produce 1.0×10^6 Btu of F, and it uses $P_2 \times 10^6$ Btu of energy (all of which is from fuel F) to distribute 1.0×10^6 Btu of F, then the ratio of production energy to fuel available for *consumption* (call this ratio E_1) can be calculated as explained in the following steps.

1. Given that the ratio of the amount of fuel F consumed in the distribution stage to the amount of F out of the distribution stage (and available for consumption) is P_2:1, the ratio of F energy consumed in the distribution stage to F energy into the distribution stage (before consumption in the distribution stage) is $P_2/(1 + P_2)$.

2. The above ratio means that distribution consumes $P_2/(1 + P_2)$ units of every 1.0 unit of F out of the production stage and into the distribution stage, a fact that, in turn, means that $1.0 - P_2/(1 + P_2)$ units of F make it out of the distribution stage and are available for consumption, given 1.0 unit out of the production stage.

3. Consequently, E_1 — the ratio of F energy produced to F energy available for consumption — is $1/[1 - P_2/(1 + P_2)]$.

4. This expression simplifies to $1 + P_2$, and thus

$$E_1 = P_1 \times (1 + P_2).$$

The correct expression or the energy intensiveness of distribution, E_2, is simply P_2, since it was assumed that no own use occurs after the distribution stage.

If P_2 was given in terms of energy into the production stage (so that P_2 was the amount of energy required to distribute 1.0 unit of F, where the 1.0 included the amount P_2), then $E_1 = P_1/(1 - P_2)$, and $E_2 = P_2/(1 - P_2)$. This method is used to calculate own use for gasoline, diesel, and residual fuel.

In general, it can be shown that if P_i units of F are used to produce 1.0 unit of F at stage i (so that the 1.0 unit output from stage i and does not include the P_i), then:

$$E_i = P_i \times (1 + P_{i+1}) \times (1 + P_{i+2}) \times (1+P_{i+3}) \ldots$$

for linear systems with no loops or feedbacks.

A final note on own use: If a tanker truck delivering fuel X also burns fuel X itself (e.g., a diesel-burning, diesel-carrying truck), then whether or not the truck's use of fuel X must be counted as own use at the fuel distribution stage depends on where the truck gets its fuel. If it fills up at service stations that are served by trucks, the truck's consumption of X must be counted as own use because, at some point, some other truck carries the fuel that the truck in question uses. Thus, in this case, if a diesel truck carries Y gallons of diesel fuel, about 0.99Y actually are available to end users outside the petroleum fuel system, because about 0.01Y will be used by other diesel-carrying trucks. However, if diesel-carrying trucks get their fuel at bulk terminals not served by trucks (bulk terminals are served primarily by pipelines and ships), none of the diesel carried by tanker trucks is used by the trucks themselves; all of it goes outside the system. Therefore, there is no own use to consider at the distribution stage.

Regardless of where the tanker gets its fuel, the tanker's use of fuel X must be counted as own use in all the preceding stages for fuel X (feedstock recovery and transport, refining, fuel distribution to the bulk terminal), because the fuel must be made, processed, etc. All that is at issue here is whether, in calculating the Btu of process energy/Btu of end-use energy intensity of the truck distribution stage, all or only nearly all of the fuel carried by a tanker counts toward Btu of end-use energy.

In practice, tanker trucks probably refuel at both service stations and storage terminals. In the analysis of the petroleum-fuel cycle, it was simplest to count all petroleum fuel consumed at the distribution stage as own use. To achieve consistency, I followed the same for own use of the other fuels at the distribution stage. Adopting a more complicated convention, in which some trucks use bulk terminals and some use service stations, would have no noticeable effect on the result: the grand total grams per mile figures would change by less than 0.01%.

I use many sources of data to calculate the amount and kind of energy used at each stage of the fuel production and use cycle. I discuss these sources and their use in the appendixes for particular fuels. Table 3 in Volume 1 shows the base-case calculated at 10^6 Btu of process energy/10^6 Btu of fuel to consumers used in this analysis. Table 5 in Volume 1 shows the breakdown of process energy, by type, at each stage of the fuel production and use cycle.

I have chosen to calculate process energy efficiencies or intensities (e.g., the energy requirements of coal mining or petroleum refining) from original data rather than finished estimates in the literature, because there are no comprehensive, up-to-date, detailed, and original estimates. One widely cited source (Aerospace Corporation, 1982, which is cited by DeLuchi et al. in *Transportation Fuels and the Greenhouse Effect*, 1987; Unnasch et al., 1989; and Ho and Renner, 1990) took its estimates of process efficiency for the NG cycle and for coal mining and preparation from a 1980 U. S. Department of Energy (DOE) report (Mertes and Hurwicz, 1980) and its estimate of the efficiency of the petroleum cycle from a 1979 Society of Automotive Engineers (SAE) paper (Alternate Fuels Committee, 1979). The 1979 SAE paper shows single efficiency numbers for each step of the petroleum cycle, with no details or references. The 1980 DOE report shows amounts and types of energy used at each stage of the fuel cycles: the data for petroleum refineries were taken from Haynes (1976, which is used as a source for this report, too); the data on energy use in the nuclear power cycle were from Rotty et al. (1975, also used here); the data for coal were from a 1976 research report; and the source of the NG data is not clear. Because more recent and disaggregated (and probably more reliable) primary data are available, I have calculated efficiencies and fuel use from scratch.

A.2.2 Calculation of $Em_{s,f}$: Grams of CO_2-Equivalent Emissions per 10^6 Btu of Process Energy Used

This is calculated as:

$$Em_{s,f} = \sum_e (Gr_e \times S_{e,s,f})$$

where:

$Em_{s,f}$ = CO_2-equivalent emissions, in grams, per 10^6 Btu of process energy used at stage s of the cycle for fuel f;

Gr_e = CO_2-equivalent emissions, in grams, from energy user e (e.g., train, tanker, pipeline compressor engine, tractor, coal-fired power plant) per 10^6 Btu of fuel consumed by energy user e; and

$S_{e,s,f}$ = total amount of energy consumed at stage s by energy user e, divided by total process energy consumed by all energy users, for the cycle for fuel f (in other words, S_e is the share of e of total process energy used at stage s).

The energy share data, $S_{e,s,f}$, are generally from the same sources that tell the total amount of process energy used at each stage of the cycle (amount of energy and kind of energy are usually reported together).

Grams of CO_2-equivalent emissions from each energy user are calculated from data on (1) the carbon and energy characteristics of the fuel used, (2) emissions of non-CO_2 greenhouse gases, and (3) emissions from the production, processing, and distribution of the process fuel itself. Table A.2 shows the calculated Gr_e.

$$Gr_e = CO2 + FC + \sum_i (G_i \times EF_i)$$

where:

CO2 = direct emissions of CO_2 from fuel combustion per 10^6 Btu of fuel consumed,

G_i = emissions of non-CO_2 greenhouse gas i (CH_4, N_2O, CO, or NMOCs) per 10^6 Btu of fuel consumed,

TABLE A.2 Greenhouse Gas Emissions from Trains, Trucks, Tankers, Pipelines, Tractors, Compressors, Wells, Engines, etc., Including Emissions from Making the Fuel, in Grams per 10^6 Btu of Fuel Input to the Device (except as noted)

Data	Diesel Trains[a]	Fuel Oil Tanker	Diesel Scrapers	Wheeled Loaders	Off-Road Trucks	Gasoline Tractor	Diesel Tractor[b]	Well Equip.	Gasoline Engine	Diesel Engine	Diesel Truck[c]	Methanol Truck[c]	Ethanol Truck[c]
Input													
CH_4	15.4	15.2	6.2	14.1	4.3	69.7	19.9	3.3	73.6	12.3	4.3	2.1	2.0
N_2O	2.0	2.0	2.0	2.0	2.0	10.0	2.0	2.0	10.0	2.0	2.6	2.5	2.4
NMHCs	147.5	136.4	87.7	150.6	64.1	513.4	218.2	42.5	689.4	133.5	88.9	220.3	187.3
CO	212.8	303.0	276.9	322.9	404.1	12112.1	389.2	425.2	14,638.6	333.9	466.4	545.5	528.7
NO_x	605.6	818.2	846.5	1051.5	936.5	561.0	1,095.6	1,635.3	379.0	1,535.3	348.3	337.8	327.4
Calculated results													
CO_2 combustion	71,566	74,188	71,678	71,386	71,558	47,872	71,053	71,595	4,333	71,428	NS	NS	NS
Non-CO_2	27,395	36,040	36,374	45,573	40,055	68,851	48,405	67,807	71,207	64,727	NS	NS	NS
Indirect energy[d]	15,0121	110,243	NE	NE	NE	NE	NE	NE	NE	NE	55,186	55,186	55,186
Making the fuel	15,964	15,474	15,964	15,964	15,964	24,956	15,964	15,964	24,956	15,964	15,964	0	0
Grand total	265,405	235,945	124,016	132,923	127,577	141,679	135,422	155,366	139,497	152,119	159,926	135,173	71,021

Data	Refinery Gas[e]	NG Turbine	NG Engine	Ethanol Plant[f]	Oil Refinery[g]	NG to MeOH[h]	Coal to MeOH[i]	Gasify Wood[j]	Wood Boiler[k]	Coal Boiler	NG Boiler	Oil Boiler	Petrol. Coke[l]
Input													
CH_4	1.3	11.2	723.5	0.2	0.4	0.4	8.3	1.8	8.1	0.7	1.3	3.0	0.0
N_2O	2.0	2.0	2.0	0.0	1.0	0.5	1.6	0.4	2.0	4.0	2.0	2.0	4.0
NMHCs	1.2	0.6	38.3	49.1	13.2	0.2	83.3	8.5	38.0	1.5	1.2	0.8	3.0
CO	15.4	49.9	187.5	42.5	8.8	1.4	7.2	60.5	271.6	13.0	15.4	15.2	30.1
NO_x	54.0	131.5	1451.5	0.0	2.8	66.9	55.6	16.9	76.1	2,27.6	54.0	152.4	225.9
Calculated results													
CO_2 combustion	56,029	53,509	51,223	0	496[m]	0[n]	0[n]	0[o]	0[o]	95,059	53,588	75,100	99,363
Non-CO_2	2,823	6,221	74,073	317	584	2,835	3,525	965	4,329	10,329	2,824	6,792	10,312
Indirect energy[d]	NE	9,133	9,133	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE
Making the fuel	0	11,115	11,115	NA	NA	NA	NA	NA	NA	9,060	11,115	15,474	NA
Grand total	58,851	79,978	145,544	317	1,079	2,835	3,525	965	4,329	114,449	67,527	97,366	109,676

Footnotes on next page.

TABLE A.2 (Cont.)

---

[a] The new Clean Air Act Amendments direct EPA to promulgate emission standards for locomotives and study whether emissions from other off-road sources should be controlled (EPA, *CAA*, 1990). I have assumed that emissions from locomotives will be reduced by 50% from the AP-42 level. I have not assumed reductions for any other sources.

[b] Diesel tractors are a proxy for all farm equipment (the actual factors are very close).

[c] The input emission factors are calculated from the data of Table B.2, to ensure internal consistency. For methanol and ethanol trucks, a zero is shown under "making the fuel," because I assume that (1) methanol-burning or ethanol-burning trucks deliver only methanol or ethanol, never diesel fuel, and (2) as discussed in the text above (with regard to the variable "FC" and double-counting, total greenhouse gas emissions from an energy user (such as a truck) include *only* direct combustion emissions and not fuel production and delivery emissions, if the fuel used by the energy user (in this case, the methanol or ethanol used by the truck) and the fuel being "processed" by the energy user (in this case, the fuel being carried by the truck) are the same. If one were to assume that methanol-burning trucks did deliver diesel fuel, however, one would have to include emissions from the production and distribution of the methanol used by those trucks *here*, because that production and distribution would not otherwise be accounted for in the crude-to-gasoline (or diesel) cycle of which the methanol-burning truck would now be a part.

[d] Emissions from energy used to build and maintain trains, tankers, trucks, and pipelines.

[e] I assume the same emission factors as those for natural-gas-fired industrial boilers.

[f] These are all emissions *other* than those from fuel combustion (which are calculated separately). Data are in units of g/10^6 Btu of products *output* from the plant. CH_4 emissions are from distillation and dehydration, and are calculated from data in USDOE, *Energy Technologies and the Environment* (1988). I assume that N_2O and NO_x emissions are produced only by fuel combustion; hence, zeros are shown here (this assumption is consistent with data shown in Sperling, 1988, and the DOE *Handbook*, 1983). CO and NMHC emissions calculated from data in Sperling (1988). I assume that the NMHC figure includes any ethanol emissions. See Appendix K.

[g] These are all emissions other than those from fuel combustion (which are calculated separately). Data are in units of gm/mmBtu of products *output* from the plant. Data on CO, NO_x, and NMHC emissions are based on the analysis in DeLuchi (1991), which uses AP-42, NEDS, NSPS, and other data to estimate controlled emissions in the year 2000. NMHC emissions include fugitive emissions, with controls. See Appendix M. Methane emissions are based on data from the Texas Air Control Board (1990), the South Coast Air Quality Management District (1990), and the EIA's *Petroleum Supply Annual.* See Appendix M. N_2O is my estimate.

[h] CO, NO_x, and NMHC emission factors are from Intech (1990). Those for N_2O and CH_4 are my estimates. See Appendix J. NO_x emissions from methanol plants are relatively high, perhpas becuase of the high temperature of steam reforming, about 1500°F. Low-temperature processes or processes using pure oxygen would have lower emissions.

[i] NMHC and NO_x factors are from Sperling (1988) for various gasification technologies. The CO factor is from Chadwick et al. (1987) for Texaco gasification. I estimate N_2O emissions from fuel combustion by using the emission factor for coal-fired industrial boilers and assuming that 20% of the input coal feed goes to the boilers (Paul, 1978; Salmon, 1986). I then assume that N_2O emissions from non-uel combustion processes are equal to emissions from fuel combustion. CH_4 emissions are estimated to be 10% of NMHC emissions. This estimate may be conservative, because CH_4 emissions from coal-burning power plants are more than 10% of NMHC emissions (Table D.4).

TABLE A.2 (Cont.)

---

[j] The NO_x emission factor is based on data in Sperling (1988; 10-190 g/10^6 Btu), the DOE *Handbook* (1983; 18 g/10^6 Btu), and DOE *Energy Technologies and the Environment* (1988; 53 g/10^6 Btu). All other emission factors, X_p, are estimated by scaling this NO_x factor by the ratio X_p/NO_x for wood boilers.

[k] All emission factors except the N_2O factor are from AP-42 for wood and waste boilers. These factors are used to estimate emissions from lignin combustion, in the wood-to-ethanol process. The NO_x emission rate shown here is well below the lowest NSPS for any industrial steam-generating unit (0.30 lb/10^6 Btu). The N_2O factor is my estimate. See Appendix K.

[l] Petroleum coke. From AP-42, third edition (1977). The latest edition does not have coke emission factors.

[m] This is CO_2 emissions from control of CO emissions from catalytic crackers. CO_2 emissions from the combustion of fuels used by the refinery (e.g., refinery gas, or fuels used to generate electricity) are calculated elsewhere, as the product of the amount of fuel used and the fuel's greenhouse gas emission factor. I assume no CO_2 is simply lost from crude. See Appendix H on petroleum for details.

[n] CO_2 emissions from the methanol plant are calculated elsewhere, as the difference between the carbon in the input feedstock and the carbon in the output fuel. See Appendix J for details. CO_2 emissions from the generation of any electricity used by the plant are calculated elsewhere, from data on the amount and kind of electricity used and electricity generation emission factors.

[o] Wood burners and ethanol plants do emit CO_2, but if the plant runs exclusively on biomass (and purchased electricity is ignored), all the CO_2 originally came from the atmosphere and so is not a net emission. Emissions from generation of any purchased electricity are counted separately.

Sources and notes: The CH_4, CO, and NMHC emission factors are from AP-42 and other EPA sources, except as noted. See the other appendixes for details. N_2O emissions from all sources that use diesel or fuel oil are assumed to be the same as N_2O emissions from fuel-oil power plants. Other N_2O emission factors are estimated on the basis of data discussed in Appendix N. With biofuels, the calculation of CO_2-equivalent emissions from CH_4, CO, and NMHCs includes a CO_2 credit; that is, the warming effect of the carbon removed as CO_2 via photosynthesis is deducted from the warming effect of the carbon emitted as CO, CH_4, or NMHC.

NA means not applicable, either because the emissions are not due to fuel use (e.g., emissions from some process areas in petroleum refineries) or because emissions from making the fuel are counted elsewhere. NE means not estimated. NS means that values are not shown here (but can be estimated from values in Table B.2).

EF_i = greenhouse-effect equivalency factor between CO_2 and non-CO_2 greenhouse gas i (Appendix O), and

FC = CO_2-equivalent emissions from fuel recovery, transport, processing, etc., per 10^6 Btu of fuel used by energy user e.

Data on the G_i are from the U. S. Environmental Protection Agency's (EPA's) *Compilation of Air Pollutant Emission Factors, Fourth Edition* (AP-42) and other EPA reports, and are discussed in Appendix M on emissions of methane and Appendix N on emissions of nitrous oxide and the appendixes on particular fuels.

The equivalency factors, EF_i, are derived in Appendix O.

The fuel-cycle emissions, FC, associated with the use of the process fuel, are calculated simply as $FC = \sum_s$, except end use $[En_{s,f} \times Em_{s,f}]$. To avoid double counting, FC is not included in the calculation of Gr_e if e uses fuel f. For example, suppose that it takes X energy units of coal and Y energy units of diesel fuel to produce all the crude oil, including the crude oil used to produce the Y units of diesel fuel, used in a particular year. To calculate the greenhouse gas emissions associated with this production of crude oil, I count emissions from the use of the coal, plus emissions from the recovery and transport of the coal, plus direct emissions from the use of the diesel fuel. However, I do not add emissions from the use of energy to recover the crude used to make the diesel fuel because, as just stated, that energy has already been accounted for: it is the coal and the diesel fuel itself. In other words, in steady state, Y units of diesel and X units of coal will yield all the crude needed, including the crude for the diesel fuel. So the energy used to recover the diesel does not need to be added; it has already been included in the coal and the diesel itself. Only direct emissions from combustion of the diesel should be counted. (There is additional energy required to refine the crude into the diesel used to recover the crude, but that energy is fully accounted for in the refining stage. In other words, in the refinery energy-use and emissions calculation, I start with that amount of energy required to refine all products, including products used to recover crude and refine crude. So, emissions from refineries that produce the diesel should not be added to direct diesel emissions in oil recovery because they are accounted for in the refinery stage.)

