Notation

Acronyms and Abbreviations

AEO98	1998 Annual Energy Outlook
AFV	alternative-fuel vehicle
AQIRP	Auto/Oil Air Quality Improvement Research Program
ATR	autothermal reforming
BD	biodiesel
BD20	mixture of 20% biodiesel and 80% conventional diesel by volume
CAAA	Clean Air Act Amendments
CAFE	corporate average fuel economy
CARB	California Air Resources Board
CARFG1	California Phase 1 reformulated gasoline
CARFG2	California Phase 2 reformulated gasoline
CD	conventional diesel
CG	conventional gasoline
CH_4	methane
CI	compression ignition
CI-AFV	compression-ignition alternative fuel vehicles
CIDI	compression ignition, direct injection
CNG	compressed natural gas
CNGV	compressed natural gas vehicle
CO	carbon monoxide
CO_2	carbon dioxide
DDGS	distillers' dried grains and solubles
DGS	distillers' grains and solubles
DI	direct injection
DME	dimethyl ether
DMM	dimethoxy methane
DOE	U.S. Department of Energy
DV	diesel vehicle
E10	mixture of 10% ethanol and 90% gasoline by volume
E85	mixture of 85% ethanol and 15% gasoline by volume
E90	mixture of 90% ethanol and 10% gasoline by volume
E95	mixture of 95% ethanol and 5% gasoline by volume
EF	emission factor
EIA	Energy Information Administration
EPA	U.S. Environmental Protection Agency
ETBE	ethyl tertiary butyl ether
EtOH	ethanol
EV	electric vehicle

EVTECA	Electric Vehicle Total Energy Cycle Analysis
FCV	fuel-cell vehicle
FFV	flexible-fuel vehicle
FG	flared gas
FRFG1	federal Phase 1 reformulated gasoline
FRFG2	federal Phase 2 reformulated gasoline
FTD	Fischer-Tropsch diesel
FT50	mixture of 50% Fischer-Tropsch diesel and 50% diesel by volume
FTP	federal test procedure
FUDS	federal urban driving schedule
GC	grid connected
GHG	greenhouse gas
GI	grid independent
GREET	**G**reenhouse Gases, **R**egulated **E**missions, and **E**nergy Use in **T**ransportation
GRI	Gas Research Institute
GV	gasoline vehicle
GVW	gross vehicle weight
GVWR	gross vehicle weight rating
GWP	global warming potential
H_2	hydrogen
H_2S	hydrogen sulfide
HC	hydrocarbon
HCHO	formaldehyde
HDT	heavy-duty truck
HEV	hybrid electric vehicle
HHV	high heating value
HLDT	heavy light-duty truck
IGCC	integrated gasification with combined cycle
ICE	internal combustion engine
ICEV	internal combustion engine vehicle
I/M	inspection and maintenance
INEEL	Idaho National Engineering and Environmental Laboratory
IPCC	Intergovernment Panel on Climate Change
K_2O	potassium oxide (potash)
LCA	life-cycle analysis
LDGT1	light-duty gasoline truck 1 with a gross vehicle weight of up to 6,000 lb
LDGT2	light-duty gasoline truck 2 with a gross vehicle weight of 6,001–8,500 lb
LDT	light-duty truck with gross vehicle weight of 0–8,500 lb
LDT1	light-duty truck 1 with gross vehicle weight of 0–6,000 lb
LDT2	light-duty truck 2 with gross vehicle weight of 6,001–8,500 lb
LEBS	low emission boiler systems
LEV	low-emissions vehicle
LHV	low heating value
LLDT	light light-duty truck
LNG	liquefied natural gas
LPG	liquefied petroleum gas

