Table 4.27 Usage Intensity of Fertilizer, Energy, and Pesticide for Soybean Farming

Parameter	Value (1990)[a]	GREET Value (2005)
Fertilizer use (g/bu)		
Nitrogen (N)	132.1	119
Phosphate (P_2O_5)	414.2	373
Potash (K_2O)	705.0	635
Herbicide use (g/bu)	53.1	47.8
Insecticide use (g/bu)	0.534	0.48
Energy use share in Btu/bu (%)		
Gasoline	10,570 (29.6)	(29.6)
Diesel	23,605 (66.1)	(66.1)
LPG	928 (2.6)	(2.6)
Natural gas	2 (0)	(0)
Electricity	571 (1.6)	(1.6)
Total	35,710 (100)	32,140

[a] Values are based on data in Sheehan et al. (1998). The data are for soybean farming in 14 states in 1990. To calculate per-bushel usage intensities, the average yield (bu/acre) of soybean production in 1990 was used (34 bu/acre).

4.4.2 Soybean Oil Extraction

At soybean oil extraction plants, soybean seeds are crushed, the oil is extracted from the crushed seeds, and the crude soybean oil is refined. Soybeans contain 18–20% oil by weight. To maximize soybean oil production, organic solvents are used during the oil extraction from the crushed soybean seeds. The solvent extraction system is a widely used and well-established technology. The standard solvent extraction process uses n-hexane produced from petroleum. Most of the n-hexane used in oil extraction is recovered and recycled, with some inevitable loss. The inputs and outputs from oil extraction plants are presented in Table 4.28. As the table shows, the Sheehan et al. (1998) study estimates higher energy use and soybean feed input than the Ahmed et al. (1994) study. In addition to steam, Sheehan et al. includes the natural gas used for drying and processing products. As the table shows, input default values for GREET rely primarily on estimates by Sheehan et al.

In calculating emissions and energy use, we assume that steam is generated from natural gas. N-hexane is a straight-chain hydrocarbon. Commercial hexane is manufactured by distillation of straight-run gasolines that have been distilled from crude oil or natural gas liquids. In GREET, hexane is assumed to be produced from crude, and its upstream production energy use and emissions are adopted from energy use and emissions calculated for producing LPG from crude. Because hexane is volatile, the amount of hexane lost during soy oil extraction is assumed to be in the form of VOC emissions to the atmosphere.

Table 4.28 Inputs and Outputs of Soybean Oil Extraction Plants

Inputs and Outputs	Ahmed et al. 1994[a]		Sheehan et al. 1998	GREET Values[b]
	Current Average	Industry Best		
Input				
Soybean (lb)	5.49	5.49	5.89	5.70
Steam (Btu)[c]	3,151	1,716	2,919	2,900 (44.5%)
NG (Btu)	0	0	2,826	2,800 (43.0%)
Electricity (kWh)	0.089	0.074	0.186	0.18 (9.4%)
N-hexane (Btu)	205	64	206	205 (3.1%)
Total energy (Btu)	3,660	2,032	6,586	6,519 (100%)
Output				
Soy oil (lb)	1	1	1	1
Soy meal (lb)	4.32	4.32	4.48	4.48

[a] The original values in Ahmed et al. were converted to the values shown by using a soy oil density of 7.7 lb/gal.

[b] We assumed in GREET that steam is produced from natural gas. Values in parentheses are percentage shares of process fuels.

[c] The amount of steam is presented as the amount of energy (in Btu) used to produce the needed steam.

As Table 4.28 shows, the process of soy oil extraction produces both soy oil and soy meals (an animal feed). Energy use and emissions from soybean farming and soy oil extraction need to be allocated between soy oil and soy feed. Three approaches are available for the allocation: weight-based, market value-based, and displacement. The weight-based approach could be used for soy oil production because the weights of both soy oil and soy meal can be measured. In contrast, the weight-based approach is not appropriate for ethanol production because the weight of the ethanol produced is not less meaningful than the Btu content. Table 4.29 presents the results of each allocation method. As discussed in Section 4.3.5, although the process energy approach can be used to allocate energy use and emissions of soy oil extraction plants, there are not enough available data to obtain an estimate by using that approach. The market value-based approach is used in GREET as the default approach.

4.4.3 Soy Oil Transesterification

The process of converting soy oil to methyl ester, the so-called transesterification process, is unique to the soybean-to-biodiesel cycle. The other upstream processes (i.e., soybean farming and soy oil extraction) are being used for soy oil production, regardless of whether the oil is used to produce biodiesel. The transesterification process involves reaction of the triglycerides present in soy oil with an alcohol such as methanol; the reaction is assisted by a catalyst (sodium hydroxide [NaOH] in this case). Table 4.30 presents inputs and outputs of biodiesel plants. To apply the values as specified in Table 4.30 to GREET, we assume that steam is generated with NG and that the energy embedded in the three chemical compounds is half oil and half NG.

Table 4.29 Split of Energy Use and Emissions between Soybean Oil and Soybean Meal

Allocation Approach	Split from Soybean Farming and Soy Oil Extraction (%)	
	Soy Oil	Soy Meal
Weight	18.2	81.8
Market value[a]	33.6	66.4
Displacement[b]	62.1	37.9

[a] The market value approach uses a price of $220.36 per metric ton for soy meal and $498.56 per metric ton for soy oil. These prices are the average of the prices predicted by the Food and Agricultural Policy Research Institute (1997) for 1996–2006.

[b] These values are based on Ahmed et al. (1994), who assumed that soy meal would displace barley and estimated the amount of energy used for production of the displaced barley. Ahmed and his colleagues also estimated an energy credit of 81,229 Btu from soy meal for each gallon of soy oil produced.

Table 4.30 Inputs and Outputs of Biodiesel Plants with the Transesterification Process

Inputs and Outputs	Ahmed et al. 1994		Sheehan et al. 1998	GREET Default Value
	Industry Average	Industry Potential		
Inputs				
Soy oil (lb)	1.04	1.04	1.04	1.04
Steam (Btu)	2,470	507	1,864	1,865
Electricity (kWh)	0.25	0.20	0.013	0.10
Methanol (Btu)	992	1,172	773	800
Sodium hydroxide (Btu)	36.3	45.4	263	263
Sodium methoxide (Btu)	NE[a]	NE	10	10
Hydrochloric acid (Btu)			32	32
Total process energy (Btu)[b]	5,217	3,489	2,802	3,311
Outputs				
Biodiesel (lb)	1	1	1	1
Glycerine (lb)	0.109	0.109	0.213	0.213

[a] NE = not estimated.

[b] The total process energy includes the energy embedded in NaOH, sodium methoxide, and hydrochloric acid.

The transesterification process produces both biodiesel and glycerine, a specialty chemical. Upstream energy use and emissions need to be allocated between biodiesel and glycerine. Table 4.31 presents the split of energy use and emissions between the two on the basis of weight-, market value-, and displacement-based approaches. For the displacement approach, we assumed that glycerine can also be produced from petroleum. In GREET, the market value approach is used as the default approach. Note that the split between biodiesel and glycerine is used to allocate soy oil-related energy use and emissions of soybean farming and soy oil extraction as well as energy use and emissions for soy oil transesterification.

Table 4.31 Split of Energy Use and Emissions between Biodiesel and Glycerine

Allocation Approach	Split (%)	
	Biodiesel	Glycerine
Weight	82.4	17.6
Market value[a]	70.1	29.9
Displacement[b]	79.6	20.4

[a] The glycerine price has varied between \$0.50 and more than \$1 per lb in the past several years. Biodiesel is currently produced in very limited volumes, so its price can be as high as \$4.50/gal. We assume that on a per-pound basis, the glycerine price is twice as high as the biodiesel price. We calculated market value split on the basis of this assumption.

[b] In the absence of glycerine production from soybeans, we assumed that glycerine can be alternatively produced from petroleum. Ahmed et al. (1994) estimated that the glycerine produced from the transesterification process was equivalent to 17,010 Btu/gal of biodiesel produced. Note that the glycerine production reported in Ahmed et al. is half of what GREET assumes. Thus, on the basis of GREET's glycerine production assumption, the energy credit can be about 34,020 Btu/gal of

4.5 Coal to Electricity

Over 50% of electricity used in the United States is generated from coal. In 1997, the United States produced 1,090 million tons of coal, and the three major coal-producing states — Wyoming, West Virginia, and Kentucky — produced 56% of the total U.S. coal (EIA 1998b). Of the 1,828 mines in operation in 1997, 874 were underground mines, and 954 were surface mines. Underground mines produced a total 421 million tons and surface mines produced 669 million tons. In 1997, the United States consumed 1,029 million tons of coal. Electric utilities consumed 88% of the total U.S. coal consumption (EIA 1998b).

Coal is classified into four types — bituminous, subbituminous, lignite, and anthracite — based on its carbon content, volatile mater content, and energy content. Bituminous coal, the most common type, is dense and black and with a moisture content of less than 20%. It is used for electricity generation, coke production, and space heating. Bituminous coal has a carbon content ranging from 69% to 86% by weight (dry matter). Its energy content ranges from 10,500 to 14,000 Btu/lb. Subbituminous coal is a dull black coal between lignite and bituminous coal with an energy content of 8,300–11,500 Btu/lb. Lignite coal is a brownish-black coal of low rank with high moisture and volatile matter. Its energy content is 6,300–8,300 Btu/lb. Anthracite coal is a hard, black lustrous coal containing a high percentage of carbon and a low percentage of volatile matter. Its carbon content ranges from 86% to 98%. In 1997, the United States produced 654 million tons of bituminous coal, 345 million tons of subbituminous coal, 86 million tons of lignite coal, and about 5 million tons of anthracite coal (EIA 1998b).

In 1997, the average quality of coal received by electric utilities was 10,275 Btu/lb energy content (HHV), 1.11% sulfur content, and 9.36% ash content. The average quality of coal received by coke and other manufacturing plants was 11,407 Btu/lb, 1.18% sulfur content, and 7.62% ash content (EIA 1998b). These specifications were used in the GREET model.

This section presents data for coal mining and coal transportation to power plants. Coal combustion in power plants and electricity transportation and distribution are discussed in Section 4.8.

4.5.1 Energy Efficiencies

On the basis of data presented in Delucchi (1991), Wang and Delucchi (1992), and Darrow (1994a), an energy efficiency of 99.3% is assumed in the GREET model for coal mining; an efficiency of 99.4% is assumed for coal transportation. Diesel fuel and electricity are used for coal mining. EIA (1998b) showed that, of the total tonnage of coal transported in 1997, 57% was moved by railroad cars; 22.3% by barges; 11.4% by trucks; and 9.3% by tramway, conveyor, and slurry pipeline. We assume that diesel fuel is used for railroad, truck, and pipeline transportation, and residual oil is used for barges. These values have been input into GREET.

4.5.2 Noncombustion Emissions

During the coal mining process, large amounts of the CH_4 contained in coal beds are released. Spath and Mann (1999) recently completed a life-cycle assessment of coal-fired power plants. They estimated 80.29 and 177.82 g of CH_4 emissions per million Btu of coal produced for surface mining and underground mining, respectively. EIA estimated that in 1997, 61% of the coal used in the United States was produced from surface mines and 39% from underground mines (EIA 1998b). Thus, we estimate an average CH_4 emission rate of 118.33 g/10^6 Btu of coal produced.

Coal is usually cleaned at mining sites to remove impurities such as sulfur, ash, and rock. By using data contained in Spath and Mann (1999), we estimate the following emission rates for coal cleaning: 7.016 g of VOCs, 4.07 g of PM_{10}, and 6.741 g of SO_x for each million Btu of coal produced.