Note that there is a circularity here: Gr_e depends on FC, which depends on $Em_{s,f}$, which depends on Gr_e. This circularity is handled by iterative calculations in the model.

Finally, direct or combustion emissions of CO_2 are calculated simply as:

$$CO_2 = (C - C_i) \times 3.6666$$

where:

C = carbon, in g/10^6 Btu of fuel, and

C_i = carbon emitted as CH_4, CO, or NMOCs per 10^6 Btu of fuel.

Additional calculations, which I will not detail, are required to determine C and C_i.

A.2.3 Calculation of 10^6 Btu/Mile Efficiency of Vehicles

This last component is calculated first for gasoline and diesel vehicles, from miles-per-gallon (mpg) data input by the user. It is then calculated for the alternative-fuel vehicles, from data on the weight and thermal efficiency of alternative-fuel vehicles relative to gasoline and diesel-fuel vehicles. The calculation for the alternative-fuel vehicles (AFVs) is:

$$1/M_i = (1 + T_i)/(1 + Wf \times W_i/W_p) \times (MPG_p/D_p)$$

where:

M_i = efficiency of AFV i in 10^6 Btu/mi;

T_i = thermal efficiency advantage or disadvantage of fuel i when compared with petroleum fuel p,

Wf = % decrease in fuel economy per 1% increase in vehicle weight,

W_i = extra weight of AFV, i, compared with petroleum-fuel vehicle p,

W_p = total driving weight of petroleum-fuel vehicle,

MPG_p = efficiency of petroleum-fuel vehicle p in mpg, and

D_p = density of petroleum fuel p in 10^6 Btu/gal.

The estimation of these factors is discussed in Appendix B. Table A.1 shows base-case, calculated mi/10^6 Btu factors relative to gasoline and diesel.

A.2.4 Other Calculations

Sources of greenhouse gases not associated with the use of energy in the fuel production and use cycle are discussed here. The model includes detailed calculations of venting, flaring, or leaking of gas (mostly methane) from coalbeds, oil wells, and NG systems (Appendix M). It also calculates emissions from the manufacture and assembly of materials used to make vehicles (Appendix P). I examine, but do not include in the quantitative base-case results, energy used to make fuel production facilities, such as power plants and petroleum refineries (Appendix P). I include a rough estimate of the energy used to build, clean, repair, and maintain tankers, trains, trucks, and pipelines. I ignore the energy used to make the iron foundry that makes the steel for the, say, coal-fired power plant that provides power to the electric vehicle (and similarly for other third-order processes).

A.3 Higher Versus Lower Heating Values

In the literature and in personal communications, I find a growing concern about whether one should use higher or lower heating values for particular fuels in particular applications. This concern stems from the observation that the higher heating value, which includes the heat of condensation of water vapor, is not available to automotive engines because the water does not condense in the engine. On the face of it, this observation seems to suggest that one should use the lower heating value for transportation fuels.

I prove here that in a properly done analysis, the heating value does not matter at all; in fact, any heating value (higher, lower, or otherwise; indeed, any real number) for any fuel will always produce the same result. The concise demonstration of this proof is straightforward. Because the primary data used in this sort of analysis are never in thermal heating units (Btu or joules) but always in what I call "physical" units (grams, meters, miles, pounds, cubic feet, gallons, liters, and tons), and because the ultimate output is in grams per mile, it follows that one can do the entire analysis without ever using thermal heating units. If one does introduce a heating value, it must cancel out at some point, since there is no heating unit in grams per mile.

Let us explore this proof in more detail. What, ultimately, are the basic data — the ultimate observations — regarding the uses and characteristics of fuels? They are given in units such as tons of coal, barrels of oil, and standard cubic feet (SCF) of gas (where "standard" is defined unambiguously); pounds of carbon per pound of fuel and moles of carbon per moles of fuel; miles driven; and kilowatt-hours of electricity consumed. All these units are precisely, uniquely, and unambiguously defined. One can conduct the analysis entirely in these terms, without ever introducing a heating value. For example, let us consider emissions from the electric vehicle (EV) fuel cycle in which a coal-fired power plant generated power. We first need basic U. S. Bureau of the Census data on the amount of energy (in barrels of oil, SCF of natural gas, gallons of gasoline, and so on) required to produce one ton of coal. We can get data from EPA emission tests on how many grams of CO, NMOCs, NO_x, and CH_4 are emitted from burning a barrel of oil, SCF of gas, gallon of gasoline, etc., in a particular application. If we also get data on the carbon content (in pounds per barrel, pounds per SCF, etc.) of these fuels, we can calculate the amount of CO_2

emitted from burning these fuels to produce a ton of coal. By converting the non-CO_2 greenhouse gases to CO_2 equivalent emissions (Appendix O) and adding them to the CO_2 emissions, we get the CO_2-equivalent emissions of greenhouse gases emitted per ton of coal produced.

We can follow the same procedure for the coal transport stage, by using data on how many gallons of diesel fuel a train uses to transport one ton of coal one mile, how many miles the coal is transported, how much non-CO_2 greenhouse gases in grams per gallon is emitted from the train, and how much carbon is in the diesel fuel. The result is CO_2-equivalent emissions per ton of coal transported.

At the power plant stage, the fundamental item of data is not the efficiency of the power plant as a percentage but rather the observation that underlies the efficiency number: kilowatt-hour out per ton of coal in. On the basis of this kWh/ton value, pounds of emissions of non-CO_2 greenhouse gases per ton of coal input (EPA's basic emission unit), and pound of carbon/pound of coal, we can calculate CO_2-equivalent emissions. Now, however, they are in g/kWh produced from the ton of coal. All estimates in g/ton of coal can be converted into estimates in g/kWh out.

Finally, at the vehicle stage, the fundamental measurement is kilowatt-hour consumed at the outlet per mile of travel by the vehicle. If we want to derive the mi/kWh figure from the fuel economy value for a comparable gasoline vehicle, we simply compare the mi/kWh data for EVs with mpg data for the comparable gasoline vehicle (which is what I do here). With this mi/kWh figure, one can convert all estimates in g/kWh to g/mi. We now have an answer in grams of CO_2-equivalent emissions per mile of travel by the vehicle, without having ever used a thermal heating value.

Of course, if we want to display intermediate results in a common energy currency, we would have to introduce heating values. At some point, however, the heating values would cancel out. For example, let us return to the EV/coal power plant case. Suppose we want to show, as intermediate results, the amount of process energy (diesel fuel, NG, etc.) required to mine or transport one energy unit of the feedstock (coal, in this case). We would have to convert the ratio of SCF of NG per ton of coal to Btu of NG per Btu of coal, using Btu per SCF and Btu per ton values. If we were to work with these Btu/Btu values throughout the calculation (as I do here), we would have to apply a gram per 10^6 Btu of NG emission factor to the NG use in order to calculate emissions. But this g/10^6 Btu figure itself is calculated as the product of g/SCF and SCF/Btu data, so that the Btu/SCF cancels out.

$$\begin{aligned}\text{g of } CO_2 \text{ from NG/Btu of coal produced} &= (\text{g/Btu of NG}) \times (\text{Btu of NG/Btu of coal produced}) \\ &= [(\text{g/SCF of NG}) \times (\text{SCF of NG/Btu of NG})] \\ &\quad \times [(\text{Btu of NG/SCF of NG}) \times (\text{SCF of NG/ton of coal}) \times (\text{ton of coal/Btu of coal})] \\ &= (\text{g/SCF of NG}) \times (\text{SCF of NG/ton of coal}) \\ &\quad \times (\text{ton of coal/Btu of coal}) \\ &= \text{g/Btu of coal.}\end{aligned}$$

This calculation procedure shows the cancellation of the heating value expression. The basic g/10^6 Btu unit (Table 6 in Volume 1) is calculated from g/Btu (Table 6 in Volume 1) and Btu/Btu (Table 4 of Volume 1) figures, as shown in the top line above. These figures, in turn, are built from heating values (SCF of NG/Btu of NG), the SCF of NG/ton of coal rate (e.g., the raw data from the U. S. Bureau of the Census), and the g/SCF of NG emission rate (from the EPA), as shown in the second line above. However, the SCF of NG/Btu of NG figure appears in the numerator and the denominator of the second line and hence cancels out the third line. Thus, in terms of the final g/Btu of coal result (last line), it does not matter what SCF of NG/Btu of NG heating value is used. (Of course, the heating value does matter in the calculation of the intermediate energy ratio in the second line.)

In the example above, Btu of coal is left in the denominator, but only because the calculation has not been carried through to g/mi. At some point (namely, at the power plant), one will have to convert back to physical units, using Btu-coal/ton-coal, and at this point the heating values for coal cancel.

In summary, two things are clear:

- In principle, the entire g/mi calculation can be made without using a single heating value.
- If one chooses to introduce heating values to express intermediate results on energy units but still begins and ends the calculation with nonheating value physical units and uses physical units as the primary data at all steps, it does not matter what heating values are used. The grams per mile results will be the same because the heating values must cancel out. (Of course, the intermediate energy ratios depend on the heating values chosen, but the point is that the final figure of interest, grams per mile, does not.)

It is also clear that if an analyst uses somebody else's Btu/ton-mile, energy-efficiency, or mi/10^6 Btu figures rather than physical units as input data for the calculation and does not check to see how these figures were calculated, the heating value used to calculate the Btu/ton-mile, etc., might not be the same as the heating value the analyst has used to get back to physical units. In this case, there will be an error (inconsistency) in the calculation.

The conclusion, then, is that one either should do the entire calculation from scratch by using physical units or make sure that any energy efficiency values used as input were calculated from the same heating values used throughout the rest of the calculation.

I have done this here. For example, I used physical emission factors for power plants, trains, ships, cars, refineries, etc., from EPA's AP-42. For power plant thermal efficiency (Btu/kWh), I used DOE's Energy Information Administration (EIA) values, which are calculated from the same higher heating values I use here. For the transport stage, I used Rose's (1979)

Btu/ton-mile values, which again are based on the same heating values I use. I calculated the relative efficiency of electric vehicles using mi/kWh data and mpg data for comparable cars. Whenever possible, I calculated relative thermal efficiency of internal combustion engine vehicles from physical units (e.g., SCF/mi versus mpg).

A.4 Carbon Dioxide Recovery and Disposal

It is possible to remove CO_2 from flue gas (or even separate the carbon from the rest of the fuel before combustion) and dispose of the carbon. I mention a few such schemes or analyses here.

The best discussions are provided by Shell International Petroleum (1990) and Hendriks et al. (1990). They show that most of the CO_2 can be recovered from coal-fired and gas-fired power plants and integrated gasification combined-cycle (IGCC) plants and disposed of in depleted natural gas fields at relatively modest cost (resulting in a \$0.01-0.03 increase per kilowatt-hour of electricity).

Steinberg (1989) has described a HYDROCARB process for producing pure particulate carbon and a hydrogen-rich gas from carbonaceous raw materials. The raw material is hydrogenated to produce a methane-rich gas, which is thermally cracked to carbon particles and hydrogen gas. Minerals, oxygen, sulfur, and fuel nitrogen are removed. The hydrogen gas can be used as ordinary hydrogen fuel. The carbon black can be mixed with oil or water and used in conventional combustion applications, at a cost competitive with the current costs of petroleum distillates, or it can be stored as a solid as a way of sequestering or removing carbon.

The difficulty with the notion of CO_2 removal is disposal. Two disposal sinks have been suggested: drained gas fields and the deep ocean. However, not only are both of these finite sources, it is not clear that disposal in the deep ocean is permanent and otherwise ecologically neutral. In fact, it is likely that it is neither permanent nor neutral; the deep waters of the ocean reach the surface eventually, and it is not unlikely that at least some biological processes are related in some way to the CO_2 concentration of the deep ocean.

The message I am stating here is that making something and then trying to dispose of it is not the same as not making the thing in the first place. From a greenhouse perspective, a CO_2-disposal scheme should not be considered in the same light as, say, a solar energy scheme. Disposal schemes should not be seen as CO_2-elimination schemes.

Appendix B:

Emissions from Vehicles; Spills, Leaks, and Other Losses of Fuel; and Heavy-Duty and Light-Duty Emission Factors Combined

Appendix B:

Emissions from Vehicles; Spills, Leaks, and Other Losses of Fuel; and Heavy-Duty and Light-Duty Emission Factors Combined

B.1 Overview of CO_2 Emissions from Vehicles

Carbon dioxide (CO_2) emissions per mile are a function of the amount of fuel consumed per mile, the carbon content of the fuel, and the amount of the fuel carbon that is fully oxidized. The model calculates gram-per-mile (g/mi) CO_2-equivalent emissions from input and calculated data on the mi/10^6 Btu efficiency of the vehicles, the percent carbon in the fuel, the energy heating value of the fuel, the density of the fuel, and emissions per mile of non-CO_2 greenhouse gases. CO_2 is also produced by combustion of engine oil. This appendix analyzes the efficiency of alternative-fuel vehicles (AFVs) relative to petroleum internal combustion engine vehicles (ICEVs), emissions of non-CO_2 greenhouse gases, and emissions of CO_2 from engine oil. Fuel characteristics are discussed in Appendix C.

B.2 Relative Thermal Efficiency and Weight of Alternative-Fuel Vehicles

The model calculates CO_2 fuel emissions for baseline gasoline- and diesel-fuel vehicles, given the characteristics of the fuels and the efficiency of the vehicles. CO_2 emissions for the alternatives are calculated relative to the petroleum-fuel baseline by using data on the energy and carbon characteristics of the alternative fuels and the efficiency of the alternative-fuel vehicles relative to the gasoline- or diesel-fuel vehicles. The relative efficiency is a function of the relative thermal efficiency of the alternative fuel and the relative weight of the AFV. Recall from Appendix A on the review of general methods that:

$$1/M_i = (1 + T_i)/(1 + Wf \times W_i/W_p) \times (MPG_p/D_p)$$

where:

M_i = 10^6 Btu/mile efficiency of AFV, i;

T_i = thermal efficiency advantage or disadvantage of fuel, i, compared with petroleum fuel, p;

Wf = % decrease in fuel economy per 1% increase in vehicle weight;

W_i = extra weight of AFV, i, compared with petroleum-fuel vehicle, p;

W_p = total driving weight of petroleum-fuel vehicle;

MPG_p = miles-per-gallon (mpg) fuel economy of petroleum-fuel vehicle, p; and

D_p = 10^6 Btu/gallon density of petroleum fuel, p.

- *Thermal Efficiency (T_i).* Methanol, natural gas (NG), ethanol, and hydrogen can all be used more efficiently than gasoline in spark-ignition engines. However, with the possible exception of hydrogen, they are generally less efficient in single-fuel, heavy-duty engines than is diesel fuel. (The efficiency of electric vehicles relative to the efficiency of gasoline vehicles is calculated differently.) Below, in separate paragraphs for each fuel, data on T_i are reviewed.

- *Extra Weight (W_i).* The extra weight, W_i, is a function of relative fuel storage, range, power, and luggage-space requirements. These factors are analyzed for each fuel in the paragraphs below.

- *Decrease in Fuel Economy as a Function of Weight (Wf).* Several studies indicate that a 10% increase in vehicle weight causes a 5-7% decrease in efficiency, all else being equal. The calculation in DeLuchi et al. (1987) arrives at a 7% decrease for each 10% increase. Bussman's (1990) statistical analysis of U. S. Environmental Protection Agency (EPA) test data on fuel economy and vehicle weight shows that a 10% increase in weight leads to a 5.1% decrease in mpg. Amann (1990) finds that a 10% increase in weight causes a 5.7% decrease in efficiency for a fleet of cars with automatic transmissions, and Bleviss (1988) concludes that a 10% reduction in weight yields a 5.7-6.7% improvement in 55/45 combined-cycle economy. Here, I assume a 6% decrease in vehicle fuel efficiency for each 10% increase in weight.

- *Fuel Economy (MPG_p) and Driving Weight (W_p).* The mpg of the petroleum vehicle is an input variable that drives the rest of the calculation. The mpg of the base-case petroleum vehicle is meant to be the in-use, average mpg over the life of the vehicle in all driving conditions. This measure is comparable to the EPA's estimate of in-use combined city/highway mpg. I have assumed that in 2000, light-duty passenger vehicles less than five years old will average about 30 mpg in city/highway driving (on reformulated gasoline) and heavy-duty vehicles less than five years old will average about 6 mpg. These values are broadly consistent with several projections of fleet average and new-car fuel city/highway economy (EIA, *Assumptions for the Annual Energy Outlook 1990*, 1990; Energy and Environmental Analysis, 1989; Millar et al., 1985). (I specify "less than five years old" because, by 2000, most alternative-fuel vehicles will be less than five years old.) I emphasize, though, that the base-case mpg figures used here are not projections and have no special significance;

they are merely points of reference. In sensitivity analyses, I examine the effects of assuming different baseline mpgs.

All of the alternatives, except the electric vehicle (EV), are compared with the gasoline vehicle in combined city/highway driving (30 mpg). The electric vehicle is compared against the gasoline vehicle in city driving only because EVs will not be used for long highway trips. My analysis of EPA fuel economy tests indicates that a gasoline vehicle that gets 30 mpg for in-use city/highway driving gets about 24.5 mpg for in-use city driving. Therefore, the EV is compared with the baseline gasoline vehicle at 24.5 mpg (the same weight as in the 30 mpg case).

The base-case gasoline vehicle uses reformulated gasoline and has a range of 350 mi.

Given this baseline, petroleum-vehicle mpg, the model calculates the weight of the gasoline-fuel vehicle by using a statistical (descriptive) relationship between weight and fuel economy. By using a 905-vehicle sample from the EPA's 1990 mpg certification test results, Wang (1991) has estimated the following relationship:

$$W_p = 6675.54 - 167.57M_{p,u} + 1.49(M_{p,u})^2$$

$$R^2 = 0.800$$

$$\text{F statistic} = 1923.7$$

where:

W_p = inertial test weight of the petroleum-fuel vehicle (curb or empty weight plus 300 lb), in pounds, and

$M_{p,u}$ = the unadjusted, 55/45 EPA-certified fuel economy of the petroleum-fuel vehicle.