LPGV	liquefied petroleum gas vehicle
M85	mixture of 85% methanol and 15% gasoline by volume
M90	mixture of 90% methanol and 10% gasoline by volume
M95	mixture of 95% methanol and 5% gasoline by volume
M100	100% methanol by volume (pure methanol)
MeOH	methanol
MSW	municipal solid waste
MTBE	methyl tertiary butyl ether
MY	model year
N	elemental nitrogen
N_2O	nitrous oxide
N_2O-N	nitrogen in N_2O
Na/S	sodium/sulfur
NaOH	sodium hydroxide
NG	natural gas
NH_3	ammonia
NLEV	National Low-Emission Vehicle
NMHC	nonmethane hydrocarbon
NMOG	nonmethane organic gas
NO	nitrogen oxide
NO_3^-	nitrate
NO_3^--N	nitrogen in nitrate
NO_x	nitrogen oxides
NREL	National Renewable Energy Laboratory
NSPS	New Source Performance Standards
OBDII	stage 2 on-board diagnosis system
OEM	original equipment manufacturer
PFB/CC	pressurized fluidized-bed combustion with combined cycle
PM	particulate matter
PM_{10}	particulate matter with diameters of 10 micrometers or less
POX	partial oxidation
P_2O_5	phosphate
REP05	representative cycle No. 5
RFD	reformulated diesel
RFG	reformulated gasoline
ROG	reactive organic gas
RVP	Reid vapor pressure
SCAQMD	South Coast Air Quality Management District
SI	spark ignition
SI-AFV	spark-ignition alternative fuel vehicle
SIDI	spark-ignition, direct-injection
SMR	steam methane reforming
SO_2	sulfur dioxide
SO_x	sulfur oxides
SULEV	super ultra-low emission vehicle
T50	temperature at which 50% of gasoline is vaporized

T90	temperature at which 90% of gasoline is vaporized
T&S	transportation and storage
T&S&D	transportation, storage, and distribution
TAME	tertiary amyl methyl ether
TECA	total energy-cycle analysis
THC	total hydrocarbon
ULEV	ultra-low emission vehicle
USDA	U.S. Department of Agriculture
VFV	variable-fuel vehicle
VMT	vehicle miles traveled
VOC	volatile organic compound
ZnO	zinc oxide
ZnS	zinc sulfide

Units of Measure

bbl	barrel
Btu	British thermal unit
bu	bushel
d	day
ft^3	cubic foot
g	gram
gal	gallon
GJ	giga joule
ha	hectare
kcal	kilocalorie
kg	kilogram
kWh	kilowatt-hour
L	liter
lb	pound
mi	mile
mpg	miles per gallon
mpgeg	miles per gasoline-equivalent gallon
nm^3	normal cubic meter
ppm	parts per million
ppmw	parts per million weight
psi	pounds per square inch
scf	standard cubic foot
yr	year

Foreword

This report is a revision to a previous Argonne National Laboratory report entitled *GREET 1.0 — Transportation Fuel Cycles Model: Methodology and Use* (dated June 1996). The 1996 report documented the methodologies, key assumptions, and results of the development and use of the first version of the **G**reenhouse Gases, **R**egulated **E**missions, and **E**nergy Use in **T**ransportation (GREET) fuel-cycle model developed at Argonne National Laboratory. Since then, the GREET 1.0 model has been significantly expanded and improved. The model has evolved into three modules (each comprising a series of versions): the first module covers fuel-cycle energy and emissions of passenger cars and light-duty trucks (GREET 1.1, GREET 1.2, etc.); the second covers vehicle-cycle energy and emissions of passenger cars and light-duty trucks (GREET 2.1, GREET 2.2, etc.); and the third module covers fuel-cycle energy and emissions of heavy-duty trucks (gross vehicle weight over 8,500 pounds) (GREET 3.1, GREET 3.2, etc.).

In September 1998, GREET 1.4 was released with a draft report documenting its development. The model was posted at Argonne's transportation website at www.transportation.anl.gov/ttrdc/publications/papers_reports/techassess/ta_papers.html, and the draft report was sent to reviewers for comment. Since then, significant revisions and expansions have been made to both the report and the model. The current version of the 1-series model is GREET 1.5. This report documents the development and use of GREET 1.5. It includes portions of the 1996 report that have few changes (e.g., the introduction and review of previous fuel-cycle studies) to eliminate the need for readers to refer to the previous report. It also reflects reviewers' comments on the August 1998 draft report.