4.6 Uranium to Electricity

Three stages of the uranium-to-electricity cycle (uranium mining, transportation, and enrichment) cause emissions because fuel combustion is involved in these stages. On the basis of data presented in Delucchi (1991), we assume an energy efficiency of 99.5% for uranium mining, 99.9% for uranium transportation, and 95.8% for uranium enrichment. No noncombustion emissions are assumed for this cycle. Natural gas, electricity, and residual oil are used for uranium mining. Diesel fuel is used in diesel locomotives and trucks for uranium transportation. Electricity is used for uranium enrichment.

4.7 Landfill Gases to Methanol

EPA (1991b) estimates that 3,000 to 6,000 landfills currently produce landfill gases primarily containing methane. The released methane is burned in flares at the landfill sites. Some companies have been developing compact, mobile facilities to produce methanol from landfill gases. Nationwide, there are about 600 landfills that generate large quantities of gases that can be used for methanol production; the GREET model includes this cycle of producing methanol from landfill gases.

4.7.1 Energy Efficiencies

During the process of converting landfill gas to methanol, energy is consumed to provide steam for the conversion process, to drive equipment, and to meet power needs in the plants. On the basis of data presented by SCAQMD for a proposed facility in southern California (SCAQMD 1994), we estimate an energy efficiency of 89.7% for the conversion process. The GREET model assumes that 99.3% of the consumed energy is electricity and the remaining 0.7% is landfill gases. Thus, 804 Btu of landfill gases and 33.4 kWh of electricity are consumed for each 10^6 Btu of methanol produced. Emissions from burning of the landfill gases are calculated from the amount of gases burned and the emission factors of natural gas combustion. Emissions from electricity consumption are estimated from the amount of electricity consumed and the average emission factors of electricity generation in a given region.

4.7.2 Emission Credits for Methanol Production

Because the production of methanol from landfill gases eliminates the practice of burning landfill gases in flares, the process of converting landfill gases to methanol earns emission credits equal to the amount of emissions that would otherwise be produced from combustion of landfill gases. On the basis of data presented in SCAQMD (1994), we calculate emissions credits of 5.582 g for VOCs, 106.1 g for CO, 21.6 g for NO_x, 35.36 g for PM_{10}, 7.393 g for SO_x, 706.8 g for CH_4, and 178,715 g for CO_2 for each 10^6 Btu of methanol produced. These emission credits, subtracted from emissions of the landfill-gas-to-methanol cycle, result in negative upstream emissions. On the other hand, as discussed later, emissions of on-vehicle methanol combustion are considered in calculating emissions from ICEVs fueled with the methanol that is produced from landfill gases.

4.8 Electricity Generation

Energy use and emissions of electricity generation are needed in GREET for two purposes: electricity usage of upstream fuel production activities and electricity use in EVs and grid-connected HEVs. Of the various power plants, those fueled by residual oil, NG, and coal produce emissions at plant sites. Nuclear power plants do not produce air emissions at plant sites, but emissions are associated with upstream uranium production and preparation stages, which are considered in GREET. The GREET model calculates emissions associated with electricity generation from residual oil, NG, coal, and uranium. Electricity generated from hydropower, solar energy, wind, and geothermal energy is treated as having zero emissions; these sources are categorized together in one group.

4.8.1 Combustion Technologies

For each fuel type, various combustion technologies can be used to generate electricity. In the GREET model, both current and future steam boilers are assumed for oil-fired plants. We also assume that current steam boilers will be phased out over time. For NG-fired power plants, the model assumes steam boilers, conventional gas turbines, and advanced combined-cycle gas turbines. For each fuel type, users can change the combustion technology mix in the GREET model to simulate emission impacts of a given combustion technology with a given fuel.

Spath and Mann (1999) recently completed a life-cycle assessment of coal-fired power plants. They assumed three coal-fired power plants: average plants operating around 1995 (energy conversion efficiency of 32%), plants meeting the new source performance standards (NSPS) (energy conversion efficiency of 34%), and plants equipped with low emission boiler systems (LEBS) (energy conversion efficiency of 42%). We treat the 1995 average plants as current plants, the NSPS plants as future plants, and the LEBS plants as advanced technology plants. Table 4.32 summarizes emission rates for the three plant types. These values have been input into GREET.

4.8.2 Power Plant Conversion Efficiencies

Table 4.33 presents power plant conversion efficiencies used in the GREET model and in some other studies. Oil-, NG-, and coal-fired boilers, NG-fired turbines, and nuclear plants are current technologies. Advanced NG combined-cycle turbines are a near-future technology, and advanced coal technologies (e.g., pressurized fluidized-bed combustion with combined cycle [PFB/CC] and integrated gasification with combined cycle [IGCC]) are a long-term future technology. Combined-cycle gas turbines are promoted because of their very high conversion efficiency and lower operating costs; some electric power plants have already incorporated this technology. The IGCC technology, first demonstrated in the mid-1980s, generates extremely low emissions, but its costs are high.

Table 4.32 Emissions Rates of Three Types of Coal-Fired Power Plants[a,b]

Emission Type	Plant Type: Average Plant (Energy Conversion Efficiency of 32%)	Plant Type: NSPS Plant (Energy Conversion Efficiency of 34%)	Plant Type: LEBS Plant (Energy Conversion Efficiency of 42%)
VOC	1.501	1.436	1.477
CO	12.567	12.617	12.309
NO_x	285.02	209.36	44.068
PM	12.661	12.617	6.524
SO_x	600.23	228.65	44.068
CH_4	0.75	0.943	5.098
N_2O	0.298	0.347	0.0328

[a] From Spath and Mann (1999).

[b] Emissions are in g/10^6 Btu coal input.

Table 4.33 Energy Conversion Efficiencies of Electric Power Plants (%)

Electric Power Plant Type	GREET	Delucchi 1991	Bentley et al. 1992		Wang and Delucchi 1992		Ecotraffic, AB 1992	Darrow 1994a	EIA 1995
Year			2010	2020	1990	2010			
Oil-fired boilers	34–35	31.8	34	34	31	35.4	38	33	36
NG-fired boilers	34–35	32.8	34	34	31.3	39	38	33	36
NG-fired turbines	34–35	33	34	36	31.4	31.4	38	33	29.8–37.3
NG-fired combined-cycle turbines	55	NE[a]	51	53	40	47	50	NE	46.3
Coal-fired boilers	34–35	32.9	38	40	33	37	38	33	35.4
Advanced coal technologies[b]	38	NE	NE	NE	37.9	44.8	NE	NE	38.7
Nuclear plants	34	NE	NE	34	NE	NE	NE	NE	NE

[a] NE = not estimated.

[b] Advanced coal combustion technologies include PFB/CC and IGCC.

Both currently used technologies and potential future technologies are included in GREET so that the model can simulate the impacts of using EVs and HEVs in the future with clean, efficient technologies to generate electricity.

4.8.3 Natural Gas-Fired Combined-Cycle Gas Turbines

In the electric utility sector, combined-cycle technology refers to the combined use of hot-combustion gas turbines and steam turbines to generate electricity. The arrangement of the two turbine types can increase the thermal efficiency of power plants far beyond the efficiency of conventional power plants using either type of turbine alone. Because of their economic and environmental superiority, NG-fired combined-cycle power plants are expected to take a significant market share of future power generation expansion (Zink 1998a; Hansen and Smock 1996).

A gas turbine consists of three major components: a compressor, a combustor, and a power turbine. Ambient air is drawn into the compressor and compressed up to 30 atmospheres (about 440 psi). The air is then directed to the combustor, where NG is introduced and burned. Hot combustion gases are diluted and cooled with additional air from the compressor and directed to the turbine. Energy from the hot, expanding exhaust gases is recovered in the form of shaft horsepower, which can be used to drive an external load generator for electricity generation. The primary environmental concerns for combined-cycle turbines are emissions of NO_x and CO. Turbine manufacturers have been working on new designs to reduce emissions as well as improve thermal efficiency. With continuously improved material coatings and cooling technologies, gas turbine inlet temperature has been increased to about 1,320°C (2,400°F), helping increase the efficiency of the combined cycle considerably (Zink 1998b; Viswanathan et al. 1999; Schimmoller 1998; Esch and DeBarro 1998; DeMoss 1996; Kuehn 1995a; Kuehn 1995b; Smith 1994). Also, by using a lean mixture of air and fuel, staging combustion at lower temperatures, and decreasing the residence time of gases in the combustor, turbine manufacturers have lowered NO_x emissions from advanced gas turbines to about 20 to 30 parts per million (ppm) without using water injection, selective catalytic reactors, or other post-combustion control devices (Kuehn 1995a; Kuehn 1995b; Smith 1994).

More efficient combined-cycle turbines may be designed by incorporating one of these options: simple lean combustion, two-stage lean/lean combustion, and two-stage rich/lean combustion (EPA 1996). Relative to a stoichiometric mixture of fuel and air, the lean mixture helps reduce the peak and average temperature within the combustor, resulting in lower rates of NO_x formation. The two-stage lean/lean combustion design involves two fuel-staged combustors; lean burning occurs in each. This design allows a turbine to operate with an extremely lean mixture and a stable flame that should not "blow-off" or extinguish. By contrast, the two-stage rich/lean design essentially involves air-staged combustors in which the primary zone is operated under fuel-rich conditions and the secondary zone under fuel-lean conditions. The rich mixture in the primary zone produces a lower temperature (compared to a stoichiometric mixture) and high concentrations of CO and H_2 (caused by incomplete combustion). The decreased temperature, the high concentration of CO and H_2, and the decreased amount of oxygen in the rich mixture help reduce NO_x formation. Before entering the secondary combustion zone, the combustion gas from the primary zone is quenched by a large amount of air, creating a lean mixture. The combustion of the lean mixture is then completed in the secondary zone with very low NO_x emissions.

The sensible heat of the hot exhaust gas from a gas turbine can either be discarded without heat recovery (the simple cycle) or used in a heat recovery steam generator (usually a Rankine-cycle generator) to generate additional electricity (the combined cycle). Because of its low capital investment, the simple cycle is often used for small, peak-load electricity generation. The combined cycle is used for large, base-load electricity generation. The thermal efficiency of a combined-cycle system with an inlet gas temperature of 2,400°F is around 56%, based on the LHV of NG. The efficiency goal of the DOE Advanced Turbine Systems Program is 60% with an inlet gas temperature approaching 2,600°F (Schimmoller 1998). We use an energy conversion efficiency of 55% for combined-cycle gas turbines.

4.8.4 Electric Generation Mixes

The electric generation mix greatly affects the fuel-cycle emissions of EVs and grid-connected HEVs. Because this mix differs significantly across regions, use of EVs and HEVs can have very different emission impacts in different regions. Table 4.34 presents the electric generation mix in various U.S. regions (Figure 4.4 shows these regions). The data show that on the West Coast and in the Northeast, where EV use is adopted or proposed, electricity is primarily generated from clean sources such as nuclear power, hydropower, and NG. Each of these electric generation mix sets can be input into the GREET model to simulate EV or HEV emission impacts.

Recharging of EVs and grid-connected HEVs will certainly not draw electricity from the average electric generation mix that is in place in the absence of EVs and HEVs. The so-called marginal electric generation mix for EVs and HEVs in a given region is determined by many factors: the excess electric generation capacity, the type of new additional power plants, the amount of total electricity needed by EVs and HEVs, the time of day that EVs and HEVs are recharged, and the way in which electric utilities determine their power plant dispatch.