I have assumed that $M_{p,u}$ is equal to the in-use lifetime fuel economy divided by 0.8, where 0.8 represents a 20% difference between unadjusted EPA fuel economy and in-use values. Ross (1989) suggests that the EPA's 15% adjustment factor may be too low because of increasing congestion and other factors; the EIA, *Assumptions for the Annual Energy Outlook 1990*, uses a 20% adjustment factor. Refer to Table 2 in Volume 1 for base-case values.

As mentioned above, the weight and efficiency of the AFV are calculated relative to the baseline values for the petroleum-fuel vehicles. In other words, we are interested in the difference between the actual weight and efficiency of the AFV and the weight and efficiency of the petroleum-fuel vehicle that would have been bought or used instead. This point is quite important: the actual weight and efficiency of the AFV, which are a function of its actual performance and range, are the relevant factors — not the weight and efficiency that the AFV would have if it had the same performance and range as the comparable petroleum-fuel vehicle. One should not estimate greenhouse gas emissions from performance- and range-equivalent vehicles if, in fact, the AFVs will not have the same performance and range.

Again, the actual weight and efficiency of the AFV, which are a function of its actual performance and range, should be compared with the weight and efficiency of the petroleum-fuel vehicle that would have been bought instead. These two factors are related, but not in a straightforward way. Consider range: for electric, hydrogen, and NG vehicles, increasing the range is very costly; for the comparable gasoline vehicle, it is virtually free and of little consideration, up to 300-400 mi. In the foreseeable future, EVs simply will not be built to have the 350-mi range that gasoline vehicles have, and gasoline-vehicle manufacturers will not try to sell gasoline vehicles with a very short range. This situation will occur because virtually no one would be willing to pay the extra cost (in dollars, handling, performance, and lost luggage space) of increasing the range of an EV to 350 mi, but virtually everyone is willing to pay the utterly trivial cost difference between a gasoline vehicle with a 100-mi range and one with a 350-mi range. Thus, EVs will have a much shorter range than the gasoline vehicles that would have been built in their stead. To model EVs with the same range as gasoline vehicles would yield inaccurate results.

The same sort of argument applies to compressed natural gas vehicles (CNGVs), especially dual-fuel vehicles, hydrogen vehicles, and fuel-cell vehicles. Most of these vehicles will not have the same range as the gasoline vehicle. Indeed, consumers will get less utility out of the AFV because of this fact, but it is important to note that this reduced utility has no obvious effect on greenhouse gas emissions. In a cost-benefit analysis, this lost utility is critical, but in a greenhouse gas analysis, it is irrelevant because the greenhouse gas emissions are determined by the physical characteristics of the vehicles and how the vehicles are driven, not by consumer utility. (Consumer utility determines market potential, and short-range vehicles may have a limited market. This situation is, however, irrelevant to the per-mile emissions of the short-range vehicles that are actually sold and used.)

With respect to performance (which bears indirectly on relative efficiency), the situation is structured analogously, but the results are different because there is less difference between the total cost (financial and nonfinancial) of increasing the power of an AFV and the total cost of increasing the power of a petroleum-fuel vehicle than there is between the cost of increasing the range of an AFV and the cost of increasing the range of a petroleum-fuel vehicle. Hence, it is possible that a vehicle manufacturer, had it not made a CNGV, would have made either (1) a gasoline vehicle with the same size engine and better performance than the CNGV, or (2) a gasoline vehicle with a smaller engine and the same performance, or (3) both kinds of vehicles (the gasoline vehicle with the same size engine will have better performance, in part, because it will weigh less). Furthermore, had the CNGV not been available, the consumer might have picked either kind of gasoline vehicle. The outcome will depend on how much more a bigger engine costs in the CNGV than in the gasoline vehicle (where cost includes effects on efficiency and range) and the consumer demand for power.

To put this in different terms: the power and especially the range supply-cost curves (where all costs are included) are different for different vehicles, so the consumer choice (the intersection of the consumer demand curve and the supply curve) will depend on the kind of vehicle. (One could also argue, plausibly, that the demand for power and range is a function of the type of vehicle, but this violates orthodox microeconomic theory.)

The preceding discussion is important because the results of this analysis definitely indicate that alcohol vehicles have a performance and range advantage over all other AFVs, and it might be tempting to correct the greenhouse-gas estimates to a performance- and range-equivalent basis. As just argued, such a correction would be wrong. The better performance and range of alcohol and petroleum-fuel vehicles make these vehicles more marketable, but these factors do not directly affect the difference in per-mile greenhouse gas emissions between these vehicles and the worse-performing AFVs that are actually sold. We are interested in greenhouse gas emissions from vehicles as they will likely be sold, and some AFVs will be sold with inferior performance and range.

B.2.1 Methanol Light-Duty Vehicles: Thermal Efficiency

The higher octane number, wider flammability limits, faster flame speed, and higher heat of vaporization of methanol, as compared with gasoline, will allow for a higher compression ratio, shorter burn time, and leaner-burn engine, and they can theoretically increase the fuel efficiency of a methanol light-duty (LD) engine by 25% or more, compared with gasoline (EPA, *Analysis of the Economic and Environmental Effects of Methanol as an Automotive Fuel*, 1989; DeLuchi et al., 1988; Sapre, 1988; Chevron, 1985). This theoretical potential has nearly been realized in recent tests with second-generation, lean-burn, optimized M100 vehicles from Toyota and Nissan, which have demonstrated efficiency gains of 12% and 19% relative to gasoline (Hellman and Piotrowski, 1990).*

Therefore, it is reasonable to assume that fully optimized, lean-burn, M100 vehicles with a high compression ratio can be 20% or more efficient than comparable gasoline vehicles. Most of this efficiency advantage is a result of their higher compression ratio and leaner operation compared with gasoline. However, the higher compression ratio and the leaner operation increase tailpipe emissions of nitrogen oxides (NO_x), all else being equal. The higher compression ratio increases

---

* EPA tests (Hellman and Piotrowski, 1990) indicated that the Nissan methanol vehicle was 33% more efficient than the comparable gasoline vehicle provided by Nissan (the methanol and gasoline vehicle weighed the same and had the same gear ratio, but the methanol vehicle was more powerful). However, Nissan stated that it had done things to improve the efficiency of the methanol vehicle that perhaps could, in principle, have been done to the gasoline vehicle (things like using a low-friction piston design and low-friction engine oil). Nissan calculated that if one excluded the effect of these changes and counted only changes unique to the use of methanol (such as a higher compression ratio and leaner operation), the M100 vehicle would be 19% more efficient than the gasoline vehicle.

The issue is not settled, though, because Nissan implied that some of the changes it made to the methanol vehicle (but did not consider in arriving at its 19% efficiency advantage) may, in fact, be easier to make to methanol vehicles than gasoline vehicles.

the temperature in the combustion chamber, so engine-out NO_X emissions increase, and lean operation renders the reduction catalyst virtually useless. Given that the new Clean Air Act Amendments have mandated an 0.40 g/mi NO_X standard be phased in beginning in 1994 (EPA, *CAA*, 1990), the question becomes: can an advanced methanol vehicle have both a high compression ratio and lean operation (and thus be much more thermally efficient than a gasoline vehicle) and still meet an 0.40 g/mi NO_X standard?

Preliminary evidence indicates that it will be difficult for lean-burn methanol vehicles with a high compression ratio to meet the 0.40 g/mi, in-use 50,000-mi standard. In the recent EPA tests, the advanced lean-burn Toyota (11:1 compression ratio) emitted 0.49 g/mi NO_X at low mileage, and the advanced lean-burn Nissan (12:1 compression ratio) emitted 0.56 g/mi, also at low mileage (Hellman and Piotrowski, 1991). These vehicles will emit more in-use, and more at 50,000 mi. A lean-burn M100 vehicle (11.5:1 compression ratio) tested by Toyota emitted 0.40 g/mi at 0 mi but deteriorated to 0.70 g/mi at 30,000 mi (Tsukasaki et al., 1990). A lean-burn Toyota Corolla demonstrated low NO_X emissions (0.31 g/mi) at low-mileage (Yasuda et al., 1989), but NO_X emissions at high-mileage were not determined (this vehicle uses two catalytic converters). A lean-burn Toyota Camry emitted very high NO_X levels when run lean (CARB, 1988).

Current evidence indicates that methanol engines may have to forego either lean operation or a high compression ratio in order to meet an 0.40 g/mi NO_X standard. They will probably give up lean operation rather than the high compression ratio because running lean increases NO_X emissions much more than does increasing the compression ratio (the NO_X reduction catalyst, which in effect is trying to increase the concentration of oxygen in the exhaust stream, does not function in an oxygen-rich, or lean, regime), and because the high compression ratio also boosts power, whereas lean operation decreases power.

If methanol vehicles must operate at a stoichiometric air-fuel mixture in order to satisfy the 0.40 g/mi standard, they will forego a substantial part of the potential 20-30% efficiency gain. Chevron (1985) estimates that lean-burn alone improves fuel efficiency by 10%, so that a methanol vehicle operating at stoichiometric will be 10-20% more efficient than a comparable gasoline vehicle (rather than 20-30% more efficient). In support of this statement, I note that first-generation, non-lean-burn methanol vehicles generally have been less than 10% more efficient than their gasoline counterparts (DeLuchi et al., 1988; McGill and Hillis, 1988).

The Clean Air Act Amendments of 1990 require the EPA to study the cost and necessity of tightening tailpipe standards further, to perhaps 0.20 g/mi in the case of NO_X. It is very unlikely that a lean-burn methanol or gasoline vehicle will be able to meet a 0.20 g/mi in-use NO_X standard at 50,000 mi.

Finally, note that even if lean-burn methanol vehicles can meet a 0.40 g/mi NO_X standard, they will have a lean-burn efficiency advantage over gasoline vehicles only if gasoline vehicles cannot also operate lean and still meet the 0.40 g/mi NO_X standard, or if gasoline vehicles do not operate as lean as methanol vehicles (which is likely because of the lower lean limit of methanol engines). It will be harder for lean-burn gasoline vehicles than for lean-burn methanol vehicles to meet the 0.40 g/mi NO_X standard because methanol's lower flame temperature, shorter burn time, higher latent heat of evaporation, and leaner lean limit result in lower engine-out emissions. (These factors probably more than compensate for the higher engine-out NO_X emissions caused by the higher compression ratio of the methanol vehicle.)

Preliminary studies indicate that it will be very difficult for lean-burn gasoline vehicles to meet a 0.40 g/mi standard. Diwell et al. (1988) tried to reduce NO_X emissions from lean-burn gasoline engines by maximizing NO_X reduction during rich transients and sustaining some NO_X reduction during lean steady-state operation. However, the catalyst converted only 10% of NO_X emissions during lean operation; overall, it reduced NO_X emissions only 20-30% compared with uncontrolled emissions — not nearly enough to bring emissions down to 0.40 g/mi. Held et al. (1990) experimented with different catalyst materials and selective catalytic reduction with lean-burn operation and converted up to 45% of NO_X emissions, but they concluded that NO_X emissions from lean-burn gasoline engines could not be brought to the level of emissions from a current stochiometric gasoline engine (meeting a 1.00 g/mi standard).

In summary, for a methanol vehicle to be 20+% more efficient than a gasoline vehicle, the methanol vehicle must be able, and the gasoline vehicle unable, to operate lean and still meet a 0.40 g/mi, in-use, 50,000-mi NO_X standard, and possibly a 0.20 g/mi NO_X standard. This situation is improbable, because it will be hard for both vehicles (albeit harder for the gasoline vehicle) to meet the standard and run lean. Therefore, I assume a base-case efficiency improvement of 15% for advanced, dedicated, non-lean-burn M100 vehicles meeting a 0.40 g/mi NO_X standard.

However, because relative fuel efficiency is such an important yet still uncertain variable, I consider higher and lower values in the scenario analyses. The higher value corresponds to a scenario in which advanced lean-burn vehicles are able to meet a stringent in-use NO_X standard and gasoline vehicles cannot.

B.2.2 Light-Duty Methanol Vehicles: Relative Weight

The relative weight of methanol vehicles will depend on how manufacturers and consumers handle the different range and power potential of methanol vehicles.

Consider power first. It is well-established, theoretically and in practice, that methanol LD vehicles will be about 15% more powerful than their gasoline counterparts because of the higher octane number and higher latent heat of vaporization of methanol (DeLuchi et al., 1988; Sapre, 1988). How these factors determine the weight difference between the methanol and the gasoline vehicle depends on whether the manufacturer would have built and sold a gasoline vehicle with the same size and weight engine (the gasoline vehicle performs worse than the methanol vehicle) or a vehicle with a larger engine providing equal performance. According to one manufacturer, the larger engine providing equal performance would weigh about 50 lb more than the methanol engine. Hence, the potential power increase with methanol could result in either no change in vehicle weight or a 50-lb difference. If one believes that consumer demand is completely independent of industry offering and advertising (i.e., that consumers should have the same demand for power in the with-methanol and without-methanol scenarios), the 50-lb difference scenario is correct (the methanol vehicle weighs 50 lb less).

However, methanol vehicles will not go as far as gasoline vehicles on a gallon of fuel. If manufacturers build methanol vehicles to have the same range as the gasoline vehicles they would have built (i.e., if consumers are willing to pay for the small extra cost of maintaining gasoline-vehicle-type range in a methanol vehicle), the methanol vehicle tank will be about 50-60 lb heavier than the gasoline vehicle tank when full (Table 2 in Volume 1 of this report) and 30-40 lb heavier on average (assuming that the tank is 60% full and accounting for the constant extra weight of the tank itself).

Thus, there are four possible outcomes: two engine outcomes (the methanol engine weighs the same or is 50 lb lighter), permutated with 2 tank outcomes (the methanol tank weighs the same or is 30-40 lb heavier). I believe that it is most likely that methanol vehicles will be about 20 lb lighter than the gasoline vehicles that would have been sold instead. This 20-lb decrease will improve fuel economy by about 0.5%. This 0.5% is well within the uncertainty of the 15% thermal efficiency advantage estimated above, so it can be ignored.

B.2.3 Flexible-Fuel Methanol/Gasoline Vehicles

Flexible-fuel vehicles will show much less of an efficiency gain when they run on methanol, because their engines cannot be fully optimized for methanol. I assume a gain of 5% in the base case, because of the faster flame speed, lower flame temperature, and higher heat of vaporization of methanol.

B.2.4 Methanol Heavy-Duty Vehicles

Methanol can be used in heavy-duty (HD) engines in two basic ways: (1) with diesel fuel in an essentially unmodified, dual-fuel, diesel engine; or (2) in a modified, spark-assisted or spark-ignited, monofuel, methanol, HD engine (IEA, *Substitute Fuels for Road Transport*, 1990).

Dual-fuel engines must use mostly diesel fuel at start-up and part load because of the poor autoignition properties of methanol (unless excellent ignition-enhancing compounds for methanol are found). Because dual-fuel engines rely partly on petroleum, they are not as attractive from an energy security or environmental standpoint and are probably, at most, an interim step toward single-fuel engines. For these reasons, most research is focusing on methanol-only, heavy-duty engines. Accordingly, I do not establish and estimate a case explicitly for dual-fuel methanol heavy-duty vehicles (HDVs). However, the efficiency of methanol use in dual-fuel HDVs is likely to be similar to the efficiency of methanol use in advanced, spark-assisted, monofuel methanol HDVs, and so the best case for spark-assisted methanol HDVs can be viewed as the base case for dual-fuel methanol HDVs.

Although most current-technology, spark-assisted methanol HDVs are less efficient (in some cases much less efficient) than their diesel HD counterparts primarily because of the lower compression ratio of spark-assisted engines compared with that of compression-ignition diesel engines (New York City, 1989; DeLuchi et al., 1988; Santini et al., 1989; King and Bol, 1988), the technology is still developing, and further engine optimization will improve thermal efficiency. Researchers expect improved methanol HDVs to be nearly as thermally efficient as diesel vehicles, except perhaps at low speeds in start-stop city driving (IEA, *Substitute Fuels for Road Transport*, 1990; Santini et al., 1989). The U. S. Department of Energy (DOE, 1990) projects that methanol HDVs will be only 3-5% less efficient than HD diesel vehicles. In support of these projections, Eberhard et al. (1990) recently reported that a 1988 glow-plug Detroit Diesel Corporation (DDC) methanol engine was roughly as efficient as its diesel counterpart in transient testing, and the International Energy Agency (IEA, 1990) reported that a German MAN stratified-charge, spark-ignited methanol engine is 5% more efficient than a comparable diesel engine.

If diesel-fuel vehicles have to use a trap oxidizer, the back pressure will reduce efficiency and improve the relative efficiency of the methanol vehicle. NO_X control down to the new CAA standard may also reduce efficiency.

On the basis of these considerations and the assumption that methanol is used heavily in buses (the new CAA amendments call for low-polluting fuels in buses), I assume that methanol HDVs will be almost, but not quite, as efficient as diesel HDVs, on average.

Finally, I assume that HD methanol vehicles will weigh the same as their HD diesel counterparts.

B.2.5 Natural Gas Light-Duty Vehicles: Thermal Efficiency

Natural gas's very high octane number (which allows for a high compression ratio), wide flammability limits (which permit lean operation), and gaseous state (which reduces fuel consumption during cold-start) can give it a large efficiency advantage when used in dedicated light-duty vehicles (LDVs) (DeLuchi et al., 1988, and EPA, 1990, *Analysis of the Economic and Environmental Effects of Compressed Natural Gas as a Vehicle Fuel*, Volume 1). However, NG has a slower flame speed than gasoline, which means that the heat release from NG combustion is more "spread out" over the piston stroke and less concentrated at or near top dead center, where the heat release is used most effectively. This factor reduces thermal efficiency. The use of fast-burn combustion chambers may be able to compensate partially for this.

Thus, a fully-optimized, lean-burn, fast-burn dedicated natural gas vehicle (NGV) with a very high compression ratio will be more thermally efficient than a stoichiometric gasoline vehicle, although probably not as efficient as a methanol vehicle. The thermal efficiency advantage could be as high as 20% (DeLuchi et al., 1988). Indeed, some engine tests with NG have shown large increases in thermal efficiency. Most vehicle tests have not; however, no advanced, lean-burn, fast-burn, electronically controlled vehicles have been built. The IEA (*Substitute Fuels for Road Transport*, 1990) estimates that NGVs should be 13.3% more efficient than gasoline vehicles, in part because of higher efficiency at warm-up.