This report is separated into two volumes. Volume 1 presents GREET 1.5 development and use and discussions of fuel-cycle energy and emission results for passenger cars. Volume 2, comprising four appendices, presents detailed fuel-cycle results for passenger cars, light-duty trucks 1, and light-duty trucks 2.

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Abstract

This report documents the development and use of the most recent version (Version 1.5) of the **G**reenhouse Gases, **R**egulated **E**missions, and **E**nergy Use in **T**ransportation (GREET) model. The model, developed in a spreadsheet format, estimates the full fuel-cycle emissions and energy use associated with various transportation fuels and advanced vehicle technologies for light-duty vehicles. The model calculates fuel-cycle emissions of five criteria pollutants (volatile organic compounds, carbon monoxide, nitrogen oxides, particulate matter with diameters of 10 micrometers or less, and sulfur oxides) and three greenhouse gases (carbon dioxide, methane, and nitrous oxide). The model also calculates total energy consumption, fossil fuel consumption, and petroleum consumption when various transportation fuels are used. The GREET model includes the following cycles: petroleum to conventional gasoline, reformulated gasoline, conventional diesel, reformulated diesel, liquefied petroleum gas, and electricity via residual oil; natural gas to compressed natural gas, liquefied natural gas, liquefied petroleum gas, methanol, Fischer-Tropsch diesel, dimethyl ether, hydrogen, and electricity; coal to electricity; uranium to electricity; renewable energy (hydropower, solar energy, and wind) to electricity; corn, woody biomass, and herbaceous biomass to ethanol; soybeans to biodiesel; flared gas to methanol, dimethyl ether, and Fischer-Tropsch diesel; and landfill gases to methanol. This report also presents the results of our analysis of fuel-cycle energy use and emissions associated with alternative transportation fuels and advanced vehicle technologies to be applied to passenger cars and light-duty trucks.

Section 1
Introduction

Alternative transportation fuels and advanced vehicle technologies are being promoted to help solve urban air pollution problems, reduce greenhouse gas (GHG) emissions, and relieve U.S. dependence on imported oil. To accurately and adequately evaluate the energy and emission effects of alternative fuels and vehicle technologies, researchers must consider emissions and energy use from upstream fuel production processes as well as from vehicle operations. This research area is especially important for technologies that employ fuels with distinctly different primary energy sources and fuel production processes, for which upstream emissions and energy use can be significantly different.

Studies were conducted to estimate fuel-cycle emissions and energy use associated with various transportation fuels and vehicle technologies. The results of those studies were influenced by the assumptions made by individual researchers regarding technology development, emission controls, primary fuel sources, fuel production processes, and many other factors. Because different methodologies and parametric assumptions were used by different researchers, it is difficult to compare and reconcile the results of different studies and to conduct a comprehensive evaluation of fuel-cycle emissions and energy use. Computer models for calculating emissions and energy use are needed to allow analysts and researchers to test their own methodologies and assumptions and make accurate comparisons of different technologies.

The Center for Transportation Research at Argonne National Laboratory has been conducting fuel-cycle analyses for various transportation fuels and vehicle technologies for the past 15 years. In 1996, with funding from the U.S. Department of Energy's (DOE's) Office of Transportation Technologies, Argonne developed a spreadsheet-based fuel-cycle model. The goal was to provide a simple computer tool that would allow researchers to evaluate fuel-cycle energy and emission impacts of various transportation technologies. Since its creation, the model has been used extensively by researchers at Argonne and other institutions to calculate the fuel-cycle energy requirements of and emissions from various alternative transportation fuels and advanced vehicle technologies. The model has evolved significantly since its introduction.