There are large uncertainties involved in estimating marginal electric generation mixes. Several past major studies on EVs estimated the marginal electric generation mixes for recharging EVs (e.g., a multilaboratory study on EVs funded by DOE [Argonne National Laboratory et al. 1998a,b]). These past studies were usually region-specific and made specific assumptions about the number of EVs introduced. Preferably, marginal generation mixes should be used in estimating energy use and emissions associated with EVs and HEVs. GREET is designed to account for marginal generation mix in its calculations. Because of the uncertainties involved in estimating marginal mixes, we use average generation mixes to estimate EV and HEV energy use and emissions in this report. To show the impacts of electric generation mix, we estimate EV and HEV energy use and emissions for several regions that have distinctly different mixes. On the other hand, average generation mix is used for calculating energy use and emissions of the electricity to be used for upstream fuel production activities. This is why, in GREET, average and marginal generation mixes are two separate entries.

Table 4.34 Electric Generation Mixes of Various U.S. Regions in 2005 and 2015[a]

Region	Energy Source (%)				
	Coal	Oil	NG	Nuclear	Others
Year 2005					
East Central (ECAR)	83.7	0.2	5.8	8.5	1.8
Texas (ERCOT)	42.1	0.1	43.8	13.2	0.8
Mid-Atlantic (MAAC)	38.5	0.5	25.3	32.9	2.8
Illinois and Wisconsin (MAIN)	62.3	0.1	4.8	31.3	1.5
Mid-Continent (MAPP)	72.0	0.2	10.5	8.8	8.4
New York State (NY)	20.6	2.0	28.9	19.2	29.3
New England minus New York (NE)	13.0	7.5	48.1	19.0	12.4
Florida (FL)	50.6	5.9	24.3	16.8	2.5
Southeast minus Florida (STV)	59.8	0.2	8.4	26.0	5.5
Southwest (SPP)	61.7	0.1	22.1	13.2	3.0
Northwest (NWP)	27.7	0.1	17.3	2.8	52.0
Rocky Mountains and Arizona (RA)	58.5	0.1	18.1	12.9	10.4
California and Southeast Nevada (CNV)	23.1	0.4	30.4	18.7	27.3
California[b]	7.0	0.2	30.6	14.1	48.1
Northeastern U.S. average[c]	28.2	2.5	31.6	26.3	11.4
U.S. average	53.8	1.0	14.9	18.0	12.3
Year 2015					
East Central (ECAR)	76.1	0.2	16.1	6.1	1.6
Texas (ERCOT)	39.1	0.1	48.8	11.2	0.8
Mid-Atlantic (MAAC)	36.2	0.3	40.7	19.9	2.8
Illinois and Wisconsin (MAIN)	63.1	0.1	12.8	22.6	1.4
Mid-Continent (MAPP)	66.3	0.2	25.7	0.0	7.8
New York State (NY)	19.1	1.3	41.4	11.5	26.7
New England minus New York (NE)	11.4	4.7	55.7	16.1	12.1
Florida (FL)	54.9	4.4	29.5	8.9	2.4
Southeast minus Florida (STV)	56.4	0.2	21.8	16.7	4.9
Southwest (SPP)	53.9	0.1	33.7	9.7	2.7
Northwest (NWP)	25.7	0.1	22.8	2.6	48.8
Rocky Mountains and Arizona (RA)	50.5	0.1	29.4	10.9	9.1
California and Southeast Nevada (CNV)	44.8	0.3	23.4	8.7	22.8
California[b]	7.0	0.2	30.6	14.1	48.1
Northeastern U.S. average[c]	26.3	1.6	44.4	17.0	10.7
U.S. average	54.0	0.8	21.1	12.4	11.7

[a] Calculated from data presented in EIA (1997d), except as noted.

[b] From California Department of Finance (1996).

[c] The electric generation mix for the northeastern United States is the generated-electricity weighted average of Mid-Atlantic states (MAAC), New York State (NY), and the New England area without New York (NE).

4.9 Vehicle Operations

4.9.1 Alternative Fuels and Vehicle Technologies Included in GREET

The GREET 1 series is designed to estimate fuel-cycle energy use and emissions for passenger cars and LDTs only. The GREET 3 series is designed to estimate fuel-cycle energy use and emissions of heavy-duty trucks and buses. Table 4.35 presents near-term and long-term vehicle technologies. Near-term technologies are those already or almost available in the marketplace. Long-term technologies are those that require further research and development. Spark-ignition (SI) engines are assumed for vehicles fueled with RFG, CNG, LNG, M85, M95 (mixture of 95% methanol and 5% gasoline by volume), LPG, E85, and E95. Compression-ignition (CI) engines are assumed for vehicles fueled with CD, RFD, DME, FTD, and biodiesel. Baseline vehicles are assumed to be SI engines fueled with CG (for near-term options) and RFG (for long-term options).

In estimating fuel-cycle energy use and emissions for HEVs, the GREET model assumes a generic HEV type. Various on-board power units that use different fuels are proposed for use in HEVs; the model includes HEV types equipped with both SI and CI engines. HEVs can be grid-connected — energy is provided from grid electricity and from on-board power generation units — or they can be operated independently from grid electricity. Overall energy use and emissions for grid-connected HEVs are calculated by using the average energy use and emissions of the grid electricity mode and on-board engines weighted by VMT in each mode. The all-electric range of an HEV depends on its battery size, its battery state-of-charge operating range, and its driving patterns. Thus, the all-electric range, which is specific to an HEV model, an HEV operation control strategy, and a driving cycle, can be determined only by using dynamic models that simulate HEV operations (Wang et al. 1997a). Recent simulations of HEVs at Argonne indicate that grid-connected HEVs could make 30% of their total VMT by using grid electricity (Vyas 1998). GREET 1.5 uses this value to calculate average energy use and emissions of grid-connected HEVs.

The GREET model assumes proton-exchange membrane fuel-cells for hydrogen-, gasoline-, methanol-, NG-, and ethanol-fueled FCVs. FCVs fueled with all fuels except hydrogen are assumed to be equipped with on-board fuel processors (steam reforming and partial oxidation technologies) to produce hydrogen from these fuels.

In running GREET, energy use and emissions of individual AFVs are calculated for near-term and long-term technology options. The near-term technologies are those available now; the near-term baseline GVs are subject to federal Tier 1 emission standards.

The long-term technology options are those that are currently in the research and development stages and may be available in about 10 years. The long-term baseline GVs are assumed to meet the federal Tier 2 emission standards proposed recently by EPA (1999). The fuel economy of baseline gasoline cars will be improved on the near-term baseline vehicles.

Table 4.35 Near- and Long-Term Vehicle Technology Options for Passenger Cars, Light-Duty Trucks 1, and Light-Duty Trucks 2[a]

Near-Term Options (MY 2000)	Long-Term Options (MY 2010)
GVs: RFG2	CNGVs: dedicated
CNGVs: bi-fuel	LNGVs: dedicated
CNGVs: dedicated	LPGVs: dedicated
LPGVs: dedicated	M90-dedicated vehicles
FFVs: M85	E90-dedicated vehicles
FFVs: E85	SIDI vehicles: RFG2
EVs	SIDI vehicles: M90
Grid-independent SIDI HEVs: RFG2	SIDI vehicles: E90
Grid-connected SIDI HEVs: RFG2	Grid-independent SIDI HEVs: RFG2
CIDI vehicles: CD	Grid-independent SI HEVs: CNG
Grid-independent CIDI HEVs: CD	Grid-independent SI HEVs: LNG
	Grid-independent SI HEVs: LPG
	Grid-independent SIDI HEVs: M90
	Grid-independent SIDI HEVs: E90
	Grid-connected SIDI HEVs: RFG2
	Grid-connected SI HEVs: CNG
	Grid-connected SI HEVs: LNG
	Grid-connected SI HEVs: LPG
	Grid-connected SIDI HEVs: M90
	Grid-connected SIDI HEVs: E90
	CIDI vehicles: RFD
	CIDI vehicles: DME
	CIDI vehicles: FT50
	CIDI vehicles: BD20
	Grid-independent CIDI HEVs: RFD
	Grid-independent CIDI HEVs: DME
	Grid-independent CIDI HEVs: FT50
	Grid-independent CIDI HEVs: BD20
	Grid-connected CIDI HEVs: RFD
	Grid-connected CIDI HEVs: DME
	Grid-connected CIDI HEVs: FT50
	Grid-connected CIDI HEVs: BD20
	Evs
	FCVs: H_2
	FCVs: methanol
	FCVs: gasoline
	FCVs: ethanol
	FCVs: CNG

[a] GV = gasoline vehicle; RFG2 = reformulated gasoline 2; CNGV = compressed natural gas vehicle; LNGV = liquified natural gas vehicle; LPGV = liquefied petroleum gas vehicle; M90 = mixture of 90% methanol and 10% gasoline by volume; FFV = flexible-fuel vehicle; M85 = mixture of 85% methanol and 15% gasoline by volume; E90 = mixture of 90% ethanol and 10% gasoline by volume; E85 = mixture of 85% ethanol and 15% gasoline by volume; SIDI = spark-ignition, direct-injection; HEV = hybrid electric vehicle; CD = conventional diesel; CIDI = compression-ignition, direct-injection; CNG = compressed natural gas; LNG = liquified natural gas; LPG = liquified petroleum gas; RFD = reformulated diesel; DME = dimethyl ether; FT50 = mix of 50% Fischer-Tropsch and 50% conventional diesel (by volume); BD20 = mix of 20% biodiesel and 80% conventional diesel (by volume); FCV = fuel cell vehicle; H_2 = hydrogen.

Fuel economy for AFVs is calculated from baseline GV fuel economy and relative improvement in fuel economy between GVs and the other vehicle types. The results of these calculations are presented in the following sections.

Emissions from vehicle operations are calculated for nine pollutants or sources: exhaust and evaporative VOCs, CO, and NO_x; exhaust PM_{10}; and PM_{10} from brake and tire wear; and exhaust SO_x, CH_4, N_2O, and CO_2. VOC emissions (both exhaust and evaporative), CO, and NO_x for GVs and CD vehicles are calculated by using EPA's Mobile model. The current version of Mobile (Mobile 5b) does not include any AFVs. EPA plans to release the next version of Mobile (Mobile 6) by the end of 1999. At present, EPA plans to include only CNGVs in Mobile 6. Emissions of PM_{10} (both exhaust and brake wear/tire wear) for GVs and CD vehicles are calculated by using EPA's Part 5 model.

In analyzing vehicle emission performance, researchers must consider that there are three types of emission rates (in g/mi). The first is emission standards to which motor vehicles are subject. These are the maximum allowable emission rates that vehicles can emit for a specified accumulated mileage. In the United States, vehicle emission standards are established by CARB for California and by EPA for the rest of the country.

The second type is emission certification rates. These are laboratory-tested emissions for new vehicles. Vehicles are tested by manufacturers under controlled laboratory conditions by following testing protocols. The certification rates are compared with applicable emission standards to determine whether a given vehicle model meets emission standards.

The third type is estimated on-road emissions of given vehicle groups. Motor vehicles experience various emission deterioration effects from laboratory-controlled conditions to actual on-road operating conditions. Estimated on-road emission rates, often based on laboratory testing results under different on-road operating conditions, account for the deterioration effects. The estimated on-road emission rates are usually used by states and local governments to estimate the mobile source emission inventory. The Mobile and Part models were developed to estimate on-road emission rates of motor vehicles. Usually, certification emission rates are lower than emission standards, and emission standards are lower than on-road emissions because on-road operating conditions are generally less ideal than laboratory testing conditions.