The key issue, as with methanol, is the effect of the tight new NO_X standard on efficiency. It probably will be at least as hard for lean-burn, high-compression-ratio NGVs to meet an 0.40 g/mi, in-use 50,000-mi NO_X standard as it will be for methanol vehicles: the longer burn time and higher compression ratio of NG engines will increase engine-out emissions compared with those of methanol engines. Therefore, I assume in the base case that NGVs cannot operate lean. However, no one has built an optimized, lean-burn, fast-burn, low-NO_X engine (with, say, only a moderately increased compression ratio and with extensive use of exhaust-gas recirculation), and it is not impossible that an NGV could retain a substantial efficiency advantage and still meet the NO_X standard. I consider this possibility in a scenario analysis (as I do with methanol).

However, it is not even clear if an optimized NGV can operate at stoichiometry (as opposed to slightly rich) and with a high compression ratio (CR) and still meet the 0.40 g/mi standard. NGVs may have to forego a very high CR (and sacrifice performance and efficiency) to reduce engine-out NO_X, and NGVs may have to operate slightly rich to make the reduction catalyst more effective. (An NGV tested by Gabele [1990] had to be run slightly rich to reduce NO_X emissions because the NGV did not produce enough reactive hydrocarbons to aid reduction over the catalyst.) An NGV operated slightly rich and with the same CR as a gasoline vehicle would not be more efficient than a gasoline vehicle and could be less efficient, depending on the play of the opposing factors: rich operation and burn time (which is affected by chamber design) on the one hand, and warm-up efficiency on the other.

The lack of fully optimized, low-NO_X NGVs and the wide range of opposing theoretical considerations make it very difficult to estimate the relative efficiency of an NGV. In the base case, I assume that advanced, dedicated CNGVs will operate at stoichiometry, with a high-compression ratio and fast-burn combustion chamber and will achieve a 10% thermal efficiency advantage while meeting the 0.40 g/mi NO_X standard. Liquefied natural gas vehicles (LNGVs) will be slightly more efficient because of the cooling effect of liquefied natural gas (LNG).

B.2.6 Natural Gas Vehicles: Relative Weight

The extra weight of LD NGVs is a function of three factors: (1) the relative weight of the fuel storage equipment, (2) the relative weight of the extra vehicle structure needed to support the tanks or extend the vehicle to preserve trunk space, and (3) the relative weight of the engine.

Table 2 in Volume 1 documents the assumptions used here regarding the weight of the compressed natural gas (CNG) and LNG storage system. Fiberglass-wrapped aluminum tanks providing a 250-mi range in a high-mileage vehicle using CNG will weigh more than 100 lb more than the gasoline tank they replace (DeLuchi et al., 1988). Kevlar wrap would reduce the weight but would increase the cost. An LNG system would be only 50 lb heavier than an equal-range gasoline tank, which is one of several advantages of using LNG as a fuel.

Note that the weight of the NG storage system is a function of the assumed range of the vehicle. Because the weight of the CNGV is sensitive to the range, I consider lower and higher ranges in a scenario analysis.

The CNGVs will either have less trunk space than the comparable gasoline vehicles or they will be extended, and thus made heavier, to accommodate the CNG tanks. I expect that CNGVs will have less trunk space (again, this will affect their marketability, but not their relative greenhouse gas emissions). LNG systems do not have so great a disadvantage in this regard since they are half the size of CNG systems for a given range and weigh about the same as methanol tanks (DeLuchi et al., 1988).

The CNG storage system weight factor in Table 2 in Volume 1 includes the weight of mounting brackets and modest structural reinforcement to the vehicle.

The last weight factor in the LD NGV analysis is the engine. It appears that a fully optimized, single-fuel LD CNG engine with a very high compression ratio, fast-burn chamber, and improved breathing characteristics will be at least as powerful as an equal-weight gasoline counterpart (DeLuchi et al., 1988). However, overall performance is a function of weight as well as vehicle power, and CNGVs will weigh about 5% more than gasoline vehicles. Thus, CNGVs will, in the best case, offer performance comparable to the gasoline vehicle with a similar weight engine. In any case, the dedicated, optimized CNGV is not likely to perform so much worse than the gasoline vehicle that it would be worth worrying about what size gasoline engine would have been built and bought in the no-CNG scenario. Thus, in the base case, I assume no significant weight difference on the engine side.

However, if the CNGV cannot use a very high compression ratio because of the tight new NO_X standard, the difference in power may become significant enough that the purchaser might have bought a gasoline vehicle with a significantly smaller engine, had he not bought the CNGV. I consider this in a scenario analysis.

The LNGVs have another advantage: less fuel storage weight for the engine to compensate for, on the one hand, and an inherently more powerful engine because of the charge-condensing effect of cold LNG, on the other. Therefore, it is possible that an LNG engine could be slightly lighter than a gasoline engine providing the equal acceleration. In the base case, I assume no extra weight in the engine compartment for LD LNGVs.

B.2.7 Dual-Fuel Natural Gas/Gasoline Vehicles

I assume that dual-fuel NG/gasoline vehicles will be as thermally efficient on NG as a dedicated gasoline vehicle on gasoline (i.e., no efficiency gain or loss). I assume that a vehicle has a 150-mi range on CNG and estimate the weight increase accordingly.

In the base case for dual-fuel, I do not make any adjustments for the lower power of dual-fuel vehicles on CNG because dual-fuel vehicles will most likely have less power when on CNG and be used by people who are willing to tolerate the power loss in order to be able to use CNG. (If this were a cost-benefit analysis, it would be important to account for the power loss, but in a greenhouse analysis, it is not important (if people simply are tolerating the power loss) because, as discussed above, emissions depend on the performance characteristics of the vehicles actually sold and used, not on consumer valuation of the characteristics.)

It could be argued, however, that the consumers who use dual-fuel CNG vehicles would have bought a dedicated gasoline vehicle that would have been much less powerful than the actual gasoline version of the dual-fuel vehicle, and hence that the dual-fuel vehicle would have a bigger, heavier engine than the gasoline vehicle they would have bought. This argument would be true if three conditions were met: (1) if the consumer were choosing between a dual-fuel vehicle and a dedicated gasoline vehicle (because if the consumer were deciding whether to convert a vehicle he or she already bought, and if he or she had not considered conversion at the time of purchase, then the engine size would be the same whether the consumer ends up with a dual-fuel vehicle or not); (2) if the dedicated gasoline vehicle were to come with a range of engine sizes, with all else being equal; and (3) if the consumer was not willing to pay much for extra power in a dedicated gasoline vehicle. In this scenario, the dual-fuel engine would be heavier than the dedicated engine that would have been bought. I consider this in a scenario analysis.

Finally, I note that it is not reasonable, in any case, to model the dual-fuel CNG vehicle to have the same range on CNG that the comparable dedicated gasoline vehicle has on gasoline. The dual-fuel CNG vehicle simply will not have the same range on CNG, and the greenhouse gas emissions from the gasoline vehicle that would have been bought (or remain unconverted) are not sensitive to range (see discussion above).

B.2.8 Compressed Natural Gas Heavy-Duty Vehicles

In spark-ignition, heavy-duty engines, CNG can be used in place of either gasoline in spark-ignition HDVs or diesel-cycle HDVs. A CNG spark-ignited HDV will be more thermally efficient than a spark-ignition HDV primarily because of the higher compression ratio possible on CNG. However, a CNG spark-ignited HDV will be less thermally efficient than a comparable diesel-cycle engine because the diesel cycle uses a higher compression ratio. In a recent analysis, the EPA (1990, *Analysis of the Economic and Environmental Effects of Compressed Natural Gas as a Vehicle Fuel*, Volume 2) projects that an optimized, lean-burn, spark-ignited NG HD engine will be 25% less thermally efficient than a comparable diesel-cycle engine. However, other investigators estimate a lower efficiency loss: Goetz et al. (1988) report an 18% drop with bus engines, Lawson (1988) reports a loss of 10-20% for a Cummins L10, and unpublished EPA data indicate a loss of 13%. Similarly, Rele and Seppen (1990) and Klimstra (1990) remark that gas engines are 15% less efficient than diesel engines.

Natural gas, like methanol, can be used with diesel fuel in dual-fuel HD engines. Diesel fuel is used to start the engine and is the primary fuel at part load. Because of this reliance on diesel fuel, dual-fuel NG HDVs are not as attractive as single-fuel, spark-ignited NG HDVs with respect to environmental considerations or energy security. Most work in the United States is on the single-fuel use of NG in HDVs. Consequently, I do not establish and estimate a case for dual-fuel NG HDVs. However, assuming that the efficiency of NG use in dual-fuel HDVs will be similar to the best-case efficiency of NG use in optimized single-fuel engines, the best case for single-fuel NG HDVs can be viewed as the base case for dual-fuel NG HDVs.

For a heavy-duty NG vehicle, the change in weight due to redesigning and resizing the engine for an alternative fuel would be so small, relative to total vehicle weight, it would be insignificant. Therefore, I have ignored the weight differences associated with HD engines. For CNG heavy-duty vehicles, I have included the effects of the extra weight of the storage tanks. If LNG is used (LNG is a perfectly viable fuel for HDVs) the weight increase will be as it is inconsequential as it is with methanol.

B.2.9 Ethanol Vehicles: Relative Thermal Efficiency and Weight

Ferchak and Pye (1981, Part II) cite seven studies that show that a gallon of ethanol can drive a vehicle as far as a gallon of gasoline. This implies that ethanol use is about 45% more thermally efficient than gasoline use, a figure which seems improbably high, even for fully optimized vehicles (I have not consulted the original references). Lynd (1989) cites several studies that estimate a 23-40% advantage for methanol and, in more recent work, reports that ethanol is expected to be slightly less efficient than methanol. Wyman and Hinman (1990) cite vehicle tests that indicate an advantage of about 20%.

Recently, the EPA (1990, *Analysis of the Economic and Environmental Effects of Ethanol as an Automotive Fuel*) analyzed the relative efficiency of ethanol engines and concluded that ethanol vehicles should show nearly the same overall efficiency improvement over gasoline that methanol vehicles show, up to 30%. Methanol will have a slight 1-2% absolute advantage over ethanol: the stoichiometric combustion of methanol results in a higher post-combustion pressure than does the stoichiometric combustion of ethanol because of the greater number of gaseous moles formed by methanol combustion. I follow the EPA and Lynd (1989) and assume that ethanol vehicles are nearly as thermally efficient as methanol vehicles. I also assume that, like methanol vehicles, ethanol vehicles will weigh roughly the same as the gasoline vehicles they replace. I also assume that ethanol will be similar to methanol in heavy-duty applications.

B.2.10 Electric Vehicles

B.2.10.1 General Information

The mile/10^6 Btu energy consumption of electric vehicles is calculated as:

$$E_{ev} = E_g \times E_b \times E_r \times W \times R_p$$

where:

E_{ev} = mi/10^6 Btu efficiency of the electric vehicle (counting from the outlet, using 3412 Btu/kWh);

E_g = mi/10^6 Btu efficiency of the gasoline vehicle;

E_b = energy out/energy in efficiency of the battery;

E_r = energy out/energy in efficiency of battery recharging;

W = factor to account for the extra weight of the electric vehicle;

R_p = mi/10^6 Btu battery-to-road energy consumption of the EV divided by the mi/10^6 Btu gasoline-tank-to road energy consumption of the ICEV in urban driving when the weight difference between the EV and the ICEV is netted out .

These variables are treated as follows:

The variable E_g is calculated from the baseline mpg of the gasoline vehicle (24.5 mpg in city driving, not 30 mpg in combined city/highway driving).

The variables E_b and E_r depend on the battery; typical values for sodium/sulfur batteries are 0.75 and 0.92 (DeLuchi et al., 1989; Auxer, 1991). The effect of varying these is considered in sensitivity analyses. (For example, developers of the Na/S battery project higher performance and efficiency values for the year 2000 than those used here.) For general discussions of advanced batteries, see DOE (1990), Shemmans et al. (1990), Sera et al. (1990), and DeLuchi et al. (1989).

Continual shallow discharging of batteries may reduce their efficiency (USDOE, August 1990). Hence, if most EV owners recharge their batteries after driving only a few miles, if advanced batteries lose efficiency after repeated shallow discharging, and if there is no technical way to prevent the loss of efficiency due to shallow discharges, then average battery efficiency may be less than is estimated here. I consider this situation in a scenario analysis.

The variable W is calculated from the extra weight of the vehicle and the factor relating extra weight to efficiency. The extra weight is calculated from data on the energy density of the battery and the desired range. A separate EV model is used for this calculation; some details of this model are given in DeLuchi et al. (1989). The resultant extra weight is shown in Table 2 in Volume 1.

The variable R_p, which is the ratio of mi/10^6 Btu vehicle energy consumption in urban driving, is an important variable. The best way to estimate it is to compare the mi/10^6 Btu efficiency of EVs with that of comparable ICEVs, netting out the effect of weight (which is captured separately by W). Because the greenhouse standing of EVs relative to ICEVs depends so much on the relative energy consumption of the EV and the ICEV, one must analyze R_p as carefully as possible. Table B.1 shows such a detailed analysis of R_p, calculated as:

$$R_p = (EV_{eff} \times (0.4 + 0.6EV_{wt}/ICEV_{wt})/3412)/(mpg/125{,}000)$$

where:

EV_{eff} = mi/kWh energy consumption from the battery terminals (Table B.1),

0.6 = 6% increase in efficiency for each 10% decrease in weight,

EV_{wt} = test weight of the EV (Table B.1),

$ICEV_{wt}$ = test weight of the ICEV (Table B.1),

3412 = Btu/kWh,

mpg = fuel economy of comparable gasoline vehicle (Table B.1), and

125,000 = Btu/gal of gasoline.

I choose my base-case value of $R_p = 5.7$ (for city driving) on the basis of the results in Table B.1. I study the effect of changing this variable in sensitivity analyses. An R_p of about 5.7 is consistent with an ICEV engine-and-drivetrain efficiency of 14% and an EV motor-and-drivetrain efficiency of about 80%, which are typical values (see note o, Table B.1).

In the base case, I compare the efficiency of EVs in urban driving with the efficiency of ICEVs in urban driving because EVs are likely to be used primarily for short trips in urban or

TABLE B.1 Ratio of Energy Consumption of Electric Vehicles to Energy Consumption of Comparable Internal Combustion Engine Vehicles for City Driving

	EV				ICEV				Result (R_p)	
	Energy Cons. (mi/kWh)					Energy Use				
Type of EV	Battery	Outlet	Test[a]	Test Wt.\ Battery Wt.	Vehicle Comparable to EV	Test Wt.	mpg	Test	Vehicle Efficiency EV/ICEV	Notes
ELVEC-EV	(4.13)	2.79	SAE D	3,600\992	Subcompact	2,300	33.0	FUDS	6.1	b
Audi	2.30	1.38	City	4,630\1,100	Audi 100	3,500	16.8	City	6.0	c
ETV-1	3.41	- -	FUDS	3,960\1,090	'79 Ply. Horizon	2,500	27.6	FUDS	6.1	d
ETV-2	3.14	- -	FUDS	3,920\1,066	'79 BMW 320i	2,750	26.0	FUDS	5.6	e
Yr 2000 EV	(4.63)	3.33	SAE D	2,560\400	Year 2000 ICEV	2,110	35.6	FUDS	5.4	f
City STROMer	3.51	2.07	SAE C	3,671\ --	'85 VW Golf GTI	2,500	28.3	FUDS	5.8	g
Griffon van	(1.66)	1.03	Urban	6,775\2,500+	'84 GMC vans	4,200	17.5	FUDS	4.8	h
4-seat BMW	(3.73)	2.35	ECE	3,600\584	'86 BMW 3 series	3,100	27.0	Comb.	5.6	i
ETX-I	2.99	- -	FUDS	3,800\1,237	'83 Ford Escort	2,500	28.0	FUDS	5.1	j
ETX-II	2.5	- -	FUDS	4,500\1,100	'88 Ford Aerostar	3,500	18.0	FUDS	6.0	k
G-van	1.77	- -	SAE D	7,780\2,540	'89 GM G-van	4,750	17.0	FUDS	5.3	l
TEVan	3.31	- -	FUDS	4,948\1,770	'89 T115 minivan	3,500	23.0	FUDS	6.6	m
DSEP	2.58	- -	FUDS	5,300\1,600	'89 stretched T115	3,850	20.0	FUDS	5.8	n
Average:									5.7	
Average without highest and lowest values:									5.7	
Ratio based on component-by-component efficiency:									5 to 6	o

EV battery efficiencies shown in parentheses were calculated by dividing the reported efficiency from the outlet by the combined efficiency of the charger and the battery, as reported in the reference.

Battery weight is included so that one can check if EV test weight less battery weight is close to ICEV test weight, which it should be.

[a] FUDS is the Federal Urban Drive Schedule, which is used by the EPA to measure "city" fuel economy. I use the unadjusted EPA city fuel economy, for proper comparison with the unadjusted SAE test results. The SAE cycles are urban test cycles designed specifically for EVs. The SAE D cycle has higher average speed and power than the FUDS, but lower maximum speed and power. The SAE C cycle is less demanding than the SAE D cycle. The European ECE cycle is a composite of FUDs and the U. S. highway cycle

TABLE B.1 (Cont.)

---

[b] EV characteristics from an EV simulation model called "ELVEC" (Hamilton, 1980). The ICEV and EV were assumed to have equal payload volume, payload, and acceleration times. The EV is assumed to have a range of 100 miles in a the SAE J227a/D cycle. Hamilton (1980) gives 2.79 from the outlet, including regenerative braking, and specifies 0.90 charger efficiency and 0.75 battery efficiency. Weight and efficiency of ICEV as specified by Hamilton.

[c] EV data from Mueller and Wouk (1980, SAE #800204), who reported 1.38 mi/kWh from the outlet in what apparently was a test in urban traffic. They calculate energy use from the batteries by assuming a combined 60% efficiency for the battery and the charger. The fuel economy for the Audi ICEV was reported in Mueller and Wouk (1980, SAE #800109), for driving in city traffic. It is not clear if the vehicle had regenerative braking.

[d] ETV-1 data from Kurtz (1981). Weight and efficiency of Horizon ICEV from 1979 EPA emissions and fuel economy test data, with the following adjustment: the ETV-1 had exceptionally low aerodynamic drag. I assume that if the Horizon ICEV had the same low coefficient of drag, fuel economy the city cycle would have been 15% higher than as measured by the EPA in 1979 (24 mpg). The ETV-1 was 11% more efficient in the SAE D cycle than the FUDS cycle. Efficiency estimate for ETV-1 accounts for about 13% energy returned to battery by regenerative braking.

[e] ETV-2 data from AiResearch (1981). The ETV-2 used a flywheel to improve acceleration and increase range. Energy from regenerative braking went to the flywheel rather than the battery. In the SAE D cycle, the ETV-2 achieved 3.64 mi/kWh, 16% better than in the FUDS. The authors state that the ETV-2 was comparable to a BMW 320i; I assume 1980 model year and use 1980 EPA test results for weight and fuel economy. The 1979 BMW ICEV weighed the same as the 1980 model but achieved only 18 mpg in the city cycle test.

[f] All ICEV and EV data from ELVEC and EVWAC computer simulations, by General Research Corporation (Carriere et al., 1982). EV and ICEV have same acceleration. EV uses a Lime/Fe-S battery and has 150-mi range. EV and ICEV have same acceleration and interior capacity. Carriere et al. specify 3.33 mi/kWh from the outlet, including regenerative braking, and 0.72 combined battery and charger efficiency. They gave curb weights of 2,260 lb (EV) and 1,810 lb (ICEV); I assume that efficiency data were reported with an additional 300-lb test payload, as used by the EPA and by Hamilton (1980b), who also used ELVEC.

[g] EV data from Driggans and Whitehead (EVS88-018, 1988). The STROMer was built from a Golf CL. However, EPA data are available only for the Golf GTI. I assume 1985 model year. Efficiency data include energy returned by regenerative braking.

[h] Griffon data from Driggans and Whitehead (EVS88-039, 1988). The Griffon is a Bedford van, and the EPA does not report test data for Bedford vans. I assumed that the Griffon is comparable to 1984 GMC vans and used 1984 EPA weight and fuel economy test results. Griffon efficiency figure includes regenerative braking. The battery weight is modules only; it does not include auxiliaries or tray. The test cycle is the TVA's urban cycle. The Griffon was 27% more efficient in the SAE C cycle. Data in reference indicate that combined battery/charger efficiency was 62%.

TABLE B.1 (Cont.)

---

[i] EV data from Angelis et al. (1987), who expect the EV to achieve 190 Wh/km in the ECE cycle, from the outlet, with an additional 75 Wh/km required for battery heating. I assume a combined battery and charger efficiency of 0.63 for Na/S batteries. Regar (1987) reports that the vehicles being tested are converted BMW series 3 cars; I use EPA weight and fuel economy data for 1986 BMW series 3 vehicles. Since the ECE is a combination of FUDS and the highway cycle, I use the unadjusted EPA combined mileage result. The 3,300 lb given by Angelis et al. for calculating energy consumption appears to be curb weight; I have assumed they added 300 lb test weight for the actual efficiency calculation. The BMWs have regenerative braking (Haase, 1987), which apparently was included in the efficiency goal.

[j] ETX-I data from MacDowell and Crumley (1988). The ETX-I was stated to be comparable to a Mercury LN7 or Ford Escort; I used EPA weight and fuel economy results for a 1983 Escort. EPA test weight of 2,500-lb (2,200-lb curb weight plus 300-lb payload weight) is consistent with 2,224 curb weight reported by Ford and GE for the ICEV, before it was converted to the ETX-I. ETX-I data include split regenerative braking.

[k] ETX-II data from Stokes et al. (1988) and Patil and Davis (1988). The efficiency figure for the ETX-II is a goal and appears to include regenerative braking. However, it is not clear if this includes energy required to heat the Na/S battery. The ETX-II will be built from a Ford Aerostar van; I use 1988 EPA fuel economy and weight data for the Aerostar. The fuel economy for 1987 was 20 mpg.

[l] G-van characteristics from Hamilton (October 31, 1988); test weight is curb weight plus test payload. Electricity consumption data from computer simulations run by Hamilton (October 31, 1988). Accounts for regenerative braking. Hamilton's simulation of energy consumption over the C cycle (the value shown is for the D cycle) was extremely close to the consumption measured for the C cycle at the TVA test track.

[m] TEVan characteristics from Hamilton (October 31, 1988); test weight is curb weight plus test payload. Electricity consumption data from computer simulations run by Hamilton (October 31, 1988). Accounts for regenerative braking. Simulation results are close to Chrysler projections. I used mpg and weight results for the Chrysler Caravan.

[n] DSEP characteristics from Hamilton (October 31, 1988); test weight is curb weight plus test payload. Electricity consumption data from computer simulations by Hamilton (October 31, 1988). Accounts for regenerative braking. I used mpg and weight results for the heavy Chrysler Caravan, since the DSEP is a heavier version of the TEVan.

TABLE B.1 (Cont.)

---

^{o} Based on the following data:

For advanced EVs with ac motors:

Source	Gosden (1990)	Falt et al. (1990)	Fenton & Sims
Drive cycle	SAE J227a-C	A city cycle?	SAE J227a-D
Efficiency			
Auxiliary power	0.938	- -	incl. below
Controller	0.967	0.98	
Inverter	incl. above	0.97	0.96
Motor	0.890	0.89	0.88
Drivetrain	0.953	0.90	0.89
Total once-through	0.769	0.74	
Regenerative braking	1.155	1.041*	
Overall net	0.888	0.770	

* Assuming 80% battery efficiency.

The regenerative braking factor is equal to one plus the fraction of energy into the controller that is returned all the way back through the system to the controller.

Note that these figures are from city-cycle tests. Over a high-speed highway test cycle (45 mph and above), the net efficiency of the electric powertrain falls slightly, because there is no regenerative braking. The motor and controller are about as efficient at a steady speed of 45 mph as over the urban cycle, according to Fenton and Sims (1990). The combined city/highway net efficiency of the EV is 75-82%.

The gas-tank-to-road efficiency of year-2000 ICEVs will be about 15% in the city cycle and 17% in the combined city/highway cycle (HHV basis; An and Ross, EEA, 1990; Falt et al., 1990). Hence, the electric powertrain (battery to road) is 5-6 times more efficient than the ICE powertrain (gasoline tank to road) in city driving, and 4-1/2 to 5 times more efficient in combined city/highway driving.

suburban areas. These base-case results for urban driving do not apply to combined city/highway driving because the electric powertrain is slightly less efficient in high-speed highway driving than it is in urban driving because of the lack of regenerative braking, whereas the ICEV is more efficient at higher loads (see Table B.1, note o). For combined city/highway driving, the R_p is about 4.7. I use this value in a scenario analysis (Table 12 of Volume 1).

Because of the importance of R_p, one should ask if, in the future, R_p will be the same as the average R_p in Table B.1. Because of two broadly counterbalancing factors, which will be discussed next, I conclude that R_p is likely to remain the same in the future.

1. On the one hand, there is more opportunity to improve the efficiency of internal combustion engine (ICE) drivetrains than electric drivetrains. Current ICEs are very inefficient at part load, whereas electric motors are more than 90% efficient over typical drive cycles. A concerted effort to improve the drivetrain efficiency of both EVs and ICEVs is likely to reduce the advantage enjoyed by EVs.

2. On the other hand, vehicle designers and manufacturers have more incentive to improve the efficiency of EVs because improved efficiency pays off more for EVs than for ICEVs. (Improved efficiency will increase the performance and range of any vehicle.) However, consumers may think it is much more important to "squeeze" more miles and power out of an EV than an ICEV (assuming diminishing marginal returns to greater range and power). If this situation is true, manufacturers will find it worthwhile to do things to the EV body, drivetrain, interior, tires, and air conditioning (A/C) system and load (A/C is discussed more below) that they would not have done to the ICEV. The all-out attempt to make the GM Impact as efficient as possible clearly supports this hypothesis. (Some of the features of the Impact, such as a streamlined underside and reduced frontal area, cannot be applied to ICEVs because of the exhaust and muffler equipment on the underside and the radiator in the front.)

B.2.10.2 Air Conditioning

The energy-use ratio calculated here (R_p) is based on standard EPA and Society of Automotive Engineers drive-cycle tests, during which A/C is apparently not used. However, the use of A/C should not, in principle, significantly change the energy-use ratio calculated here, except perhaps in a way that favors EVs, as mentioned above and explained below. The calculations in Table B.1 indicate that it takes roughly six times more Btu of gasoline from the tank than electricity from the battery to provide a mile's worth of engine or motor output. In other words, in general, the electric motor uses six times less energy per unit of any kind work than does the ICEV. Assuming that the power demand for A/C is the same for both EV and ICEV vehicles (regardless of how the power is supplied), the A/C system in the EV should use about six times fewer Btu per unit of cooling provided than the A/C system in the ICEV. In short, the use of A/C increases the work that an ICE or electric motor must do but does not change the amount of energy required to produce a unit of any work.

The foregoing statement is true if the power demand for A/C is the same in the EV and the ICEV. This situation may not be the case because of the great impetus to reduce the power demand of A/C in EVs. The diversion of gasoline or battery energy to the A/C system reduces the range of either vehicle; this reduction is unimportant in an ICEV but is fairly serious in an EV, which has a limited range. Consequently, researchers are searching for ways to reduce the power demand of A/C systems for EVs (Schwarz, 1990; Tamura and Ikeda, 1990). Some methods of reducing power demand, such as reducing heat flow into the vehicle, may be applied to an EV but not to an ICEV because, as just noted, it is not as important to improve the range of an ICEV. If this happens, A/C systems in EVs will use less energy than A/C systems in ICEVs, and the EV powertrain will be even more efficient than the ICEV powertrain when the A/C is used.

B.2.11 Liquefied Petroleum Gas Light-Duty Vehicles: Relative Efficiency and Weight

Liquefied petroleum gas (LPG, which is primarily propane) is similar to NG as an engine fuel. It has a higher octane rating than gasoline, which permits the use of a higher compression ratio in a dedicated vehicle (which in turn improves efficiency), and it does not need enrichment at start-up, which saves fuel during the cold-start portion of a drive cycle. LPG has wider flammability limits than gasoline, so vehicle operation can be leaner and more efficient (Bechtold and Timbario, 1983), if a lean-burn liquefied petroleum gas vehicle (LPGV) can meet the 0.40 g/mi NO_x standard. Although a lean-burn LPG vehicle should have an easier time meeting the 0.40 g/mi NO_x standard than a lean-burn NG vehicle because of the faster flame speed and lower octane rating of LPG (which will reduce, directly or indirectly, emissions out of the engine), it will still be very difficult for a lean-burn LPG vehicle to satisfy the new standard. I assume, in the base case, that lean burn cannot be used with LPG.

Vehicles that run on LPG should be about as thermally efficient as NGVs. LPG has a lower octane rating and narrower flammability limits than NG, but LPG has a faster flame speed, which improves efficiency (Bechtold and Timbario, 1983). These properties will probably balance each other out. Both fuels should be more efficient than gasoline during cold start.

Fleming and Bechtold (1982) estimate that optimized LPG vehicles should be about 8% more thermally efficient than gasoline vehicles. The Western Liquid Gas Association (1990) implies that propane vehicles are 5-25% more efficient than gasoline vehicles. Webb (1990) assumes a 10-14% improvement for optimized monofuel propane LDVs over gasoline vehicles. I assume they have the same thermal-efficiency advantage as CNG.

Because of their heavier fuel tanks, LPG vehicles are slightly heavier than comparable gasoline vehicles. The extra weight of the LPG vehicle is calculated in Table 2 in Volume 1; the effect of this extra weight on vehicle efficiency is calculated by assuming a 6% decrease in efficiency for each 10% increase in weight. I ignore any differences in engine power and weight.

B.2.12 Liquefied Petroleum Gas Heavy-Duty Vehicles

Because of the lower compression ratio used in the spark-ignition vehicles, LPG HD, spark-ignition vehicles are less efficient than HD diesel, compression-ignition vehicles. Goetz et al. (1988) measured thermal efficiency to be 13% lower in an LPG bus engine than the diesel version of the same engine. Rele and Seppen (1990) remarked that gas engines are about 15% less efficient than diesel engines. Turner et al. (1990) reported even greater losses in thermal efficiency, 25-30%, for a HD propane GMC and W-star truck compared with a diesel Mack truck driven under similar conditions, but part of the thermal efficiency loss may have resulted from differences between the engines. I assume the thermal efficiency loss relative to heavy-duty diesel vehicles (HDDVs) is the same as that of HD CNG vehicles.

B.2.13 Hydrogen Vehicles: Relative Thermal Efficiency and Weight

The thermal efficiency and weight data in Table 2 in Volume 1, for both light- and heavy-duty vehicles, are determined on the basis of the analysis in DeLuchi (1989). The very large efficiency advantage of hydrogen vehicles is primarily due to the extremely wide flammability limits of hydrogen, which permit ultra-lean operation. Hydrogen vehicles may be able to run lean and meet an 0.40 g/mi NO_X standard. The reason is because NO_X emissions from the engine (i.e., engine-out emissions) decrease continuously with an increasing air/fuel ratio, and, at some ultra-lean point, engine-out emissions will be below 0.40 g/mi. (See Das, 1990; Wolpers et al., 1988; and DeLuchi, 1989, for a discussion of the prospect of near-zero NO_X emissions from hydrogen vehicles.) Hydrogen vehicles alone may be able to operate at such an ultra-high air/fuel ratio. An optimized hydrogen vehicle might be designed for ultra-lean operation at steady load, with engine-out NO_X emissions of less than 0.40 g/mi and stoichiometric operation under high load to provide extra power for acceleration. NO_X emissions from high-load operation could be controlled by a reduction catalyst since the air/fuel mixture under high load would be stoichiometric. The base-case values in Table 2 in Volume 1 assume that hydrogen vehicles will be significantly more efficient than gasoline vehicles and still meet an 0.40 g/mi NO_X standard by running ultra-lean at constant load. The weight changes with hydrogen use are discussed in DeLuchi (1989).

B.2.14 Fuel Cell Vehicles

A fuel cell is a device that converts the chemical energy in hydrogen to electrical energy. The conversion occurs when a porous and electrically conductive electrode (the anode) takes electrons away from hydrogen molecules. The electrons constitute an electric current that provides work against a load, such as an electric traction motor. In a proton-exchange-membrane (PEM) fuel cell, the stripped hydrogen (a proton) is transferred from the anode to the opposite electrode, the cathode, by a proton-conducting material called an electrolyte. At the cathode, the stripped hydrogen combines with atmospheric oxygen and the electrons (which now have done their work) to form water. The reactions at the electrodes are facilitated by catalysts, which, in the case of the PEM fuel cell, are made of a noble metal such as platinum.

Fuel cells are classified primarily by the kind of electrolyte they use. At least two kinds of fuel cells, phosphoric-acid and alkaline, are commercially available. However, phosphoric-acid fuel cells are expensive and too bulky and heavy to be used in LDVs, and alkaline fuel cells are too susceptible to poisoning by atmospheric CO_2 at the cathode (the air electrode) to be used easily in terrestrial applications. Consequently, researchers are developing other advanced fuel cells for vehicles, including PEM fuel cells (also called solid-polymer-electrolyte fuel cells), molten-carbonate fuel cells, and solid oxide fuel cells. In this analysis, I assume that a PEM fuel cell is used.

The hydrogen fuel used by a fuel cell can be stored on board the vehicle as hydrogen or effectively stored in a hydrocarbon, such as methanol or NG, which is decomposed by an on-board reformer to hydrogen and carbon monoxide (CO). I consider both hydrogen and methanol storage. Hydrogen can be produced by many processes from many hydrogen-containing compounds; I consider gasification of biomass and solar electrolysis of water. I assume that the hydrogen is stored as a metal hydride. For methanol, I consider gasification of biomass, gasification of coal, and reforming of NG.

Because fuel cell vehicles (FCVs) are the furthest from commercialization and the least well-characterized vehicle technologies analyzed here, I do not calculate their relative overall efficiency in detail and do not have a separate column for them in Table 2 in Volume 1. Rather, I model reformed-methanol FCVs by making appropriate changes to the relative efficiency data and emissions data pertaining to methanol vehicles in the model. I model hydrogen FCVs by making parallel changes to the input data pertaining to hydrogen FCVs.

DeLuchi et al. (1991a, 1991b) developed a detailed cost and performance model for FCVs that use methanol or hydrogen. Their literature review and analysis indicate that hydrogen-powered FCVs would be two to three times more thermally efficient than gasoline ICEVs on a mile/10^6 Btu basis. I conservatively assume that hydrogen-powered FCVs would be about 2.2 times more thermally efficient than gasoline ICEVs. Methanol-powered FCVs would be about 15% less efficient than hydrogen FCVs because of the energy requirements of reforming. The thermal efficiency advantage of FCVs over diesel ICEVs would be somewhat less than their advantage over gasoline ICEVs because diesel engines are more efficient than gasoline engines.

The thermal efficiency advantage of fuel cells is adjusted to account for the extra weight of the FCVs. The methanol FCV is assumed to weigh 100 lb more than the gasoline ICEV and 300 lb more than the diesel ICEV. The weight of the hydrogen FCV is calculated based on the amount of hydride required for a 200-mi range in a LDV and a 300-mi range in a HDV.

Fuel-cell vehicles using pure hydrogen would emit only water. They simply could not emit CO, nonmethane organic compounds (NMOC), methane (CH_4), or CO_2 because there would be no source of carbon, not even a lubricant. Moreover, low-temperature fuel cells do not emit NO_x because the temperature is far below that required for NO_x formation. Consequently, in the case of a hydrogen FCV, I assume no vehicular emissions of CH_4, CO, nitrous oxide (N_2O), NO_x, NMOC, and CO_2.

Fuel cell vehicles using reformed methanol would have minor emissions of CO and NO_x from the reformer and minor evaporative emissions of the stored methanol. I assume that there would be no tailpipe emissions of CH_4, NMOC, CO, or N_2O; no emissions of CO_2 as a result of the combustion of lubricating oil; only 0.01 g/mi of NO_x emissions from the reformer on LDVs; and only 0.02 g/mi of NO_x emissions from the reformer on HDVs. Evaporative emissions of NMOC from methanol vehicles are calculated automatically as a function of the overall fuel efficiency of the vehicle. Emissions of CO_2 from the reforming of fuel are calculated on the basis of the carbon content of the fuel and the overall efficiency of fuel use.

I can only crudely approximate emissions from the manufacture of materials in FCVs. I assume that the materials breakdown in an FCV, excluding the fuel storage system, would be the same as the breakdown in an ICEV. This obviously is not correct because the powertrain in an FCV would be very different from that in an ICEV. Unfortunately, there are no data available to make an accurate characterization. I assume that the methanol FCV would weigh 100 lb more than the comparable gasoline LDV and 300 lb more than the comparable HDV. The weight of the hydrogen FCV is calculated by assuming hydride storage, an LDV range of 200 mi, and an HDV range of 300 mi.