Ideally, Mobile and Part should include conventional and advanced vehicle technologies. In that case, the models could be used to estimate on-road emission rates for each vehicle type. However, the models include only vehicles fueled by conventional gasoline and diesel fuel. For GREET simulations, Mobile and Part are used to develop on-road emission rates for baseline gasoline and diesel vehicles. Then, emission changes between baseline vehicles and alternative-fueled/advanced vehicles are estimated on the basis of laboratory-tested emissions of baseline vehicles and new vehicle types. GREET model is intended to estimate on-road emissions. And although Mobile and Part have problems in estimating on-road emissions, until better models are developed, they are still the most widely used models for estimating on-road emissions.

4.9.2 Gasoline Vehicles Fueled with Reformulated Gasoline

The 1990 CAAA required the use of RFG in some of the nation's worst ozone nonattainment areas. The requirement was designed in two tiers. The so-called federal Phase 1 RFG (FRFG1) took into effect in January 1995, and the Phase 2 RFG (FRFG2) will take effect in 2000. The CAAA requires a minimum VOC reduction of 15% by FRFG1 and a minimum reduction of 25% by FRFG2. FRFG1 could be certified with composition requirements or emission performance standards. FRFG1 composition requirements are less than 1% (by volume) benzene, less than 25% (by volume) aromatics, and more than 2% (by volume) oxygen. Under the performance standard requirements, FRFG1 is required to reduce per-gallon VOC emissions by 16% (northern regions) to 35% (southern regions) and air toxics emissions by about 15%, relative to CG (EPA 1994). Note that the reduction for VOC emissions is the combined reduction of exhaust and evaporative emissions, with evaporative emissions reductions accounting for the greater share. FRFG2 will be certified by using emission performance standards under which FRFG2 is required to reduce VOC emissions by 27.5% in southern regions and 25.9% in northern regions, air toxic emissions by 20%, and NO_x emissions by 5.5%, all relative to CG.

California established its own RFG requirements. The California RFG requirements were designed in two tiers, too. The California Phase 1 RFG (CARFG1) standards took effect in January 1992. CARFG1 has the following composition requirements: maximum aromatic content of 32% (by volume), maximum sulfur content of 150 ppm (by weight), maximum olefin content of 10% (by volume), and maximum 90% distillation temperature of 330°F (CARB 1991). The California Phase 2 RFG (CARFG2) took effect in January 1996. Table 4.36 presents its specifications (CARB 1998). Gasoline producers are allowed to certify RFG by using the specification requirements or by the emission performance requirements under which producers need to demonstrate a different set of specifications can meet predetermined emissions reduction requirements.

Table 4.36 Specifications of California Phase 2 Reformulated Gasoline[a]

Parameter	"Flat" Limit	"Average" Limit	"Cap" Limit
RVP (psi)	7.0	none	7.0
Sulfur (weight ppm)	40	30	80
Benzene (volume %)	1.0	0.80	1.20
Aromatics (volume %)	25	22	30
Olefins (volume %)	6.0	4.0	10
Oxygen (weight %)	1.8–2.2	none	3.5 (max)
T50 (°F)	210	200	220
T90 (°F)	300	290	330

[a] From CARB (1998).

Recently, EPA proposed Tier 2 emission standards for passenger cars and LDTs up to 8,500 lb gross vehicle rated weight. The proposed Tier 2 standards call for new motor vehicles (manufactured after 2004) to meet a 0.07-g/mi NO_x standard and 0.01-g/mi PM standard. To allow new vehicles to meet these standards, EPA proposes a reformulated gasoline (RFG2) with an average sulfur content of 30 ppm and a sulfur content cap of 80 ppm to be produced by 2006. The newly proposed RFG is similar to California RFG2. In our analysis, we assume that the federal RFG2 after 2005 will be the same as California RFG2.

Because the newly proposed federal RFG2 is similar to California RFG2. We estimate energy and emissions changes for only the federal RFG2. Table 4.37 shows changes in fuel economy and emissions achieved by using RFG, relative to CG. The study by Battelle (Battelle Memorial Institute 1995a,b; Orban et al. 1995) was conducted for the South Coast Alternative Fuels Demonstration Project, also known as the CleanFleet Project. The purpose of the project was to gather data on the AFV types available in the early 1990s. Through the project, Federal Express delivery vans were recruited for laboratory emissions tests as they accumulated mileage. A total of 111 vans (weighing between 4,800 and 5,700 lb) from service fleets in Los Angeles were tested or monitored. These vans were fueled with CG, CARFG2, LPG, CNG, M85, and electricity. Laboratory emissions tests were performed by CARB on 36 vans: 12 Chevrolet vans (three aftermarket-converted LPG vans, three aftermarket-converted CNG vans, three gasoline vans fueled with CARFG2, and three gasoline vans fueled with CG), nine Dodge vans (three CNG vans produced by original equipment manufacturers [OEMs], three gasoline vans fueled with CARFG2, and three gasoline vans fueled with CG), and 15 Ford vans (three OEM-produced methanol flexible-fuel vans, three aftermarket converted LPG vans, three OEM-produced CNG vans, three gasoline vans fueled with CARFG2, and three vans fueled with CG). Emissions were measured for THC, NMHC, NMOG, CO, NO_X, CH_4, N_2O, and air toxics.

The Auto/Oil Air Quality Improvement Research Program (AQIRP) was established in 1989 with the participation of 14 oil companies and the big three domestic automakers. The program was intended to provide data on emissions and air quality effects associated with the fuel quality of gasoline and alternative fuels. Between 1989 and 1993, the AQIRP researchers conducted more than 5,000 emissions tests in which they used more than 90 fuel compositions in more than 100 vehicles (AQIRP 1997). Emission tests were conducted with CARFG2 on three vehicle categories: an “older” vehicle fleet (1983–1985 MY vehicles), current vehicle fleet (1989 MY vehicles [current when the AQIRP program started]), and federal Tier 1 fleet (1994 MY vehicles). Another vehicle group — the advanced technology fleet — was not tested with average gasoline, so emission changes between RFG and CG could not be estimated for this group. The study showed that CARFG2 used in federal Tier 1 vehicles generally achieved greater emissions reductions than when it was used in other vehicles. This finding implies that newer vehicles can be designed to tap the emissions reduction potential of RFG to a greater extent than older vehicles.

Table 4.37 Changes in Fuel Economy and Emissions by Use of Reformulated Gasoline: Test Results[a]

		Change Relative to CG (%)				
Source	Vehicle Model	Economy (mpg[b])	Exhaust VOCs	CO	NO_x	CH_4
Battelle[c]	1992 Chevy 4.3-L van	0.7[d]	-34.4[e]	-25.0	-15.2	2.5
	1992 Dodge 5.2-L van	-3.0	-34.1	-18.9	-27.1	-16.7
	1992 Ford 4.9-L van	-2.2	-14.3	-1.9	4.9	-3.3
AQIRP [f]	Older vehicles[g]	-2	-12	-23	-9	NA[h]
	Current vehicles[i]	-3	-22	-21	-7	NA
	Tier 1 vehicles[j]	-4	-27	-28	-16	NA
	Three MeOH FFVs[k]	-1.0	-31.3	-18.3	-25.5	NA
	Three large LDVs[l]	0.0	-20.5	-29.9	-21.5	-13.6
	Three EtOH FFVs[m]	-7.5	-11.8	8.3	-7.0	NA
GRI[n]	Two 1996 Ford large cars[o]	-3.1	-2.7	10.8	6.3	16.7
	Two 1995 Dodge Caravans	-2.3	-9.9	-8.0	-16.3	12.9
	Two 1995 Dodge Ram Vans	-3.0	-16.2	-8.6	-7.7	0

[a] Values are measured in percent relative to use of CG, under the federal test procedure (FTP) cycle.

[b] mpgeg = miles per gasoline-equivalent gallon.

[c] From Battelle Memorial Institute (1995a,b) and Orban et al. (1995). Emissions were tested in three phases as vehicle mileage accumulated. The values here are the average of the results from the three phases. The RFG was CARFG2.

[d] In the Battelle study, mpg was determined in two ways: first, on the basis of actual fuel consumption and mileage for each fuel, and second, on the basis of laboratory tests under the FTP cycle. The on-road results were affected by driving patterns, traffic conditions, and many other factors. With RFG and CG, mpg could be tested under exactly the same driving conditions. Laboratory-tested mpg results were used here to determine mpg changes by RFG.

[e] For NMOG.

[f] From AQIRP (1995a; 1996). The tested RFG was CARFG2.

[g] The older vehicles tested were seven 1983–1985 MY vehicles.

[h] NA = not available.

[i] The current vehicles tested were ten 1989 MY vehicles.

[j] The Tier 1 vehicles tested were six 1994 MY vehicles.

[k] From AQIRP (1995c). The three methanol FFVs were a 1993 Dodge 2.5-liter (L) Spirit, 1993 Ford 3.0-L Taurus, and 1992 Chevrolet 3.1-L Lumina.

[l] From AQIRP (1995b). The three large LDVs were a 1992 Chevrolet 5.7-L C20 pickup, 1993 Ford 4.6-L Crown Victoria, and 1992 Dodge 5.2-L B150 Ram Wagon. The three vehicles were the baseline GVs tested together with CNG vehicles for emission comparisons.

[m] From AQIRP (1995c). The three ethanol FFVs were a 1993 Chevrolet 3.1-L Lumina, 1993 Ford 3.0-L Taurus prototype, and 1993 Plymouth 2.5-L Acclaim prototype.

[n] From Engine, Fuel, and Emissions Engineering, Inc. (1997). The tested RFG was FRFG2.

[o] The two cars were a Ford Crown Victoria and a Ford Grand Marquis.

In summary, the AQIRP concluded that with Tier 1 vehicles, CARFG2 achieved 18–36% reductions in HC emissions, 19–38% in CO emissions, 6–27% in NO_x emissions, and 23–41% in air toxics emissions (AQIRP 1997; *Automotive Engineering* 1996a,b). CARFG2 reduced volumetric fuel economy by 2–4%. Note that the baseline CG used in the AQIRP was a blend to represent 1988 national average gasoline composition.

The study for GRI was conducted with newer vehicles fueled with FRFG2. Because of the use of FRFG2, the study showed consistently lower emission benefits than the other two studies.

On the basis of the results presented in the Table 4.37, we assume emission and fuel economy changes of CARFG2 and FRFG2 relative to CG (Table 4.38). Note that in our application of GREET in this study, we assume an RFG similar to California RFG2 because of EPA's newly proposed federal RFG (EPA 1999).

Table 4.38 Reductions in Emissions and Fuel Economy by Use of Reformulated Gasoline: Regulatory Specifications

Parameter	Reduction (%) CARFG2	Reduction (%) FRFG2[a]
Exhaust VOCs	27[b]	26[c]
Evaporative VOCs	27[d]	26[c]
CO	28[b]	20[d]
NO_x	15[b]	5[c]
PM_{10}	5[d]	5[d]
CH_4	8[b]	8[d]
N_2O	0[d]	0[d]
Volume mpg	2[b]	2[d]
Btu mpg	0[d]	0[d]

[a] The federal RFG2 before the newly proposed federal RFG2 with 38 ppm sulfur content.

[b] Based on testing results from Battelle (1995a,b) and AQIRP (1995a,b,c; 1996).

[c] Based on EPA's emissions performance standards for federal RFG2.

[d] Assumed in this study.

4.9.3 Compressed Natural Gas Vehicles

For model year 1999, the following CNGV models are offered for purchase: Chrysler Ram wagon, Chrysler Ram van, Ford Contour (bi-fuel), Ford Crown Victoria, Ford Econoline Super Club, Ford Econoline E-350 van, Ford F-Series pickup truck, Chevrolet Cavalier, and GMC Sierra 2500 truck (*New Fuels and Vehicles Report 1998*). Table 4.39 summarizes changes in fuel economy and emissions by CNGVs relative to GVs. In studies conducted by NREL for DOE on AFV emissions (Kelly et al. 1996a,b,c), NREL tested CNGVs and methanol and ethanol FFVs. For methanol FFVs, NREL tested 71 1993-MY methanol Dodge Spirit FFVs and 16 1993-MY methanol Econoline FFVs. The FFV Spirit was an EPA-certified production vehicle, while the FFV Econoline was an uncertified prototype demonstration vehicle. A similar number of gasoline Spirits and E150 Econolines were tested. The FFVs were fueled with M85, M50, and CARFG2 (as the baseline fuel). For ethanol FFVs, NREL tested 21 1992/93-MY ethanol variable-fuel vehicle (VFV) Luminas and a similar number of gasoline Luminas. The ethanol VFVs were tested with E85, E50, and CARFG2. For CNG vehicles, NREL tested 37 dedicated CNG Dodge B250 vans and 38 gasoline B250 vans, all of which were 1992–94 MY vehicles. The CNG van, equipped with a catalytic converter specifically designed for reducing emissions from CNGVs, was certified to meet CARB's low-emissions vehicle (LEV) emissions standards. Because CARFG2 was used as the baseline fuel, emission changes of CNG, methanol, and ethanol were calculated relative to CARFG2, not CG.

Table 4.39 Changes in Fuel Economy and Emissions by Use of Compressed Natural Gas Vehicles[a]

		Change Relative to CG (%)					
Source	Vehicle Model	Fuel Economy	Exhaust VOCs	CO	NO_x	CH_4	N_2O
Battelle[b]	Chevy 5.7-L van[c]	-15.7	-81.7	-72.3	-57.6	3,626.1	-82.8
	Dodge 5.2-L van	-9.7	-93.8	-78.8	-45.1	808.3	-56.4
	Ford 4.9-L van	-2.2	-61.1	-69.0	105.4	2,167.2	35.2
AQIRP[d]	1992 GM 5.7-L Sierra Pickup[e]	-17.0	-86.5	-21.0	-74.6	1,311.5	NA[f]
	1993 Ford 4.6-L Crown Victoria [e]	-14.4	-80.0	-59.3	-47.7	1,223.3	NA
	1992 Chrysler 5.2-L B150 van[e]	-22.8	-89.1	-72.7	-8.6	900.0	NA
NREL[g]	92 and 94 MY 5.2-L Dodge B250 van	-7.9	-80.4	-45.4	-31.1	NA	NA
						NA	NA
SWRI[h]	1994 MY 4.3-L GMC 1500 pickup (aftermarket conversion)	5.5	-87.9	-18.3	-37.2	1,168.3	NA
GRI[i]	1996 MY Ford Crown Victoria dedicated	-4.7	-66.2	-4.6	-63.3	975.0	NA
	1995 MY Dodge Caravan dedicated	-14.1	-88.4	-83.2	-63.9	187.1	NA
	1994 Dodge Ram van dedicated	2.3	-93.1	-12.4	36.3	478.7	NA
	1996 Dodge Ram van dedicated	-6.1	-83.1	-87.0	-32.9	278.7	NA
Ford[j]	1997 Ford 5.4-L F-250 pickup dedicated	-16.0	-91.0	-39.0	-50.0	NA	NA
	1997 Ford 5.4-L E-250 van dedicated	-18.0	-95.0	-65.0	-65.0	NA	NA
Honda[k]	1998 Honda Civic GX	-6.1	-96.4	-90.9	-85.4	NA	NA
EPA	1995 Dodge Caravan dedicated	NA	-80.0	-85.8	-39.2	NA	NA
certification[l]	1995 Dodge Caravan dedicated	NA	-85.7	-82.1	-37.5	NA	NA
	1996 Ford Crown Victoria dedicated	NA	-57.1	32.8	-88.2	NA	NA
	1996 Ford 2.0-L Ford Contour[l,m]: bi-fuel	NA	15.7	4.8	100.0	NA	NA
	1997 Ford Crown Victoria dedicated	NA	-51.7	-50.0	-86.7	NA	NA
	1997 Chrysler minivan dedicated	NA	-85.8	-72.9	-52.6	NA	NA
	1998 Ford Crown Victoria dedicated	NA	-86.5	-35.1	34.8	NA	NA
	1998 Chevy C2500 pickup bi-fuel (OEM)	-4.6	-77.3	-23.0	-12.1	1,472.0	NA
	1998 Chevy C2500 pickup bi-fuel (OEM)	-5.9	-77.1	-29.4	-4.2	1,437.0	NA
	1998 Chevy Cavalier bi-fuel (OEM)	NA	-52.2	-15.8	0	NA	NA
	1998 Chevy Cavalier bi-fuel (OEM)	NA	-77.1	-29.4	-4.2	NA	NA
	1998 Ford 2.0-L Contour: bi-fuel[k]	NA	-66.7	-23.7	-8.2	NA	NA
	1998 Ford 2.0-L Contour: bi-fuel[k]	NA	-42.0	-16.7	0.0	NA	NA
Santini and	Passenger cars	NA	-76.0	-33.0	0.0	NA	NA
Saricks[n]	Pickup trucks	NA	-81.0	3.0	-6.0	NA	NA
	Standard vans	NA	-95.0	-76.0	-63.0	NA	NA
NREL[o]	1996 Ford Crown Victoria	-11.6	-67.9	-62.8	-2.1	1,760	NA
NGVC[p]	1996 Ford Crown Victoria	NA	-20.0	-69.8	-58.5	23,00	NA

Continued

Table 4.39 (Cont.)

[a] Values are in % relative to vehicles fueled by CG, under the FTP cycle.

[b] From Battelle Memorial Institute (1995a,b) and Orban et al. (1995). Emissions were tested in three phases during which mileage accumulated. The values here are the average of the results from the three phases.

[c] The CNG vans were converted from gasoline vans by IMPCO Technologies, Inc.

[d] From AQIRP (1995b).

[e] The three CNG vehicles were a 1992 MY Chevrolet 5.7-L C20 pickup, 1992 MY Dodge 5.2-L Ram van, and 1993 MY Ford 4.6-L Crown Victoria.

[f] NA = not available.

[g] From Kelly et al. (1996a). The results were based on tests conducted in two emission testing laboratories. The emission and fuel economy changes are relative to GVs fueled with CARFG2. The study showed an evaporative HC emissions reduction of 50.8% by the CNG van.

[h] From Southwest Research Institute (1995). The bi-fuel CNG pickup was converted from a gasoline pickup with a bi-fuel conversion kit provided by Mesa Environmental.

[i] From Engine, Fuel, and Emissions Engineering, Inc. (1997).

[j] From Vermiglio et al. (1997).

[k] Fuel economy change is from Suga et al. (1997). Emission changes are from EPA certification data for CNG Civic GX and gasoline Civic LX. The CNG Honda Civic GX was designed to have emissions that are one-tenth of ULEV standards.

[l] From certification data obtained by Argonne National Laboratory from EPA.

[m] Bi-fuel CNG vehicle converted by GFI Control Systems, Inc.

[n] From Santini and Saricks (1999). Their emission changes were based on emission certification rates and FTP emission rates estimated with Mobile for CNGVs and their gasoline counterparts.

[o] From Whalen et al. (1999). Results are from vehicles selected from Barwood Cab fleet in Maryland. Results here are an average of the results at 60,000, 90,000, and 120,000 mi. Emission changes are relative to emissions of CARFG2. The fuel economy result is laboratory-tested fuel economy.

[p] From Chan and Weaver (1998). The study was conducted for the Natural Gas Vehicle Coalition. Vehicles were taken from the Barwood Cab fleet in Maryland. Emission tests were conducted with the I/M 240 cycle.

A Southwest Research Institute (1995) study conducted for GRI involved performing emissions testing of a 1994 MY bi-fuel, aftermarket converted GMC 1500 CNG pickup. Fuels tested on the pickup included CNG, CG, and FRFG1. Emissions were measured under the normal federal test procedure (FTP) temperature (75°F), the cold FTP (20°F), and the hot, stabilized REP05 (representative cycle No. 5) cycles. Emissions tests were conducted under the cold FTP and the REP05 cycles because under cold temperature and aggressive driving conditions, GVs are expected to switch to fuel enrichment operations, while CNGVs are not required to do so, resulting in larger emissions reduction potentials for CNGVs under these two cycles. Emissions were measured for NMOG, CO, NO_x, CH_4, CO_2, and air toxics.

The EPA has certified some AFV models for meeting applicable emission standards, and Argonne has obtained these certification data from the EPA. Emissions for vehicle certification were usually measured for vehicles with an accumulated mileage of around 4,000 miles. Emissions deterioration factors — multipliers to the measured emissions — were then used to estimate emission certification levels at 50,000 miles and/or 100,000 miles. Emissions deterioration factors were usually greater than one. However, in some cases, the EPA showed deterioration factors that were less than one. In these cases, the EPA applied a factor of one to measured emissions; meaning that in these cases, emissions were not subject to deterioration at all, which is questionable.

In theory, CNGVs can be designed more energy efficient because NG has a higher octane number than gasoline, so NG engines can be designed with a higher compression ratio. However, on-board CNG cylinders cause an additional weight penalty; cylinders can weigh 200–500 lb. In addition, CNGVs have lower volumetric energy efficiency than gasoline. On the basis of testing results, it seems that manufacturers have not designed CNGVs to realize their potential engine efficiency advantage, which results in a substantial fuel economy penalty for CNGVs. Thus, for near-term CNGVs, we assume a fuel economy penalty of 5–7%. For long-term CNGVs, we assume that the potential engine efficiency gain will offset the extra weight penalty, and CNGVs will achieve the same or better fuel economy than those of comparable GVs.

Because of the nature of CNG, CNGVs should not have fuel-related evaporative emissions; we assume zero evaporative emissions from CNGVs. Some actual tests have shown that CNGVs undergoing evaporative emissions tests did generate evaporative emissions (Kelly et al. 1996a). Researchers speculated that the evaporative emissions were from tires, seats, and other plastic and rubber parts, which we do not include in this analysis. CNGV evaporative emissions could be from fuel leakage from CNG cylinders and fuel lines. In this case, the so-called evaporative emissions are mainly methane.

No emission tests are available for LDTs fueled by LNG. Southwest Environmental Consultants converted a 1994 GM 7.4-liter (L) HDT fueled by CG into an LNG truck (Smith 1997). Emissions testing on that LNG truck demonstrated emissions reductions of 97% for NMOG, 25% for CO, and 25% for NO_x. Because of the limited data for LNG vehicles, we use emissions and fuel economy changes of CNGVs for LNGVs.

On the basis of these test results, we assume fuel economy and emission changes for CNGVs in the near term and in the long term (Table 4.39).

4.9.4 Methanol Vehicles

In the early 1990s, automakers offered methanol FFVs, but they have recently stopped offering these vehicles. Table 4.40 summarizes emissions testing results for methanol FFVs. Fuel economy and emissions changes by M85 in the NREL study are relative to CARFG2, not CG. Note that EPA certification data for the Ford Taurus FFV show emissions increases by M85. The certification emissions for both the M85 FFV and the gasoline Taurus at 50,000 mi were calculated from emissions tested at 4,000 mi and emission deterioration factors developed for GVs only. It is not clear whether M85 will have the same deterioration rates (say, in g/10,000 mi) as gasoline. Thus, the certification data may not reveal true emission changes by M85.