B.2.15 Gasoline Versus Diesel Vehicles

Diesel fuel vehicles emit fewer greenhouse gases per mile than do gasoline vehicles because diesel vehicles are more efficient and it takes less energy to refine crude to diesel than to gasoline. Until recently, however, policymakers have not viewed diesel vehicles as an alternative to gasoline vehicles, primarily because diesel vehicles typically have had relatively high particulate matter (PM), sulfur-oxide, and NO_x emissions. However, recent EPA regulations limit the sulfur content of diesel fuel to 0.05% (Federal Register, August 21, 1990), and the Clean Air Act of 1990 (CAA) sets limits on PM and NO_x emissions (1.0 g/mi NO_x at 50,000 mi, and 0.08 g/mi PM at 50,000 mi) (EPA, *CAA*, 1990). Diesel-fuel vehicles, then, may be clean enough to be considered an alternative to gasoline vehicles.

To compare the CO_2-equivalent emissions of diesel and gasoline vehicles, one must specify the fuel economy, weight, and (CO, NMOC, CH_4, N_2O, and NO_x) emissions of the two kinds of vehicles. Turbocharged, indirect-injection, diesel-fuel vehicles have 25-30% better fuel economy than their gasoline counterparts (Bleviss, 1989; Energy and Environmental Analysis, 1988; Millar et al., 1985; Sekar et al., 1984; Barnes-Moss and Scott, 1976). Direct-injection, turbocharged diesels have a 40-45% fuel economy advantage (Energy and Environmental Analysis, 1990, 1988). Diesel engines also weigh about 100 lb more than spark-ignition engines (Energy and Environmental Analysis, 1990).

The fuel economy increases cited above are determined on the basis of unadjusted mpg fuel economy. The in-use fuel economy advantage of diesels may be even greater because diesel vehicles may perform closer to their unadjusted ratings than do gasoline vehicles (Duleep, 1991).

However, the use of trap oxidizers to control PM emissions will reduce the efficiency of diesel vehicles. I assume that these factors cancel each other out.

Emission factors for light-duty diesel vehicles (LDDVs) are in Section B.3.2.

B.2.16 Summary

The weight and efficiency assumptions used in this analysis and discussed above are shown in Table 2 in Volume 1. The basic input data are the desired range, the weight of the fuel storage tank per pound of fuel, and the relative thermal efficiency. With these data, the model first calculates the amount of fuel needed to satisfy the range requirement. Then the model calculates the tank size that will be needed for the calculated amount of range. It then sums the weight of the fuel and tank and compares it with the weight of the gasoline or diesel-fuel system. It calculates the relative weight and the relative efficiency factor due to the relative weight. It combines the relative-weight efficiency factor and the relative thermal-efficiency factor to give overall relative efficiency. The advantage of this approach is that the vehicle range is explicitly included as a variable; there is no cheating on weight (and thus efficiency and greenhouse gas emissions) by hiding assumptions about range. (This approach also introduces circularity into the calculation since the amount of fuel required to satisfy a given range depends on the efficiency of the vehicle, but the efficiency depends in part on the weight of the fuel. The model solves these circularities by iteration.)

B.3 NMOC, NO_x, and CO Emissions from Vehicles

Emissions of CO, NMOC, and NO_x from vehicles contribute to the greenhouse effect indirectly by affecting the concentration of ozone and methane. (CH_4 and N_2O emissions, which affect climate directly, are analyzed in Appendixes M and N.) Also, as discussed below, one must know vehicular CO and NMOC emissions to calculate CO_2 emissions because vehicular carbon emissions as CO_2 are calculated as the total amount of carbon available in the fuel, minus the amount of carbon emitted as NMOC and CO.

To estimate NMOC, NO_x, and CO emissions from petroleum-fuel vehicles, I begin with the output of MOBILE4, the EPA's detailed computer emissions model. MOBILE4 can be set to estimate composite, fleet-average emission factors for light-duty gasoline vehicles (LDGVs) and HDDVs in the year 2020. I program MOBILE4 for the year 2020 rather than 2000 because the MOBILE4 fleet includes a few old, uncontrolled vehicles, and because AFVs will replace only relatively new, tightly controlled vehicles. Then I adjust the MOBILE4, year-2020 output to account for those requirements of the new CAA that cannot be incorporated easily into MOBILE4.

In the following section, I discuss how I adjust the emissions results of MOBILE4 and the California version of MOBILE4 to reflect the new CAA requirements. I then estimate emissions from alternative-fuel vehicles, considering the clean-fuel emissions standards of the CAA (which, by and large, are the same as the standards for gasoline and diesel vehicles) and data on emissions from AFVs relative to emissions from petroleum-fuel vehicles.

B.3.1 Heavy-Duty Diesel Vehicles

The MOBILE4 emission factors for HDDVs fully incorporate the 1994 HDV standards that were adopted prior to the CAA Amendments of 1990. The CAA left the hydrocarbon (HC) and CO standards intact but lowered the NO_X standard from 5.0 to 4.0 g/brake-horsepower-hour (bhp). However, the MOBILE4 g/mi emission factors translate to less than 4.0 g/bhp, so that no adjustment is necessary to account for the lowering of the NO_X standard. Hence, the MOBILE4 factors for HDDVs can be used to represent year-2000 emissions from HDDVs under the new CAA (Tables B.2 and B.3). There are no evaporative emissions from HDDVs because of the extremely low volatility of diesel fuel.

B.3.2 Light-Duty Diesel Vehicles

Under the new CAA, LDDVs have the same CO and NMOC standards as gasoline LDGVs. The new NO_X standard for LDDVs, 1.0 g/mi, is higher than the standard for gasoline vehicles. MOBILE4 projects that (1) CO emissions from LDDVs will be well below the CO standard, (2) NO_X emissions will be very close to the standard, and (3) NMOC emissions will exceed the 0.25 g/mi standard (see Table B.3). Therefore, I use the MOBILE4 projections of CO and NO_X emissions. (The ratio of NO_X emissions from LDDVs to NO_X emissions from LDGVs equals the ratio of the NO_X standard for LDDVs to the NO_X standard for LDGVs.) For N_2O, I use the estimate from Table N.1 in Appendix N. Finally, I assume that LDDVs will emit the same level of NMOC as LDGVs since both will certify to the same standard, and both will have to use some form of control to meet the standard. (The MOBILE4 projections do not take account of the new NMOC standard.)

B.3.3 Heavy-Duty Alternative-Fuel Vehicles

For two reasons, I assume that alternative-fuel HDVs will emit as much as NO_X as diesel HDVs. First, HD AFVs face the same 4.0 g/bhp NO_X standard. Although it will be easier for some vehicles and fuels to meet the standard (e.g., easier for methanol than for diesel fuel), all vehicles will either have to sacrifice performance and fuel economy or add emission control equipment in order to meet the standard. In other words, all vehicles must in some sense pay for meeting the NO_X standard, which means that manufacturers will not try to go much below the standard (unless EPA allows credits for doing so).

TABLE B.2 Lifetime Average Vehicle Emissions, Input and Calculated Data (g/mi)

	Gasoline							
Emission	Standard	Reformulated[a]	Diesel	Methanol/LD[b]	Methanol/HD[c]	NG/LD	NG/HD	EVs[d]
In actual g/mi:								
CH_4[e]	0.05	0.05	0.10	0.03	0.05	1.20[f]	3.00[f]	0.00
N_2O[g]	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.00
Upstream evaporative NMOC[h]	0.13	0.13	0.01	0.06	0.38	0.00	0.00	0.00
Vehicle evaporative NMOC[i]	0.30	0.30	0.00	0.13	0.86	0.00	0.00	0.00
Tailpipe NMOC	0.40	0.34	2.05	0.43	4.00	0.22	0.60	0.00
Total NMOC[j]	0.83	0.77	2.06	0.62	5.25	0.22	0.60	0.00
CO	7.21	6.13	10.78	7.21	13.00	3.60	7.00	0.00
NO_x as NO_2	0.45	0.45	8.05	0.45	8.05	0.45	8.05	0.00
CO_2 from oil[k]	2.00	2.00	4.00	2.00	4.00	1.00	2.00	0.00
CO_2 from EV heater[l]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CFCs[m]	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031
CO_2 from fuel[n]	275.45	268.52	1,651.41	214.64	1,495.41	195.51	1,463.94	0.00
In CO_2-equivalent g/mi:								
CFCs[m]	220.37	220.37	220.36	220.37	220.36	220.37	220.36	220.37
CH_4, CO, N_2O, NO_x, NMOCs	67.02	63.16	396.66	60.75	406.69	72.45	426.64	0.00
Total without CFCs[o]	344.47	333.68	2,052.07	277.39	1,906.10	268.95	1,892.58	0.00
Total with CFCs[p]	564.85	554.05	2,272.43	497.76	2,126.46	489.32	2,112.94	220.37
For biofuels case (total g/mi):[q]								
Without CFCs				51.40	386.01	64.44	408.92	
With CFCs				271.77	606.38	284.81	629.29	

TABLE B.2 (Con't)

	Hydrogen/LD	Hydrogen/HD	Ethanol/LD[r]	Ethanol/HD[r]	LPG/LD	LPG/HD
In actual g/mi:						
CH_4[e]	0.005	0.005	0.03	0.05	0.05	0.10
N_2O[g]	0.000	0.060	0.06	0.06	0.06	0.06
Upstream evaporative NMOC[h]	0.00	0.00	0.03	0.19	0.02	0.10
Vehicle evaporative NMOC[i]	0.00	0.00	0.06	0.42	0.00	0.00
Tailpipe NMOC	0.040	0.040	0.32	4.00	0.22	1.80
Total NMOC[j]	0.04	0.04	0.40	4.60	0.24	1.90
CO	0.70	0.100	7.21	13.00	5.50	9.00
NO_x as NO_2	0.45	8.05	0.45	8.05	0.45	8.05
CO_2 from oil[k]	2.000	4.000	2.00	4.00	1.50	3.00
CO_2 from EV heater[l]	0.000	0.000	0.00	0.00	0.00	0.00
CFCs[m]	0.031	0.031	0.031	0.031	0.031	0.031
CO_2 from fuel[n]	0.00	0.00	0.00	0.00	226.72	1,695.56
In CO_2-equivalent g/mi:						
CFCs[m]	220.37	220.36	220.37	220.36	220.37	220.36
CH_4, CO, N_2O, NO_x, NMOCs	20.65	340.25	49.03[s]	385.38[s]	55.35	388.16
Total without CFCs[o]	22.65	344.25	51.03	389.38	283.57	2,086.72
Total with CFCs[p]	243.02	564.61	271.40	609.75	503.94	2,307.09

---

[a] Reformulated gasoline, as specified in Appendix C. This is used as the base-case gasoline here.

[b] Emissions shown are for M100. For methanol/gasoline mixtures, the model calculates evaporative emissions and methane emissions as a function of the methanol proportion.

[c] Assumes 100% methanol.

[d] Emissions from vehicle only. Other fuel-cycle emissions calculated elsewhere.

[e] See Appendix M, for discussion of sources and data.

TABLE B.2 (Con't)

---

[f] Emissions from a CNGV. An LNGV has additional minor methane emissions from boil-off.

[g] See Appendix N for discussion of sources and data.

[h] Emissions of nonmethane organic compounds (including alcohols) from bulk terminals, refineries, loading and unloading, tankers, ships, stage I refueling, and so on. Uses data of Table 4 in Volume 1. See this Appendix for data and sources. Any alcohol emissions are included at their full mass (i.e., the NMOC g/mi emissions shown do not exclude alcohols or the oxygen in alcohols, nor do they convert alcohols to some "organic-material equivalent"). However, in converting NMOC to CO_2-equivalent mass emissions, only the carbon weight of the NMOC is counted, to properly account for the relative reactivity of NMOC (see Appendix O). I assume that evaporative emissions have the same carbon content as the fuel itself (Table C.1).

[i] Hot-soak, running loss, and refueling emissions. See this Appendix for discussion. Alcohol emissions counted at full mass. However, in converting NMOC to CO_2-equivalent mass emissions, only the carbon weight of the NMOC is counted, to properly account for the relative reactivity of NMOC (see Appendix O). I assume that evaporative emissions have the same carbon content as the fuel itself (Table C.1).

[j] Sum of upstream evaporative emissions, vehicular evaporative emissions, and tailpipe evaporative emissions. NMOCs include alcohol emissions, at full mass. However, in converting NMOC to CO_2-equivalent mass emissions, only the carbon weight of the NMOC is counted, to properly account for the relative reactivity of NMOC (see Appendix O).

For NMOC emissions from vehicles and other combustion sources, I make the following assumptions about the carbon content of NMOC emissions:

	C in NMOC	Explanation
Current gasoline	0.866	Same as fuel itself
Reformulated gasoline	0.833	Same as fuel itself
Diesel fuel	0.858	Same as fuel itself
Methanol	0.400	Almost all methanol (0.375); a few HCs
Ethanol	0.550	Almost all ethanol (0.522); a few HCs
Gaseous fuels	0.800	Ethane is typical (CH_4 counted separately)
Coal	0.600	Same as fuel itself
Wood	0.500	Same as fuel itself

[k] Estimated based on NMOC emissions from hydrogen vehicles and an analysis of oil consumption.

[l] Currently, EVs use oil-powered heaters. However, it is possible that high-temperature batteries could provide heat. I assume no fuel is burned to provide heat in the vehicle.

TABLE B.2 (Con't)

[m] See Appendix Q for methods and sources.

[n] Calculated by carbon-balance method. See this Appendix for details.

[o] The sum of CO_2 from fuel, CO_2 from oil, and the CO_2-equivalent of CH_4, N_2O, CO, and all NMOC. NMOC converted to CO_2-equivalent based on the carbon content of the NMOC. See Appendix O.

[p] Sum of CO_2-equivalent emissions from fuel use and CO_2-equivalent emissions of CFCs.

[q] Emissions if methanol and NG are made from biomass; equal to the CO_2 equivalent of emissions from the combustion of engine oil (assuming that engine oil is made from fossil-fuels), plus the CO_2-equivalent of CH_4, CO, NMOC, and N_2O emissions, less a CO_2 credit for the carbon in CH_4, CO, and NMOC (i.e., the greenhouse effect of an emission of CH_4 from a biofuel is equal to the difference between CH_4 and CO_2, because the carbon is taken from the atmosphere as CO_2 and returned as CH_4).

[r] Assumes 100% ethanol.

[s] With the CO_2 credit for carbon removed by photosynthesis, as per note q.

TABLE B.3 MOBILE4 Fleet-Average, Year-2020, g/mi Emission Factors[a]

Pollutant	LDGVs[b]	LDGT1[b]	HDGV[b]	LDDV	HDDV
Total HC[c]	1.01	1.11	2.77	0.52	2.13
Exhaust NMOCs	0.59	0.78	1.33	0.50	2.03
CH_4	0.05	0.07	0.18	0.02	0.10
Evaporative HC[d]	0.38	0.26	1.27	0.00	0.00
CO	7.21	9.08	16.53	1.45	10.78
NO_x	0.92	1.13	4.26	1.10	8.05
California NO_x[e]	0.56	0.84	4.28	1.08	8.33
N_2O[f]	0.06	0.06	0.06	0.054[g]	0.06

LDGV = light-duty gasoline vehicle; LDGT1 = light-duty gasoline truck, class 1; HDGV = heavy-duty gasoline vehicle; LDDV = light-duty diesel vehicle; HDDV = heavy-duty diesel vehicle.

[a] Assumed in-use summertime RVP of 8.05, stage-II (pump) and on-board refueling controls, and inspection and maintenance and anti-tampering programs (but with no check for lead in the tailpipe).

[b] These results are for a low-RVP but otherwise unreformulated gasoline. The gasoline vehicles would have lower CO and tailpipe NMOC emissions on reformulated gasoline.

[c] Evaporative emissions plus NMOC tailpipe emissions plus methane emissions. Total may not equal sum of components because of independent rounding.

[d] Hot-soak + diurnal (0.13 g/mi) + refueling (0.02 g/m) + running loss (0.23 g/mi) emissions.

[e] The result of the running the California version of MOBILE4, CALI4, for the year 2020.

[f] From Tables B.2 and N.1.

[g] Based on tests of one vehicle (Table N.1).

Second, the MOBILE4 g/mi NO_x estimate for HDDVs is consistent with measurements and projections of NO_x emissions from HD AFVs (Sperling and DeLuchi, 1991; EPA, Economic and Environmental Analyses of Alternative Fuels, 1990). Thus, the MOBILE4 HDDV NO_x emission estimate probably will be representative of emissions from all vehicles.

The new CAA directs the EPA to promulgate standards for ultra-low-emission vehicles (ULEVs) and zero-emission heavy-duty vehicles (ZEVs). I assume here that the ULEV and ZEV standards will not have any significant effect by the year 2000. Also, under the new CAA, clean-fuel HDVs weighing between 8,500 and 26,500 lb must meet a lower combined NO_x and NMOC standard. I do not consider this requirement.

The CO and HC standards are not constraining for HDDVs and are not likely to be constraining for HD AFVs that meet the NO_x standard. I estimate CO and tailpipe NMOC emissions from alternative-fuel HDVs, relative to diesel-fuel HDVs, on the basis of the review in Sperling and DeLuchi (1991). I assume there will be lean-burn, spark-ignition NGVs. In support of this, the EPA (*Analysis of the Economic and Environmental Effects of Compressed Natural Gas as a Vehicle Fuel, Volume II*, 1990) projects that lean-burn HD NGVs will meet the HD emission standards relatively easily.

There will be small amounts of evaporative emissions from HD ethanol and alcohol vehicles. I calculate these by scaling the g/mi evaporative-emission rate from LDVs by the ratio of the mi/10^6 Btu efficiency of LDVs to the mi/10^6 Btu efficiency of HDVs. This method assumes that evaporative emissions are a function of fuel use and, hence, fuel economy. The calculation of g/mi evaporative emissions from LDVs is discussed below.

B.3.4 Light-Duty Vehicles Using Unreformulated Gasoline

The new CAA Amendments and recent EPA regulations mandate a lower Reid vapor pressure (RVP) for gasoline; lower NO_x and NMOC certification standards; 100,000-mi in-use standards; controls on vehicle refueling; reformulated gasoline; and, in most ozone nonattainment areas, inspection and maintenance (I&M) programs (EPA, *CAA*, 1990). MOBILE4 has variables to represent RVP, on-board and pump-side controls on refueling, and inspection and maintenance programs; but not tailpipe standards, gasoline composition, or in-use testing requirements (although the California version of MOBILE4 can be used to estimate the effects of a lower NO_x standard, as discussed below). Table B.3 shows the results of running MOBILE4 for the year 2020, programmed with the new RVP standards, onboard and pump-side (Stage-II) refueling controls, and inspection and maintenance parameters.