Table 4.40 Changes in Fuel Economy and Emissions by Use of M85 Flexible-Fuel Vehicles[a]

		Change Relative to CG (%)						
Source	Vehicle Model	Economy (mpgeg)	Exhaust VOCs	Evap. VOCs	CO	NO_x	CH_4	N_2O
AQIRP[b]	Three 1993 FFVs[c]	4.1	-37.3	-2.1	-12.7	-10.6	NA[d]	NA
Battelle[e]	Ford 4.9-L van	-1.4	-46.3		-54.0	-9.9	-56.1	170.5
NREL[f]	1993 Dodge 2.5-L Spirit	-0.1	-16.9	-6.8	2.0	27.2	NA	NA
	1993 Ford 4.9-L Econoline E150	-3.0	-12.4	-28.1	-32.3	13.5	NA	NA
EPA	1997 Ford 3.0-L Taurus FFV		58.6		6.5	15.4	NA	NA
Certification	1996 Ford 3.0-L Taurus FFV		20.0		-20.0	0	NA	NA

[a] Values in % relative to GVs using CG, under the FTP cycle.

[b] From AQIRP (1994).

[c] The three FFVs were a Chrysler 2.5-L Acclaim, Ford 3.0-L Taurus, and GM 3.1-L Lumina.

[d] NA = not available.

[e] From Battelle Memorial Institute (1995a,b) and Orban et al. (1995). Emissions were tested in three phases as vehicle mileage accumulated. The values here are the average of the results from the three phases.

[f] From Kelly et al. (1996c). Changes in emissions and fuel economy by M85 are relative to CARFG2.

In the near term, FFVs seem to be the plausible vehicle option for using methanol, when the limited methanol refueling infrastructure and cold start problems with M100 are considered. In the long term, as the methanol refueling infrastructure becomes relatively extensive and the cold start problem is solved, dedicated methanol vehicles using high methanol blends — such as M90 — may be a practical option. At present, no fuel economy and emissions testing data are available for dedicated methanol vehicles. We assume greater fuel economy and emissions benefits for M95 dedicated vehicles than for M85 FFVs.

4.9.5 Ethanol Vehicles

At present, Ford is selling an FFV Taurus (3.0-L engine), and Chrysler is selling its FFV minivan (3.3-L engine). Ford will produce an FFV Ranger pickup (3.0-L engine) and an FFV Windstar minivan (3.0-L engine) in MY 2000. Table 4.41 shows fuel economy and emission changes of E85 FFVs relative to CG. Again, changes from the NREL study are relative to CARFG2, not CG. Note that EPA certification data show moderate emissions benefits and large fuel economy benefits for the 1998 MY Ford Taurus FFV.

We expect that in the near term, FFVs using E85 will continue to be introduced. We assume fuel economy and emission changes of near-term FFVs. There are no dedicated ethanol vehicles now. As an ethanol refueling infrastructure is developed, dedicated vehicles using high-ethanol blends — such as E90 — may be introduced. No fuel economy and emission testing data are available for dedicated E90 vehicles. We assume that they will achieve greater fuel economy and emissions benefits than E85 FFVs.

Table 4.41 Changes in Fuel Economy and Emissions by Use of E85 Flexible-Fuel Vehicles[a]

		Change Relative to CG (%)						
Source	**Vehicle Model**	**Economy (mpgeg)**	**Exhaust VOCs**	**Evap. VOCs**	**CO**	**NO_x**	**CH_4**	**N_2O**
AQIRP[b]	1992 GM 3.1-L Lumina FFV	3.3	-28.1	NA[c]	-68.8	-60.3	NA	NA
	1994 Ford 3.0-L Taurus FFV	-4.7	14.2	NA	21.5	-56.6	NA	NA
	1993 Chrysler 2.5-L Acclaim FFV	0.5	-5.9	NA	58.2	-42.7	NA	NA
NREL[d]	1993 Chevrolet 3.1-L Lumina FFV	-0.2	-23.9	-2.4	-18.2	-27.4	62.8	NA
EPA Certification	1996 Ford 3.0-L Taurus FFV	NA	-57.1	NA	-35.7	0.0		
	1997 Ford 3.0-L Taurus FFV	NA	98.2	NA	74.8	-9.0		
	1998 Ford 3.0-L Taurus FFV	10.0	-14	NA	-7.0	-7.0		
Chrysler Corp.	1998 3.3L minivan: 50k mi	NA	0	NA	39.5	-3.8		
	1998 3.3L minivan: 100k mi	NA	12	NA	111.7	68.6		

[a] Values in % relative to GVs using CG, under the FTP cycle.

[b] From AQIRP (1995c).

[c] NA = not available.

[d] From Kelly et al. (1996b). Fuel economy and emission changes by E85 are relative to CARFG2, not CG.

At present, more than 1.2×10^9 gal of ethanol is used a year in the United States in the form of gasohol and oxygenated fuel (E10). In evaluating fuel-cycle energy and emissions impacts of using E10, we assume no changes in gasoline-equivalent fuel economy and emissions between gasoline and E10 except for CO and evaporative VOC emissions. Because E10 generally has a higher RVP than gasoline, we assume a 10% increase in evaporative emissions by E10 relative to CG.

4.9.6 Liquefied Petroleum Gas Vehicles

Although a large number of LPGVs are in use, a limited number of fuel economy and emission tests have been conducted for them. Table 4.42 presents LPGV testing results. Ford offers an LPG bi-fuel Econoline van and an LPG bi-fuel F-Series pickup truck. But most LPGVs on the road have been converted from GVs. Usually, aftermarket conversions have higher emissions than OEM-produced vehicles. In our analysis, we assume bi-fuel aftermarket conversions as well as bi-fuel OEM LPGVs for the near term and dedicated LPGVs for the long term.

4.9.7 Other Vehicle Types

Tested fuel economy and emissions data are scarce for other vehicle types. This section summarizes our assumptions for these other vehicle types.

Significant technological advances have been made for CIDI diesel engines in the last several years. CIDI engines can achieve a 35% improvement in gasoline-equivalent fuel

Table 4.42 Changes in Fuel Economy and Emissions by Use of Liquified Petroleum Gas Vehicles[a,b]

		Change Relative to CG (%)					
Source	Vehicle Model	Economy (mpgeg)	Exhaust VOCs	CO	NO_x	CH_4	N_2O
Battelle[c]	1992 Chevy 5.7-L van	-10.4	28.6	-54.5	-71.9	66.5	-71.0
	1992 Ford 4.8-L van	-5.8	39.3	-24.1	12.1	23.2	269.5
NREL[d]	1994 Ford F150 pickup	NA[e]	362.4	-57.2	0.0	NA	NA
	1994 Ford Taurus	NA	43.0	-62.5	677.6	NA	NA
EPA Certification	1996 GM 4.3-L Caprice	NA	-14.4	68.4	88.2	NA	NA
	1998 Ford 5.4-L F-Series pickup	NA	-35.3	83.3	50.0	NA	NA

[a] All the tested LPGVs here were converted from GVs.

[b] Values in % relative to GVs using CG, under the FTP cycle.

[c] From Battelle Memorial Institute (1995a,b) and Orban et al. (1995). Emissions were tested in three phases as vehicle mileage accumulated. The values here are the average of the results from the three phases.

[d] From Motta et al. (1996). The vehicles are aftermarket conversions with IMPCO conversion kit.

[e] NA = not available.

economy relative to conventional GVs. Advances have also been made recently in spark-ignition, direct-injection (SIDI) engines. Toyota began to sell an SIDI gasoline car in Japan in MY 1998. The Toyota has a fuel economy improvement of 30% (under the Japanese 10/15-mode cycle) relative to CG cars (*Automotive Engineering* 1997). The fuel economy gain by the car as measured under the U.S. FTP may be smaller. A fuel economy gain of 25% is assumed for SIDI gasoline vehicles under the FTP cycle in our study. Direct-injection engines usually have high NO_x emissions. These vehicles will have to meet the same emission standards as conventional vehicles in the United States. We assume that emission control technologies for direct-injection engines will improve so that their emissions will be comparable to those of counterpart conventional vehicles.

Fuel economy improvements for grid-connected HEVs under the grid electric model will be the same as those for EVs. We assume that near-term electric cars and LDT1 will achieve a fuel economy 3.5 times that of conventional GVs, and electric LDT2 will achieve a fuel economy 3 times that of conventional GVs. The fuel economy of near-term HEVs under the internal combustion engine (ICE) mode is assumed to be 50% higher than the fuel economy of conventional GVs. This assumption is based on Argonne’s simulations of HEVs. Emissions of HEVs during ICE operations are assumed to be 20% lower than those of conventional GVs, on a per-mile basis.

For the long-term EVs, we assume improved fuel economy relative to that of near-term EVs. In particular, we assume that long-term electric cars and LDT1 will achieve a gasoline-equivalent fuel economy 4 times that of conventional GVs, and electric LDT2 will achieve a fuel economy 3.5 times that of conventional GVs. We assume long-term HEVs under ICE operations will achieve a 75% improvement in fuel economy relative to conventional GVs. In comparison, a recent report by Thomas et al. (1998) presented an mpg improvement of 25–70% for NG-fueled HEVs and 39–93% for diesel-fueled HEVs.

On the basis of our review of existing literature, we assume that hydrogen (H_2)-fueled FCVs achieve a fuel economy 2.5 times that of GVs. For methanol-fueled FCVs, the increase in fuel economy is calculated from the improvement of H_2-fueled FCVs and the efficiency of on-board methanol processors. Although both steam reforming and partial oxidation reforming can be used to produce H_2 from methanol, we assume that steam reforming is used because the technology is already mature, and partial oxidation does not offer great benefits for methanol reforming relative to steam reforming. We assume that methanol-fueled FCVs achieve a fuel economy twice that of GVs. In comparison, Thomas et al. (1998) estimated that methanol FCVs may achieve a fuel economy improvement of only 45–62%.

Recent developments in partial oxidation reforming of H_2-containing fuels show promise for using other fuels such as gasoline, NG, and ethanol to produce H_2 on board a vehicle. These fuels are generally more difficult to reform than methanol. We assume that FCVs fueled with gasoline, NG, and ethanol via partial oxidation reforming achieve a 75% improvement in fuel economy over that of conventional GVs. This estimate is 25% less than the fuel economy improvement by methanol FCVs. In comparison, Thomas et al. (1998) estimated a fuel economy improvement for gasoline-fueled FCVs of 40%.

For conventional diesel vehicles fueled with CD (the currently available low-sulfur diesel), we assume a gain of 10% in gasoline-equivalent fuel economy, relative to conventional GVs. Emissions of CD vehicles are estimated by using EPA's Mobile 5b and Part 5.

With lower sulfur and aromatic content, RFD is proposed for use in CIDI engines to meet stringent NO_x and PM emission standards such as ultra-low emission vehicle (ULEV) standards. The likely specifications of RFD are unknown now. In a study to estimate the potential costs of producing RFD, McNutt and Hadder (1998) assumed an RFD with 30 ppm sulfur content by weight and 10% aromatics content by volume. We use this RFD specification in our analysis. We assume that CIDI engines fueled with RFD may be able to meet Tier 2 NO_x (0.07 g/mi) and PM (0.01 g/mi) emission standards.

Besides RFD, the following other fuels have been proposed for use in CIDI engines: DME, FTD, and biodiesel. DME has a high cetane number (55–60, compared to 40–55 for CD) and contains no sulfur and aromatics. Use of DME can reduce emissions of NO_x and PM drastically. Emissions of VOCs and CO may be increased slightly by using DME. However, tests have shown that the majority of HC emissions from DME combustion are unburned DME and methane (Mikkelsen et al. 1996). We assume, then, that CH_4 emissions are increased by 100% by use of DME relative to use of CD. Because there is no DME production for transportation use at present, we consider that it is a long-term technology option. Limited emissions testing has been conducted for use of DME in compression-ignition engines. Table 4.43 presents emissions testing results of vehicles fueled with DME.

FTD has a high cetane number and contains virtually no sulfur and aromatics, making it an excellent fuel for CIDI engines with significant potential for lowering NO_x and PM emissions.

Table 4.43 Changes in Fuel Economy and Emissions by Use of DME in Compression-Ignition Engines[a]

		Change Relative to CD (%)				
Source	Vehicle Model	Economy (mpgeg)	Exhaust VOC	CO	NO_x	PM
Mikkelsen et al. (1996)	Single-cylinder engine	0	0	40	-90	-95
Christensen et al. (1997)	1.0-L engine for boat applications	NA[b]	95	100	-50	-95
Fleisch et al. (1995a)	Navistar 7.3-L engine	0	NA	NA	-15 to -65	-60
Fleisch and Meurer (1995b)	HDTs	NA	0	NA	-57	-75
Sorenson and Mikkelsen (1995)	A small engine	0	0	NA	-75	-93

[a] Values in percent relative to use of CD.

[b] NA = not available.

After reviewing limited fuel economy and emissions test data for diesel engines fueled with FTD, Gaines et al. (1998) assumed that FTD achieves a 25% reduction in NO_x emissions relative to CD. Because FTD contains no aromatics, we expect that it is more economical to blend FTD with CD and use the blend in CIDI engines. We assume a blend of 50% FTD and 50% CD by volume (FT50). We also assume that, relative to RFD, FT50 achieves a 10% reduction in PM emissions; fuel economy and emissions of other pollutants for RFD and FT50 are assumed to be the same.

Biodiesel has been proposed for use in CI engines to reduce NO_x and PM emissions. Because it is renewable, biodiesel helps reduce GHG emissions. The cost of producing biodiesel (mainly driven by soybean feedstock cost) is prohibitively high. We assume that biodiesel will be used in a 20% blend with CD (BD20). We assume the same fuel economy and emission performance for BD20 as for FT50.

4.9.8 Summary

Many of the vehicles included in the summary of testing results for AFVs presented in the previous section were tested under laboratory-controlled conditions to understand the emission differences between AFVs and comparable GVs. Several caveats are associated with this method of summarizing AFV relative emission changes.

First, many more vehicle models are available for some of the AFV types (such as CNGVs) than for others. The emissions results for the types for which significant testing data are available are more reliable than the results for the less readily available types.

Second, there are tradeoffs among pollutants, emissions, and fuel economy, as well as other vehicle performance attributes for the various vehicle technologies. Individual vehicle models can be designed for different intended tradeoffs — for example, to minimize emissions or to maximize performance. So researchers cannot average results from different vehicle models together to generate average results for a vehicle type.

The third caveat is that, although tests within an individual study may follow a strictly consistent test procedure (e.g., an AFV type and a baseline GV may be tested the same way), testing procedures and calibrations may not be exactly the same among different studies. Thus, emission testing results for AFVs from one study usually cannot be compared with emission testing results for GVs from a different study. This is why, in this study, we calculated emission changes for each individual study in order to evaluate AFV emission changes.

Often, AFV emission benefits are cited in statements based on a single study or a single vehicle model. As the above summary reveals, emission changes can vary considerably among studies and vehicle models for the same vehicle type. Also, data from tests that were conducted on vehicle models that are already out of production should not be given significant consideration in evaluating the effects of future vehicle models. In assuming future AFV emission impacts, we rely heavily on the results from models still in production.

Some believe that, because future vehicles will be subject to the same emission standards, the emissions of different vehicle types should be the same or similar. If manufacturers designed vehicles only to meet emission standards, this would be a valid argument. But because different fuels have different inherit emission performance characteristics, manufacturers can meet a set of standards with a low-emission fuel with less difficulty than with a high-emission fuel. Also, California regulates vehicle emissions with several emission categories (e.g., LEV, ULEV, super ultra-low-emission vehicle [SULEV]), and EPA will probably regulate emissions with different vehicle bins (see Table 6.3) subject to different emission standards. That is, future emission standards will provide incentives to manufacturers to produce vehicles with different emission levels. Alternative-fueled vehicles, with inherently low emissions, will certainly be produced at emission levels lower than those of baseline gasoline or diesel vehicles.

The fuel economies of available AFV models are published in the *MY 1999 Fuel Economy Guide* released by DOE and EPA (1998a). On the basis of data contained in the guide, we estimate fuel economy changes of MY 1999 AFV models (Table 4.44). Fuel economy changes in the table are based on on-road adjusted fuel economy. The table shows that, while ethanol FFVs have small gains in fuel economy, CNGVs have large fuel economy penalties.

Tables 4.45 and 4.46 present the default values of fuel economy and emission change rates used in the GREET model for the vehicle types included in GREET. Fuel economy and emission changes by alternative fuels and advanced technologies are assumed for passenger cars and LDT1 as one group and for LDT2 as another group. Alternative transportation fuels and advanced vehicle technologies are separated into near-term and long-term technologies. Near-term technologies are already available. Long-term technologies will be likely become available in 10 years. Baseline GVs fueled with CG for near-term technologies are assumed to

Table 4.44 Fuel Economy Changes of 1999 MY Alternative-Fuel Vehicle Models[a,b]

	FUDS Cycle (%)	Highway Cycle (%)	55/45 Cycle (%)
Ethanol Vehicles			
Chrysler Caravan 3.3-L (L4)	1	5	3
Ford Ranger 3.0-L (L4, 4WD)	3	-2	1
Ford Ranger 3.0-L (M5, 4WD)	7	2	5
Ford Ranger 3.0-L (L4, 2WD)	-1	2	0
Ford Ranger 3.0-L (M5, 2WD)	7	3	5
Ford Taurus 3.0-L (L4)	3	0	2
CNG Vehicles			
Ford Contour 2.0-L (L4, bi-fuel)	-26	-26	-26
Ford Crown Victoria 4.6-L (L4)	-18	-17	-18
Ford F-250 Pickup 5.4-L (L4)	-15	-12	-14
Ford E-250 Van 5.4-L (L4, bi-fuel)	-15	-17	-16

[a] Based on data contained in DOE and EPA 1998a.

[b] Fuel economy changes by AFVs are relative to fuel economy of comparable gasoline vehicle models. L4 = automatic lockup 4-speed, M5 = manual 5-speed, 4WD = 4-wheel drive, 2WD = 2-wheel drive.

meet federal Tier 1 emissions standards. In Table 4.45, emission reductions by RFG2 are based on emission performance of California RFG2. Fuel economy and emission changes for bi-fuel and dedicated CNGVs rely on testing results of recently introduced vehicle models. FFVs fueled with M85, E85, and LPG are generally assumed to have emissions similar to those of vehicles fueled by RFG2. The fuel economy and performance of HEVs powered by grid electricity are assumed to be the same as the fuel economy and performance of battery-powered EVs. Emissions performance of HEVs powered by on-board engines is assumed to be similar to that of vehicles fueled by RFG2. The emissions performance of diesel-engine vehicles is assumed to be similar across vehicle types.

For the long-term technology options, baseline GVs fueled with RFG2 are assumed to meet the proposed federal Tier 2 standards. Few data are available for long-term technology options. Through our research, we sought inputs from experts on these technology options. The assumptions made here reflect expert opinions together with our understanding of the potential of each technology option. So the assumptions for long-term technology options are more speculative than those for near-term technology options. In general, we assume that long-term technologies will be able to meet the newly proposed Tier 2 standards. If a technology has inherently low emission potential, we assume emission reductions relative to Tier 2 standards.

Few data on the fuel economy of long-term technology options are available. Recently, Stodolsky et al. (1999) completed a study on advanced vehicle technologies. The study was widely reviewed. Fuel economy changes for SIDI vehicles, SIDI HEVs, CIDI vehicles, CIDI HEVs, and FCVs in this study are derived primarily from the Stodolsky study.

Table 4.46 presents fuel economy and emission changes for LDT2. In most cases, fuel economy and emission changes are the same as those for passenger cars and LDT1. In a few

Table 4.45 Changes in Fuel Economy and Emissions by Various Vehicle Types: Passenger Cars and Light-Duty Trucks 1[a]

Vehicle Type	Change (%) Economy (mpgeg)	Exhaust VOC	Evap. VOC	CO	NO_x	Exhaust PM_{10}[b]	CH_4	N_2O
Near-Term Technologies: % Relative to National Low-Emission Vehicle (NLEV) GVs Fueled with CG (except as noted)								
GVs: RFG2[c]	0	-10	-30	-20	-5	-5	-8	0
CNGVs: bi-fuel[d]	-10	-40	-50	-20	0	-90	900	-40
CNGVs: dedicated	-7	-60	-90	-30	-10	-95	900	-20
LPGVs: dedicated	0	-20	-90	-25	-10	-90	30	0
FFVs: M85[d]	5	-15	-15	-25	-10	-60	-50	0
FFVs: E85[d]	5	-15	-15	-25	-10	-60	50	0
GVs: E10	0	0	20	-20	0	0	0	0
EVs	200	-100	-100	-100	-100	-100	-100	-100
Grid-independent SIDI HEVs: RFG2	90	-10	-40	-20	0	20	0	0
Grid-connected SIDI HEVs: RFG2[e]								
Grid operation	200	-100	-100	-100	-100	-100	-100	-100
ICE operation	80	-10	-40	-20	0	20	0	0
CIDI vehicles: CD[f]	35	NN[g]	NN	NN	NN	NN	NN	NN
Grid-independent CIDI HEVs: CD[h]	100	0	0	0	0	0	0	0
Long-Term Technologies: % Relative to Tier 2 GVs Fueled with RFG2 (except as noted)								
CNGVs/LNGVs: dedicated	5	-10	-90	-20	0	-80	400	-50
LPGVs: dedicated	10	0	-90	-20	0	-80	10	0
M90-dedicated vehicles	10	0	0	0	0	-40	-50	0
E90-dedicated vehicles	10	0	0	0	0	-40	50	0
SIDI vehicles: RFG2	25	0	-10	0	0	40	0	0
SIDI vehicles: M90	25	0	-10	0	0	0	-50	0
SIDI vehicles: E90	25	0	-10	0	0	0	50	0
Grid-independent SIDI HEVs: RFG2	90	0	-30	0	0	20	0	0
Grid-independent SI HEVs: CNG/LNG	70	-10	-90	-20	0	-50	400	-50
Grid-independent SI HEVs: LPG	70	0	-90	-20	0	-50	10	0
Grid-independent SIDI HEVs: M90	90	0	-30	0	0	-15	-50	0
Grid-independent SIDI HEVs: E90	90	0	-30	0	0	-15	50	0
Grid-connected SIDI HEVs: RFG2[e]								
Grid operation	300	-100	-100	-100	-100	-100	-100	-100
ICE operation	85	0	-30	0	0	20	0	0
Grid-connected SI HEVs: CNG/LNG[e]								
Grid operation	300	-100	-100	-100	-100	-100	-100	-100
ICE operation	65	-10	-90	-20	0	-50	400	-50
Grid-connected SI HEVs: LPG[e]								
Grid operation	300	-100	-100	-100	-100	-100	-100	-100
ICE operation	65	0	-90	-20	0	-50	10	0
Grid-connected SIDI HEVs: M90[e]								
Grid operation	300	-100	-100	-100	-100	-100	-100	-100
ICE operation	85	0	-30	0	0	-15	-50	0
Grid-connected SIDI HEVs: E90[e]								
Grid operation	300	-100	-100	-100	-100	-100	-100	-100
ICE operation	85	0	-30	0	0	-15	50	0

Table 4.45 (Cont.)