California has a 0.40 g/mi 50,000-mi NO_x standard, with an option to meet an 0.70 g/mi standard and a lower CO standard. Hence the California version of MOBILE4 provides an approximation of the newly mandated federal NO_x standard. The California version estimates in-use emissions of 0.56 g/mi NO_x for the year 2020 (Table B.3).

The results from MOBILE4 must be adjusted to capture the effects of those aspects of the CAA that cannot be modeled. The California NO_X result, which is based on a 50,000-mi certification standard and assumes that a small portion of vehicles certify under an 0.70 g/mi standard, must be reduced to account for the imposition of in-use standards and the absence of the 0.70 g/mi option in the new CAA. The new CAA Amendments require that vehicles meet the 0.40 g/mi, 50,000-mi certification standard in use, as well as during certification, and they require that vehicles meet the 0.60 g/mi in-use standard at 100,000 mi. Accordingly, I assume a fleet-average emission rate of 0.45 g/mi in 2000.

The current MOBILE4 CO emission rate should be reduced to account for the imposition of the in-use standards (3.4 g/mi at 50,000 mi and 4.2 g/mi at 100,000 mi) and the new cold-temperature CO standard. There is evidence, however, that MOBILE4 substantially underestimates CO emissions from vehicles by inadequately accounting for so-called "superemitters." I assume that these countervailing factors cancel each other, and I use the current MOBILE4 year-2020 output without adjusting it.

The NMOC tailpipe emission rate must be adjusted to reflect the lower tailpipe standard (0.25 g/mi NMOC, down from 0.39 at present) and the imposition of the in-use standards. I assume exhaust NMOC emissions of 0.40 g/mi, down from the 0.59 value in MOBILE4's year-2020 projection. (As discussed below, MOBILE4 probably does not dramatically underestimate NMOC emissions.)

Evaporative emissions from conventional gasoline vehicles will probably be slightly lower than the amount projected by my runs of MOBILE4. These runs incorporate the new RVP, refueling, and I&M regulations but not the new CAA mandate to further control vehicular evaporative emissions (EPA, *CAA*, 1990). This mandate will lead to a revision of the evaporative emissions test and standard and will reduce running losses. Therefore, I assume that total evaporative emissions will be slightly lower than those predicted by MOBILE4: 0.30 g/mi rather than 0.38 g/mi.

B.3.5 Vehicles Using Reformulated Gasoline

The new emission standards discussed above apply to vehicles that use conventional gasoline (vehicles must be certified to meet the standards on conventional gasoline). The CAA specifically states that reformulated gasoline must either contain no more than 25% aromatics or provide a 15% reduction in emissions of volatile organic compounds (VOC) and toxics based on the emissions from a baseline gasoline vehicle, whichever is more stringent (EPA, *CAA*, 1990; the baseline is to be defined by the EPA later). Thus, a vehicle using reformulated gasoline will emit fewer VOC than a vehicle using conventional gasoline. In the base case in which I assume the use of reformulated gasoline, I assume a 15% reduction in emissions of VOC and CO and no change in NO_X emissions (compared with a vehicle using conventional gasoline). These assumptions are consistent with the requirements of the CAA and with preliminary emission comparisons and projections (Boekhaus et al., 1990; U. S. GAO, 1990; Wall Street Journal, 1990; Piel, 1989).

Because of the wording of the CAA and because gasoline vehicles must certify to the new CAA standards on conventional gasoline, reformulated-gasoline vehicles will produce lower emissions than conventional-gasoline vehicles. In effect, reformulated-gasoline vehicles are required to meet a lower VOC standard than conventional-gasoline vehicles and a lower CO standard than any other LDV.

B.3.6 Alternative-Fuel Light-Duty Vehicles

Alternative or clean-fuel vehicles must meet emission standards of 0.125 g/mi for NMOC, 3.4 g/mi for CO, and 0.4 g/mi for NO_X. (These are Phase I standards for vehicles up to 5,750 lb, which apply through the year 2001.) The NO_X and CO standards are the same as those for gasoline vehicles; the NMOC standard is half. I estimate emissions from methanol, CNG, and hydrogen vehicles relative to emissions from gasoline and diesel-fuel vehicles, considering both these clean-fuel standards and the emissions data reviewed in Sperling and DeLuchi (1991) and other sources.

B.3.6.1 Nitrogen Oxides

I assume that all single-fuel, optimized ICEVs will emit the same level of NO_X because the new NO_X standard, which is the same for all vehicles, will be difficult enough for all vehicles to meet that none will emit significantly below the standard (e.g., see discussion above, about the difficulty of meeting the NO_X standard with lean burn). However, a flexible-fuel methanol or ethanol vehicle should emit less NO_X than a comparable dedicated gasoline vehicle, assuming that the same NO_X standard applies to flexible-fuel vehicles (FFVs) on gasoline and dedicated gasoline vehicles, because an FFV will emit less NO_X when running on alcohol because of alcohol's lower flame temperature, faster flame speed, and higher latent heat of vaporization (Sperling and DeLuchi, 1991).

B.3.6.2 Carbon Monoxide

I assume that methanol, ethanol, LPG, and NG vehicles must operate near stoichiometry to meet the NO_X standard (see discussion above). Thus, these vehicles will have to forego the large CO and NMOC emissions benefits of very lean operation (the stoichiometry of a hydrogen engine has little effect on CO and NMOC emissions since in hydrogen vehicles these are produced only from combustion of engine oil). Therefore, I assume that no AFV will achieve huge CO reductions when compared with a gasoline vehicle.

However, CO emissions are also a function of the how well the fuel mixes with air and how fully the fuel is vaporized at cold start. Alcohol-fuel vehicles have no comparative advantages in these areas, so they can be expected to emit as much CO as conventional gasoline vehicles (at stoichiometry). Emissions data clearly support this assumption (Sperling and DeLuchi, 1991). Indeed, alcohol vehicles may have higher CO emissions during cold start because of the low vapor pressure of ethanol and methanol. Therefore, I assume that alcohol vehicles emit as much CO as conventional-gasoline vehicles.

Since reformulated gasoline is intended to produce less CO than conventional gasoline, and because conventional-gasoline and alcohol-fuel vehicles will certify to the same standard and probably will emit the same amount CO, reformulated gasoline will result in less CO emissions than will alcohol. Boekhaus et al. (1990) make a similar assumption.

I assume that NG vehicles will emit somewhat less CO than conventional- and reformulated-gasoline vehicles, even at stoichiometry, because of reduced CO emissions at start up and because, if a CNG vehicle operates even slightly lean, CO emissions drop dramatically. However, I do not assume the very low CO emissions levels associated with uniformly lean operation on CNG.

If NGVs must operate slightly rich to meet the NO_X standard, they will produce at least as much CO as the conventional gasoline vehicle. I consider this in a scenario analysis.

I assume that LPG vehicles emit only slightly less CO than do gasoline vehicles and slightly more than NGVs on the basis of data and statements in Bechtold and Timbario (1983), WLGA (1988), CARB (1989), and Goetz et al. (1988, for bus engines).

B.3.6.3 Nonmethane Organic Compounds: Tailpipe Emissions

The standard for NMOC emissions from the tailpipe of clean-fuel vehicles is half that for gasoline vehicles. In its 1989 rules for methanol vehicles, the EPA established that NMOC emissions from methanol vehicles were to be represented by converting the actual, full weight of all the organic emissions to the mass amount of gasoline-vehicle emissions with the same total carbon (where gasoline emissions are assumed to contain 86.6% carbon) (Federal Register, April 11, 1989). Applied to the new CAA standards, this convention means that methanol vehicles must certify to a 50%-lower carbon-emission standard. I assume, then, that methanol vehicles will emit half the total carbon from the tailpipe that conventional (gasoline) vehicles do. Thus, (1) if gasoline vehicles emit 0.40 g/mi NMOC from the tailpipe (see above; on conventional, not reformulated, gasoline), and (2) if the organic emissions from methanol vehicles are 40% carbon (most of the organic emission is methanol, which is 37.5% carbon, but there is a small amount of hydrocarbons emitted, with a much higher carbon content), methanol vehicles will emit 0.43 g/mi of total organics. This assumption is quite consistent with emissions data from methanol vehicles (Sperling and DeLuchi, 1991) and the EPA's projection (1989, *Analysis of the Economic and Environmental Effects of Methanol as a Automotive Fuel*).

I follow the same convention in estimating NMOC emissions from ethanol, NG, and LPG vehicles: 50% lower carbon emissions compared with conventional gasoline. My assumptions regarding the carbon content of organic emissions from these vehicles are shown in the notes to Table B.2. The resulting NMOC g/mi emission for NG is consistent with expected results for optimized vehicles (Sperling and DeLuchi, 1991).

The NMOC input data in Table B.2 (e.g., 0.315 g/mi for ethanol and 0.43 g/mi for methanol) show the full weight of NMOC emissions (carbon, hydrogen, and oxygen). However, in converting these emissions to CO_2-equivalents, only the carbon weight is counted because the amount of CO_2 and ozone formed from NMOC is a function of the carbon content (see Appendix O).

B.3.7 Vehicles Using Liquid Fuels: Evaporative NMOC Emissions

In general, evaporative emissions from vehicles, vehicle refueling, and product distribution and storage are proportional to the true vapor pressure (TVP) of the liquid, amount of liquid, molecular weight of the vapors, and the extent and effectiveness of emission controls. The use of emission controls, in turn, is determined in part by the stringency of the evaporative emissions standard for the particular fuels. Given g/gal evaporative emissions from gasoline, g/gal evaporative emissions from methanol and ethanol vehicles can be estimated by comparing the TVP and molecular weights of methanol and ethanol to those of gasoline for a given level of control. (Grams-per-gallon evaporative emissions from gasoline vehicles and gasoline-vehicle refueling can be inferred from the data in Table B.2; g/gal gasoline evaporative emissions from upstream processes are discussed below.)

New EPA rules will reduce the RVP of gasoline to 7.8 or 9.0 during five months (May-September) (Federal Register, June 11, 1990); the rest of the year, RVP will be about 11.5. The year-round average will be about 10 (DeLuchi et al., 1991; recall that in a greenhouse-gas analysis, year round, national averages are of interest). Assuming a national-average, year round temperature of 60°F (based on data in the U. S. *Statistical Abstract*), the year-round national-average TVP of gasoline will be 5.2 (EPA, 1985, AP-42). At 60°F, the TVP of methanol is 1.4; of ethanol, 0.6 (EPA, AP-42). This means that molar evaporative emissions from 1 gal of methanol will be 26% of the molar emissions from 1 gal of gasoline. Molar emissions from ethanol will be 12% of molar emissions from gasoline. Since the molecular weight of methanol vapor is 48% of the molecular weight of 10-RVP gasoline vapor, and the molecular weight of ethanol vapor 70% of it, g/gal methanol evaporative emissions will be 13% and g/gal ethanol emissions will be 8% of g/gal gasoline evaporative emissions, at a given level of control.

To determine final, in-use evaporative emissions from alcohol vehicles and systems relative to gasoline, one must project the level of control of evaporative emissions from the alcohol system, compared with the control of the gasoline system. The level of control will be determined in part by emission standards, which the EPA sets by considering both the cost and benefits of emission control. I have not attempted to quantify these costs and benefits here; rather, I touch briefly on a few of the issues.

Presently, the evaporative emission standard for methanol vehicles is 2 g of gasoline-equivalent hydrocarbons per test (2 g/test) (Federal Register, April 11, 1990). This, like the tailpipe standard, is meant to result in equivalent carbon emissions (the gasoline-vehicle evaporative emissions standard also is 2 g/test). One could argue from this that evaporative carbon emissions from methanol vehicles will be the same as those from gasoline vehicles and (per mile, not per gallon) because manufacturers will take advantage of methanol's lower evaporative potential by cutting the cost of evaporative emission-control equipment to the point that methanol vehicles just meet the standard. The EPA explicitly acknowledges this tradeoff between control cost and emissions in its analysis for the standards (Federal Register, April 11, 1990).

The argument thus far is that methanol vehicles will produce as much hot-soak, diurnal, and running-loss evaporative VOC as gasoline vehicles. However, most of the in-use evaporative emissions from gasoline vehicles are a result of the failure of the evaporative emission control system, most typically, overloading of the canister. A failed methanol evaporative-control system will clearly produce fewer VOC than a failed gasoline control system because of the lower TVP and molecular weight of methanol. Also, in order to pass the 2 g/test standard, methanol vehicles may have to have emission controls that are nearly as effective as those for gasoline vehicles because in a new vehicle, uncontrollable background sources of VOC, such as upholstery, emit almost 2 g/test. This means that evaporative emissions from the fuel must be virtually eliminated (Federal Register, April 11, 1989).

I weigh these factors qualitatively and assume that g/gal emissions of VOC from methanol vehicles are 26% of the g/gal emissions from gasoline vehicles and that g/gal evaporative emissions from ethanol vehicles are 16% of those from gasoline vehicles — about twice the rate one would expect if alcohol vehicles had the same degree of control as gasoline vehicles.

The situation with vehicle refueling is also uncertain, although probably less so. If methanol vehicles are built with the same on-board refueling controls as gasoline vehicles, as is likely, the full evaporative emissions-reduction potential of methanol refueling will be realized. It is possible, but seems unlikely, that the EPA will relax the refueling control requirement for methanol vehicles. I assume the same on-board controls.

There are similar cost/emission tradeoffs associated with upstream evaporative emissions. At all stages, the basic question is: will the much lower evaporative emissions potential of alcohol vehicles translate into reduced emissions, reduced control costs, or some combination of both? Because of the difficulty of quantifying this tradeoff and because the tradeoff will result in different outcomes for different stages of the fuel marketing system, I simply assume that methanol vehicles will have 26% of the g/gal emissions of gasoline vehicles and that ethanol vehicles will have 16% (twice the rate one would expect if alcohol and gasoline vehicles had the same level of control at every stage).

Both evaporative and tailpipe NMOC emissions from alcohol/gasoline mixtures depend in a nonlinear way on the concentration of alcohol. When doing alcohol/gasoline scenario analyses, I use EPA (*Analysis of the Economic and Environmental Effects of Methanol as an Automotive Fuel*, 1989) estimates of evaporative and tailpipe emissions from methanol FFVs (for ethanol as well) and Sapre's (1988) data on evaporative and tailpipe emissions from methanol and gasoline blends.

The NGVs and EVs have no fuel-related evaporative emissions. I do not include background emissions of VOCs from vehicle upholstery and paint for three reasons. First, and most importantly, the EPA has apparently excluded such background emissions in its MOBILE4 program because MOBILE4 shows zero evaporative emissions from diesel-fuel vehicles. I therefore assume that background emissions are not included in the gasoline vehicle totals. Second, background emissions are hard to quantify and change greatly over the life of the vehicle. Third, background emissions are probably relatively small (on the order of 0.1 g/mi average) over the life of the vehicle. They amount to about 1 g/mi of CO_2-equivalent emissions or 0.2% of total life-cycle CO_2-equivalent emissions.

B.3.8 Questions about MOBILE4

Recently, researchers compared emissions measured from vehicles on the road with emissions predicted by early EPA and California models and found that the models (e.g., MOBILE3 and EMFAC7C) can greatly underestimate actual on-road emissions of CO and NMOC (Ingalls et al., 1989; Pierson et al., 1990). Ingalls et al. (1989) found that on-road HC emissions were 1.4 to 6.9 times higher than the emission factors calculated by the California Air Resources Board's EMFAC7C; CO emissions were 1.1 to 3.6 times higher; and NO_x emissions were 0.6 to 1.4 times higher. These factors are generally consistent with the results of other on-road emission studies (Pierson et al., 1990). It appears that MOBILE3 and EMFAC7C do not account adequately for emissions from poorly tuned, poorly maintained, and tampered-with vehicles and emissions from overloaded HC evaporative canisters. Neither one of these models estimates running evaporative losses.

The most recent EPA model, MOBILE4, does include running losses as well as a more sophisticated treatment of evaporative emissions in general and appears to predict HC emissions much better than its predecessor, MOBILE3 (Pierson et al., 1990). MOBILE4 is currently the best emissions model available. It probably underpredicts CO emissions; its performance with respect to HC emissions is not well known. However, the inaccuracies in MOBILE4 probably do not have a significant effect on absolute emissions of CO_2-equivalent greenhouse gases and probably would not have a significant effect on relative emissions from HC-burning vehicles since the inaccuracies are likely to be the same for all such vehicles. If MOBILE4 does greatly underestimate HC and CO emissions, the reductions in greenhouse gas emissions from hydrogen and electric vehicles will be slightly higher than the greenhouse gas reductions estimated here since these vehicles do not emit much CO and NMOC.

B.4 Carbon Balance

The greenhouse gas emissions model, by accounting for all carbon emitted by vehicles, produces an exact estimate of CO_2 emissions from fuel combustion. It calculates total fuel carbon into the engine per mile and then subtracts the portion of the fuel carbon that is emitted as CO, NMOC, or CH_4. The remaining carbon is calculated as being fully oxidized to CO_2.

The model accounts for the fact that a portion of the total tailpipe emissions of CO, NMOC, and CH_4 come from lubricating oil, not from fuel. The model asks for total tailpipe emissions in the federal test procedure and for the percentage of this total that results from the burning of fuel rather than the burning of lubricating oil. Thus, the model multiplies total CO, NMOC, and CH_4 emissions per mile by the percentage due to fuel and then deducts the carbon content of these calculated fuel-based CO, NMOC, and CH_4 emissions from total fuel carbon into the engine per mile. The calculated remaining carbon reveals fuel-based CO_2 emissions.

B.5 Oil Consumption

Some of the lubricating engine oil is burned in the engine and forms CO_2, CO, CH_4, and NMOC. The model asks for an estimate of g/mi CO_2 emissions from oil consumption. I make this estimate on the basis of data on CO_2 emissions from hydrogen vehicles since all CO_2 from hydrogen engines comes from the oil. These CO_2 emissions appear to be between 1 and 16 g/mi, with values above 2 g/mi indicating excessive oil consumption (DeLuchi, 1989). This result suggests an average estimate of 1-2 g/mi. As a check, I estimate that about one quart of oil should be burned every 3,000 mi. This corresponds to about 1 g/mi of CO_2 emissions, assuming 3,100 g/gal and 86% carbon. In the model, I entered 2 g/mi for gasoline LDVs rather than 1 g/mi to account for poorly tuned cars and nonrecycled oil (which eventually oxidizes to CO_2). I have arbitrarily assumed twice as much oil-derived CO_2 per mile from HDVs as from LDVs.