Vehicle Type	Change (%) Economy (mpgeg)	Exhaust VOC	Evap. VOC	CO	NO_x	Exhaust PM_{10}[b]	CH_4	N_2O
CIDI vehicles: RFD[i]	50	NN	NN	NN	NN	NN	NN	NN
CIDI vehicles: DME[h]	50	-30	NN	0	0	-30	100	0
CIDI vehicles: FT50[h]	50	0	NN	0	0	-20	0	0
CIDI vehicles: BD20[h]	50	0	NN	0	0	-10	0	0
Grid-independent CIDI HEVs: RFD[h]	130	0	NN	0	0	0	0	0
Grid-independent CIDI HEVs: DME[h]	130	-30	NN	0	0	-30	100	0
Grid-independent CIDI HEVs: FT50[h]	130	0	NN	0	0	-20	0	0
Grid-independent CIDI HEVs: BD20[h]	130	0	NN	0	0	-10	0	0
Grid-connected CIDI HEVs: RFD								
Grid operation	300	-100	-100	-100	-100	-100	-100	-100
ICE operation	120	0	0	0	0	0	0	0
Grid-connected CIDI HEVs: DME[e]								
Grid operation	300	-100	-100	-100	-100	-100	-100	-100
ICE operation	120	-30	0	0	0	-30	100	0
Grid-connected CIDI HEVs: FT50[e]								
Grid operation	300	-100	-100	-100	-100	-100	-100	-100
ICE operation	120	0	0	0	0	-20	0	0
Grid-connected CIDI HEVs: BD20[e]								
Grid operation	300	-100	-100	-100	-100	-100	-100	-100
ICE operation	120	0	0	0	0	-10	0	0
EVs	300	-100	-100	-100	-100	-100	-100	-100
FCVs: H_2	200	-100	-100	-100	-100	-100	-100	-100
FCVs: MeOH	160	-80	-60	-80	-80	-100	-80	-80
FCVs: RFG2	100	-80	-30	-80	-80	-100	-80	-80
FCVs: EtOH	100	-80	-60	-80	-80	-100	-80	-80
FCVs: CNG	100	-80	-95	-80	-80	-100	100	-80

[a] A positive value means an increase; a negative value means a decrease; and a zero value means no change.

[b] Very few data on PM emissions from AFVs are available. Emissions reduction rates here are primarily our own assumptions.

[c] Based on Mobile 5b runs for CG and FRFG2. In running Mobile 5b, NLEV Stage 2 on-board diagnosis system (OBDII), and enhanced I/M were included.

[d] For vehicles using both gasoline and an alternative fuel, only use of the alternative fuel is evaluated. Use of gasoline in these vehicles is assumed to produce the same energy and emissions results as baseline GVs.

[e] For grid-connected HEVs, the results of grid and ICE operations are combined with VMT share of each operation within GREET. We assumed that, on average, 30% of the VMT by HEVs is with grid electricity, and the remaining 70% is with ICE operations.

[f] Emissions from CIDI engine vehicles fueled with CD are estimated with Mobile 5b and Part 5. The fuel economy changes for these vehicles are relative to those of conventional GVs.

[g] NN = not needed. Mobile 5b-estimated values will be used.

[h] For these vehicle types, fuel economy changes are relative to GVs and emission changes are relative to CIDI diesel engines. Furthermore, near-term technologies are relative to CIDI engines fueled with CD that meet NLEV standards, and long-term technologies are relative to CIDI engines fueled with RFD that meet proposed Tier 2 standards.

[i] Emissions of CIDI engine vehicles fueled with RFD are estimated on the basis of the assumption that RFD will help conventional CI engines meet Tier 2 standards. Their fuel economy changes are relative to those of conventional GVs.

Table 4.46 Changes in Fuel Economy and Emissions by Various Vehicle Types: Light-Duty Trucks 2[a]

	Change (%)							
Vehicle Type	Economy (mpgeg)	Exhaust VOC	Evap. VOC	CO	NO_x	Exhaust PM_{10}[b]	CH_4	N_2O
Near-Term Technologies: % Relative to Tier 1 GVs Fueled with CG (except as noted)								
GVs: RFG2[c]	0	-10	-30	-20	-5	-5	-8	0
CNGVs: bi-fuel[d]	-10	-50	-50	-30	0	-90	900	-40
CNGVs: dedicated	-7	-70	-90	-40	0	-95	900	-20
LPGVs: dedicated	0	-30	-90	-25	-15	-90	30	0
FFVs: M85[d]	0	-25	-25	-25	-15	-60	-50	0
FFVs: E85[d]	0	-25	-25	-25	-15	-60	50	0
GVs: E10	0	0	20	-30	0	0	0	0
EVs	200	-100	-100	-100	-100	-100	-100	-100
Grid-independent SIDI HEVs: RFG2	90	-25	-40	-25	-15	20	0	0
Grid-connected SIDI HEVs: RFG2[e]								
Grid operation	200	-100	-100	-100	-100	-100	-100	-100
ICE operation	80	-25	-40	-25	-15	20	0	0
CIDI vehicles: CD[f]	35	NN[g]	NN	NN	NN	NN	NN	NN
Grid-independent CIDI HEVs: CD[h]	100	0	0	0	0	0	0	0
Long-Term Technologies: % Relative to Tier 2 GVs Fueled with RFG2 (except as noted)								
CNGVs/LNGVs: dedicated	0	-20	-90	-20	0	-80	400	-50
LPGVs: dedicated	5	0	-90	-20	0	-80	10	0
M90-dedicated vehicles	5	0	0	0	0	-40	-50	0
E90-dedicated vehicles	5	0	0	0	0	-40	50	0
SIDI vehicles: RFG2	25	0	-10	0	0	40	0	0
SIDI vehicles: M90	25	0	-10	0	0	0	-50	0
SIDI vehicles: E90	25	0	-10	0	0	0	50	0
Grid-independent SIDI HEVs: RFG2	90	0	-30	0	0	20	0	0
Grid-independent SI HEVs: CNG/LNG	70	-10	-90	-20	0	-50	400	-50
Grid-independent SI HEVs: LPG	70	0	-90	-20	0	-50	10	0
Grid-independent SIDI HEVs: M90	90	0	-30	0	0	-15	-50	0
Grid-independent SIDI HEVs: E90	90	0	-30	0	0	-15	50	0
Grid-connected SIDI HEVs: RFG2[e]								
Grid operation	250	-100	-100	-100	-100	-100	-100	-100
ICE operation	85	0	-30	0	0	20	0	0
Grid-connected SI HEVs: CNG/LNG[e]								
Grid operation	250	-100	-100	-100	-100	-100	-100	-100
ICE operation	65	-10	-90	-20	0	-50	400	-50
Grid-connected SI HEVs: LPG[e]								
Grid operation	250	-100	-100	-100	-100	-100	-100	-100
ICE operation	65	0	-90	-20	0	-50	10	0
Grid-connected SIDI HEVs: M90[e]								
Grid operation	250	-100	-100	-100	-100	-100	-100	-100
ICE operation	85	0	-30	0	0	-15	-50	0
Grid-connected SIDI HEVs: E90[e]								
Grid operation	250	-100	-100	-100	-100	-100	-100	-100
ICE operation	85	0	-30	0	0	-15	50	0

Table 4.46 (Cont.)

Vehicle Type	Change (%) Economy (mpgeg)	Exhaust VOC	Evap. VOC	CO	NO_x	Exhaust PM_{10}[b]	CH_4	N_2O
CIDI vehicles: RFD[i]	50	NN	NN	NN	NN	NN	NN	NN
CIDI vehicles: DME[h]	50	-30	NN	0	0	-30	100	0
CIDI vehicles: FT50[h]	50	0	NN	0	0	-15	0	0
CIDI vehicles: BD20[h]	50	0	NN	0	0	-10	0	0
Grid-independent CIDI HEVs: RFD[h]	130	0	NN	0	0	0	0	0
Grid-independent CIDI HEVs: DME[h]	130	-30	NN	0	0	-30	100	0
Grid-independent CIDI HEVs: FT50[h]	130	0	NN	0	0	-15	0	0
Grid-independent CIDI HEVs: BD20[h]	130	0	NN	0	0	-10	0	0
Grid-connected CIDI HEVs: RFD[e]								
Grid operation	250	-100	-100	-100	-100	-100	-100	-100
ICE operation	120	0	0	0	0	0	0	0
Grid-connected CIDI HEVs: DME[e]								
Grid operation	250	-100	-100	-100	-100	-100	-100	-100
ICE operation	120	-30	0	0	0	-30	100	0
Grid-connected CIDI HEVs: FT50[e]								
Grid operation	250	-100	-100	-100	-100	-100	-100	-100
ICE operation	120	0	0	0	0	-15	0	0
Grid-connected CIDI HEVs: BD20[e]								
Grid operation	250	-100	-100	-100	-100	-100	-100	-100
ICE operation	120	0	0	0	0	-10	0	0
EVs	250	-100	-100	-100	-100	-100	-100	-100
FCVs: hydrogen	200	-100	-100	-100	-100	-100	-100	-100
FCVs: MeOH	160	-80	-60	-80	-80	-100	-80	-80
FCVs: RFG2	100	-80	-30	-80	-80	-100	-80	-80
FCVs: EtOH	100	-80	-60	-80	-80	-100	-80	-80
FCVs: CNG	100	-80	-95	-80	-80	-100	100	-80

[a] A positive value means an increase; a negative value means a decrease; and a zero value means no change.

[b] Very few data on PM emissions from AFVs are available. Emissions reduction rates here are primarily our own assumptions.

[c] Assumed to be the same as for cars and LDT1.

[d] For vehicles using both gasoline and an alternative fuel, only use of the alternative fuel is evaluated. Use of gasoline in these vehicles is assumed to produce the same energy and emissions results as baseline GVs.

[e] For grid-connected HEVs, the results of grid and ICE operations are combined with VMT share of each operation within GREET. It is assumed that, on average, 30% of the VMT by HEVs is with grid electricity, and the remaining 70% is with ICE operations.

[f] Emissions of CIDI engine vehicles fueled with CD are estimated with Mobile 5b and Part 5. The fuel economy changes for these vehicles are relative to those of conventional GVs.

[g] NN = not needed. Mobile 5b-estimated values will be used.

[h] For these vehicle types, fuel economy changes are relative to GVs, and emission changes are relative to CIDI diesel engines. Furthermore, near-term technologies are relative to CIDI engines fueled with CD that meet NLEV standards, and long-term technologies are relative to CIDI engines fueled with RFD that meet proposed Tier 2 standards.

[i] Emissions of CIDI engine vehicles fueled with RFD are estimated based on the assumption that RFD will help CIDI engines meet the proposed Tier 2 standards. Their fuel economy changes are relative to those of conventional GVs.

cases, the changes are different, for example, the reductions in the actual *amount* of fuels used and the actual emissions are larger for LDT2 than for passenger cars and LDT1, simply because per-mile fuel consumption and emissions are larger.

As stated in Section 3, emissions of SO_x for each vehicle type are calculated by assuming that all sulfur contained in a given fuel is converted to SO_2. Emissions of CO_2 for all vehicle types are calculated by subtracting the carbon contained in emissions of VOC, CO, and CH_4 from the carbon contained in a given fuel. For vehicles fueled with E85, E90, E10, and BD20, the amount of CO_2 emissions from the carbon contained in the portion of ethanol and biodiesel are treated as being zero, because these CO_2 emissions originally come from the atmosphere through the photosynthesis process during farming of corn, biomass, and soybeans.