Oil analyses of the Federal Methanol Fleet indicate that engine wear may be higher with methanol than with gasoline; otherwise, there are no abnormal trends (McGill and Hillis, 1988). King and Bol (1988) found that oil consumption in HD methanol vehicles is the same as in diesel counterparts. Therefore, I assume no difference in the rate of oil consumption between methanol (and ethanol) and petroleum-fuel vehicles and hence use the same CO_2 g/mi rate.

Since it is likely that oil will last much longer in NGVs (DeLuchi et al., 1988), I assume that CO_2 emissions from engine oil in NGVs are half those in methanol and gasoline vehicles. LPG vehicles, too, are expected to consume less oil (Fleming and Bechtold, 1982). Recently, Turner et al. (1990) compared the oil consumption in propane and diesel trucks. They measured substantially lower oil consumption in the propane trucks. EVs do not consume oil.

B.6 Leaks and Emissions from Storing, Transferring, and Distributing Fuel

Fuel is lost during production, storage, and distribution. For example, gasoline evaporates, leaks, and spills when it is delivered to service stations, stored at bulk terminals, carried by tankers or tank trucks, and transferred between storage facilities and tankers and trucks. NG leaks from field production facilities, transmission lines, distribution lines, and probably CNG stations. Liquid hydrogen boils and evaporates when it is transferred between containers.

Fuel lost to the atmosphere affects the greenhouse calculation in two ways. First, all fuels, with the exception of hydrogen, are direct or indirect greenhouse gases. Second, the loss of fuel increases the amount of fuel that must be sent through the system to deliver a net unit to the motorist, which in turn increases emissions from fuel production and transport per unit of fuel that actually makes it to the end-user. Both of these effects must be accounted for.

Table 4 in Volume 1 shows the data necessary to estimate fuel losses from both of the effects mentioned above. The table shows, among other things, the fraction of gaseous fuel that leaks from the production and distribution system and the fraction of liquid fuel that evaporates during production, distribution, and storage. With this information, one can calculate the direct greenhouse effect of the loss, per unit of fuel actually delivered, and the make-up effect of the lost fuel. The direct greenhouse effect of the loss is converted to g/mi CO_2-equivalent emissions and incorporated into Table B.2. The make-up effect is expressed as a multiplication factor and is built into the model at various points.

The estimates in Table 4 of Volume 1 of leaks of NG from production and distribution systems are discussed and documented in Appendix M. This section discusses the estimates of the losses of liquids and liquefied gases.

B.6.1 Losses of Gasoline and Alcohols

Evaporative losses, in grams, are a function of the volatility of the fuel, molecular weight of the vapor, and degree of control used. DeLuchi et al. (1991) analyzed the loss from the gasoline system for the year 2000, taking into the account the emission control requirements of the new CAA Amendments and assuming the low-RVP gasoline required in recent EPA legislation. The result is about 4 g/gal for a fairly tightly controlled gasoline-marketing system. The evaporative loss rate for diesel and residual fuels is essentially zero because they have such low RVPs (EPA, 1985, AP-42). The evaporative loss rate for alcohol vehicles is estimated relative to the rate for gasoline vehicles, considering the lower TVP and lower molecular weight of alcohols but also accounting for the possibility of less stringent emission controls (so the alcohol system still will produce much lower evaporative emissions but also save on emission control costs; see discussion above).

In calculating upstream emissions from the use of methanol/gasoline mixes, the model assumes that methanol and gasoline are delivered in separate streams and not mixed until the motorist mixes them in the fuel tank. Thus, the g/mi nonvehicular NMOC emission rate for methanol vehicles is equal to the gasoline g/mi rate multiplied by the gasoline fraction, plus the pure methanol g/mi rate multiplied by the methanol fraction. This method is correct for estimating upstream emissions from mixes used by FFVs but not quite accurate for estimating emissions from M85 because M85 is blended before it gets to the service station. The model will be inaccurate to the extent that upstream evaporative emissions from delivery of an M85 mixture are different from the emissions from a gasoline stream weighted 85% and a methanol stream weighted 15% (this weighted average is what the model calculates). This difference is inconsequential.

The net greenhouse impact of evaporative emissions from biofuels is calculated as the gross impact of the evaporated fuel carbon, less a credit for the carbon (as CO_2) originally removed from the atmosphere by the plant from which the biofuel was made.

Evaporative emissions that occur after the fuel is metered at the dispensing pump are not included in the calculation of the make-up effect, end-use is considered to have occurred after the fuel is metered to the vehicle. Any evaporative loss that occurs after the fuel is dispensed to the vehicle affects the mpg efficiency of the vehicle because the "g" in "mpg" is measured as the fuel is dispensed, but it does not affect the amount of fuel that must be delivered to the pump. Put another way, the make-up effect of evaporative losses that occur after the pump is accounted for in the mpg figure itself; the greater the loss, the lower the mpg figure. However, one must still account for the direct, atmospheric effects of the evaporative emissions of NMOC and the boil-off losses of LNG. This accounting is in Table B.2 ("Vehicular evaporative emissions;" the estimation of this is discussed above).

B.6.2 Boil-off Losses of Liquefied Gases

If a liquid hydrogen (LH_2) vehicle is not used for a few days or an LNG vehicle is not used for more than a few weeks, the liquid fuel stored on the vehicle will warm up, boil off, and vent from the vehicle. (If the vehicle is driven before the vapor pressure reaches the venting point, the vapor will be burned in the engine, and the vapor pressure will be reduced.) This fuel is lost permanently and must be made up all the way back to the fuel production stage. The vaporized LNG is also a greenhouse gas. Because LNG vehicles can sit for a long period of time before they vent (DeLuchi et al., 1988), it is not likely that much fuel will be lost this way. I assume that 0.05% of the fuel will be vented from LNG vehicles. On average, LH_2 vehicles have a much shorter period before they vent because LH_2 is much colder (DeLuchi, 1989); I assume an average loss of 1%. I assume the same for LPG as for LNG.

A liquefied gas also will partially vaporize when it is transferred from a production facility to a tanker truck, from a tanker truck to a service station tank, or from a service station tank to a vehicle tank, if the transfer lines and containers are warmer than the liquid. However, these vapors will not be vented to the atmosphere but will instead be recovered and sent to back to the original container and eventually put to some use. Thus, vaporized and recovered gas will not be lost or have to be made up by increased gas production. Also, the vaporized liquid will not be a direct greenhouse gas since it will never reach the atmosphere. However, the vaporization of the liquid during transfers affects energy use and greenhouse gas emissions; it reduces the amount of liquid that reaches the motorist per unit of liquefaction energy at the plant and, hence, increases liquefaction energy requirements per unit of liquid gas actually delivered to the motorist. This effect must be accounted for.

Since LNG is likely to be made at service stations (DeLuchi et al., 1988), the only transfer of liquid will occur when it is transferred from the station to the vehicle. Because of this fact, and because of the relatively high temperature of LNG, I assume that vaporization losses will not be more than 1%.

By contrast, LH_2 will probably be made at large centralized facilities and, in many cases, will be transferred three times (production plant to truck, truck to station, and station to vehicle) before it reaches the vehicle. At least 10% of the LH_2 will vaporize at each stage if the lines and tanks are warm; if they are cold, about 5-7% will vaporize (DeLuchi, 1989; private communications from LH_2 suppliers). On average, around 16% of the LH_2 will boil off. Overall, about 84% of the originally liquefied LH_2 will reach the vehicle as LH_2. If advanced technology requires 0.26 Btu-electric to produce a Btu of LH_2 out of the liquefier (Blazek et al., 1986), it will take 0.26/0.84 = 0.31 Btu-electric to deliver a Btu of LH_2 to the motorist. This figure is entered in Table 3 of Volume 1.

B.7 Composite LDV/HDV Methanol Emission Factor

An alternative fuels program is likely to involve both heavy-duty and light-duty vehicles. For example, the 1994 heavy-duty vehicle NO_x and PM emission standards may force the use of methanol or NG. AFVs fare worse against HDDVs than they do against LDVs. Consequently, the aggregate effect of an alternative fuels package depends on the amount of heavy-duty diesel vehicle miles traveled (VMT) affected and the amount of light-duty gasoline VMT affected. Although VMT by HDDVs is very small compared to VMT by gasoline LDVs, HDDVs emit several times more greenhouse gases per mile, which means that the use of alternative fuels in HDDVs can significantly influence the aggregate greenhouse effect of an alternative fuels program.

The aggregate g/mi emissions of an alternative-fuel, heavy-duty, and light-duty fleet can be calculated as:

$$A_e = D_e \times D_m + L_e \times L_m$$

where:

A_e = aggregate g/mi emission factor for alternative-fuel vehicles that replace the gasoline and diesel-fuel fleet;

D_e = g/mi emissions from alternative-fuel HDVs that replace diesel vehicles;

D_m = VMT by alternative-fuel HDVs that replace diesel vehicles, divided by VMT by the whole alternative-fuel fleet;

L_e = g/mi emissions from alternative-fuel LDVs that replace gasoline vehicles; and

L_m = VMT by alternative-fuel LDVs that replace gasoline vehicles, divided by VMT by the whole alternative-fuel fleet.

The variable A_e can then be compared with the similar aggregate factor calculated for the gasoline and diesel fleet to determine the percentage change in g/mi emissions that result from the alternative fuels program continue. To make this calculation, one must determine current and future D_m and L_m for the gasoline and diesel-fuel vehicle fleet. Table B.4 shows that in 1987, diesel-fuel heavy-duty trucks and buses accounted for about 4.5% of all highway VMT, and gasoline-powered autos and light-duty trucks accounted for about 92% of all highway VMT. (The remaining VMT was by medium-duty and diesel LDVs, which I assume are less likely to use alternative fuels.) Overall, diesel-fuel vehicles, including medium- and light-duty vehicles, accounted for about 6% of total VMT. The VMT share of HDDVs is likely to increase because VMT by HDVs is likely to grow slightly faster than VMT by LDVs (EIA, *Assumptions for the Annual Energy Outlook 1990*, 1990; Millar et al., 1985) and because diesel's share of the HDV market may increase even further (EIA, *Assumptions for the Annual Energy Outlook 1990*, 1990).

The data in Table B.4 and the discussion above indicate that if policy mandates that alternative fuels displace gasoline in light-duty applications (autos and trucks) and diesel fuel in heavy-duty bus and truck applications, 5-6% of the VMT will be miles that would have been traveled by diesel vehicles and 94-95% will be miles that would have been traveled by gasoline vehicles. If the alternative fuels are used in both light- and medium-duty trucks, the diesel share of displaced VMT will increase slightly. In the base-case analysis, I assume that of the total VMT displaced by alternative fuels, 94% of the VMT being displaced will be gasoline VMT and 6% will be diesel VMT. There is a considerable difference between the percentage change for alternative-fuel LDVs only and that for light- and heavy-duty vehicles combined, even with only 5% of the VMT by HDVs.

TABLE B.4 VMT by Type of Vehicle and Fuel, 1987 U. S. Data

Fuel and Vehicle	Consumption (10^9 gal)[a]	Average mpg[b]	VMT (10^9 mi)[c]	VMT (%)[d]
Gasoline				93.55
Automobiles	69.72	19.26	1342.8	69.8
Buses	0.498	5.89	2.9	0.15
Trucks	40.08	(11.3)[e]	453.6	23.6
Light trucks	30.72	(13.9)[e]	426.0	22.1
Heavy trucks			13.5	0.7
Diesel				6.11
Automobiles	1.06	19.26	20.4	1.1
Buses	0.682	5.89	4.0	0.21
Trucks	15.16	(6.11)[e]	92.6	4.8
Heavy trucks			83.0	4.3

[a] From *Transportation Energy Data Book* (Davis et al., 1989).

[b] From *Highway Statistics* (USDOT, 1988). The average mpg figures are for all autos and buses; I assume diesel and gasoline vehicles of each class have the same efficiency.

[c] For autos and buses, VMT is calculated as product of total fuel consumed and average mpg, by class.

VMT for trucks is calculated differently. The *1982 Truck Inventory and Use Survey* (USDOT, 1985) reports VMT by weight class and type of fuel, for 1982. In billions of VMT, the numbers are 377.3 (all trucks), 310.1 (all gasoline trucks), 291.2 (light gasoline trucks), 9.19 (heavy gasoline trucks), 63.3 (all diesel trucks), and 56.6 (heavy diesel trucks) ("heavy" is the sum of values for "light-heavy" and "heavy-heavy"). No disaggregated data are available for 1987; however, in 1987, all trucks traveled 551.9 billion miles (USDOT, *Highway Statistics*, 1988; which follows the *Truck Inventory...* classification system). I have scaled the 1982 disaggregated data by the ratio of 551.9/377.3.

[d] Percent of total 1.924 trillion highway VMT in 1987 (USDOT, *Highway Statistics*, 1988). The sum of VMT percentages is slightly less than 1.00 because a small percentage (about 0.4%) of VMT is by LPG vehicles.

[e] Back-calculated from data on fuel consumed and scaled VMT, as a check. These values are reasonable: Most diesel-using trucks are heavy vehicles, averaging between 5 and 6 mpg, whereas most gasoline-using trucks are light vehicles, averaging between 10 and 15 mpg.

Appendix C:

Fuel Specifications and the Fate of Fuel Carbon

Appendix C:

Fuel Specifications and the Fate of Fuel Carbon

The grams of carbon dioxide (CO_2) emitted per mile of travel are equal to the efficiency of combustion (expressed in 10^6 Btu/mi) multiplied by the (oxidized) carbon (C) energy content of the fuel (expressed in grams of C converted to CO_2 per 10^6 Btu of fuel energy). Consequently, to calculate the emissions of greenhouse gases per mile, one must know the amount of carbon in the fuel per unit of the energy of the fuel. This value can be calculated for each fuel from data on fuel characteristics.

Tables C.1-C.3 show the fuel characteristics used in this study. All the characteristics are variable in the model, so they can be changed if better data become available. Unless otherwise noted, all numbers represent higher heating values (HHVs).

The choice of heating-value convention (higher or lower) is immaterial if one does the analysis properly. Strictly speaking, properly calculated g/mi results are completely (exactly or mathematically, not just "roughly") independent of the choice of heating value because heating values cancel out entirely. This is discussed more in Appendix A.

C.1 Crude Oil and Petroleum Products

The important characteristics of petroleum products are mass density, HHV, and carbon content. Different petroleum products (diesel fuel, gasoline, residual fuel, etc.) have different energy and carbon characteristics, so they must be specified differently. There also are differences among grades of the same kind of fuel, among different types of gasolines (e.g., premium unleaded and regular unleaded), and different grades of diesel fuel and residual fuel oil; however, these variations are relatively minor and are not considered here.

C.1.1 Crude Oil

The Energy Information Administration (EIA) and the American Petroleum Institute (API) specify the HHV and the density of crude oil (Table C.1). Gaines and Wolsky (1981) show that the carbon content of crude oil ranges between 83% and 87%, with most crude oils containing about 85.6% carbon. They also show that crude oil consists mainly of alkanes (including cycloalkanes), with a very small amount of aromatics. By comparison, gasoline contains a much smaller amount of alkanes and a much larger amount of aromatics (refining converts some of the alkanes to aromatics and other compounds). Since aromatics have a higher carbon to hydrogen

TABLE C.1 Characteristics of Fuels

Fuel	Higher Heating Values[a]		Density[b]	Carbon[c]	Sulfur
Domestic crude oil	0.1381 × 10^6 Btu/gal	5.800 × 10^6 Btu/bbl	3,191 g/gal	0.855	
Residual fuel oil	0.1497 × 10^6 Btu/gal	6.287 × 10^6 Btu/bbl	3,575 g/gal	0.858	
Diesel fuel	0.1387 × 10^6 Btu/gal	5.825 × 10^6 Btu/bbl	3,192 g/gal	0.858	
Petroleum coke	0.1434 × 10^6 Btu/gal	6.024 × 10^6 Btu/bbl	4,321 g/gal	0.900	
Marketable coke		6.024 × 10^6 Btu/bbl		0.900	
1987 gasoline	0.1251 × 10^6 Btu/gal	5.253 × 10^6 Btu/bbl	2,791 g/gal	0.866	0.0003
Reformulated gas	0.1222 × 10^6 Btu/gal	5.132 × 10^6 Btu/bbl	2,749 g/gal	0.833	0.0003
Methanol	0.0645 × 10^6 Btu/gal[d]		2,996 g/gal[e]	0.375[f]	
Ethanol	0.0846 × 10^6 Btu/gal[g]		2,988 g/gal[e]	0.522[f]	
Generic coal		21.340 × 10^6 Btu/ton		0.610[h]	0.0131[i]
Coal to power		20.923 × 10^6 Btu/ton		0.600[h]	0.0099[i]
Coal to methanol		21.340 × 10^6 Btu/ton		0.610[h]	0.0131[i]
Hydrogen	7,470 g/10^6 Btu	338.000 Btu/SCF[j]		0.00	
LPG for refineries[k]	0.0920 × 10^6 Btu/gal	3.863 × 10^6 Btu/bbl	2,053 g/gal		
NGLs		3.812 × 10^6 Btu/bbl[l]			
Electricity		3,412 Btu/kWh			
Steam		1,200 Btu/lb[m]			
Petroleum products		5.395 × 10^6 Btu/bbl[n]	6.68 bbl/ton		
Other refinery oil		5.825 × 10^6 Btu/bbl			
Oven-dried wood		8,350 Btu/lb			

---

[a] Values are from EIA's *Monthly Energy Review*, for the year 1988, unless otherwise noted. Where 10^6 Btu/gal and 10^6 Btu barrel are both shown, the former is calculated from the latter assuming 42 gal/bbl.

[b] From EIA *International Energy Annual* (1989), unless otherwise noted.

[c] Values for petroleum products from various sources, including Rose and Cooper (1977), Gaines and Wolfsky (1981), Francis and Peters (1983), Marks (1982), Rotty and Masters (1985), EPA mpg and emissions certification data, and my analysis of the composition of gasoline (see text and Table C.2).