This report describes the development and use of the latest version of the **G**reenhouse Gases, **R**egulated **E**missions, and **E**nergy Use in **T**ransportation (GREET) model (Version 1.5). The GREET 1.5 model calculates, for a given fuel/transportation technology combination, the fuel-cycle emissions of five criteria pollutants: volatile organic compounds (VOCs), carbon monoxide (CO), nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate matter with diameters of 10 micrometers or less (PM_{10}). The model also calculates the fuel-cycle emissions of greenhouse gases — primarily carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) — and the fuel-cycle consumption of total energy, fossil fuel, and petroleum. The model is designed to allow researchers to readily input their own assumptions and generate fuel-cycle energy and emission results for specific fuel/technology combinations.

This report comprises two volumes. Volume 1 addresses three areas of GREET development and use: (1) review of past and ongoing fuel-cycle studies; (2) methodologies, parametric assumptions, and data sources for the assumptions used in the GREET model; and (3) fuel-cycle energy and emission results for various fuel/technology combinations for passenger cars, as calculated by using the GREET model. Volume 2 contains four appendices that provide detailed fuel-cycle energy and emission results for passenger cars, light-duty trucks 1, and light-duty trucks 2.

Section 2
Review of Previous Fuel-Cycle Studies

This section describes the methods and assumptions used in previous studies conducted to estimate fuel-cycle emissions and energy use.

2.1 Delucchi 1991, 1993

In 1991, Delucchi completed a study to estimate fuel-cycle emissions of GHGs for various transportation fuels and for electricity generation (Delucchi 1991, 1993). The GHGs considered in the study included CO_2, CH_4, CO, N_2O, NO_x, and nonmethane organic gases (NMOGs). In addition to studying the emissions and energy use of the fuel-cycle stages (ranging from primary energy recovery to on-vehicle fuel combustion), Delucchi examined the emissions and energy use involved in the manufacture of motor vehicles, maintenance of transportation systems, manufacture of materials used in major energy facilities, and changes in land use caused by the production of biofuels. Through his study, Delucchi developed a model of calculating GHG emissions. The model included the following fuel cycles: petroleum to gasoline, petroleum to diesel, petroleum to liquefied petroleum gas (LPG), natural gas (NG) to methanol, NG to compressed natural gas (CNG), NG to liquefied natural gas (LNG), NG to LPG, coal to methanol, wood to methanol, corn to ethanol, wood to ethanol, nuclear energy to hydrogen, solar energy to hydrogen, and electricity generation from various fuels.

To calculate GHG emissions for a specific fuel-cycle stage, Delucchi first estimated the total amount of energy burned at that stage. He allocated the total amount of energy to different fuels (e.g., residual oil, NG, electricity, coal), then estimated combustion-causing emissions of GHGs (except CO_2) by using emission factors. He calculated CO_2 emissions by using a carbon balance approach: the carbon contained in CO, CH_4, and NMOG emissions was subtracted from all available carbon in a combusted fuel, and the remaining carbon was assumed to be oxidized to CO_2. Besides combustion-causing emissions, Delucchi included GHG emissions from fuel losses such as leakage and evaporation. He combined emissions of all GHGs together with their global warming potentials (GWPs) and presented the results of fuel-cycle, vehicle life-cycle GHG emissions in CO_2-equivalent emissions per mile of travel.

To derive process energy efficiencies and energy source shares for total energy consumption, Delucchi relied primarily on Energy Information Administration (EIA) surveys on manufacturing energy consumption. Delucchi estimated the emission factors of various energy combustion processes primarily on the basis of information in the fourth edition of the U.S. Environmental Protection Agency (EPA) AP-42 document (EPA 1988).

Using his model, Delucchi estimated GHG emissions for the year 2000 from a baseline gasoline car with a fuel economy of 30 miles per gallon (mpg). He generally assumed energy efficiency improvements for alternative-fuel vehicles (AFVs) relative to gasoline vehicles (GVs). To address uncertainties in future energy production processes and vehicle technologies, Delucchi designed various scenarios representing potential improvements in fuel production efficiencies, GWPs of GHGs, relative efficiencies of AFVs, and regional differences in fuel production.

From his study, Delucchi drew the following general conclusions:

- Coal-based fuels generally increased GHG emissions;
- Slight to moderate reductions in GHG emissions resulted from using NG-based fuels (e.g., methanol, CNG, LNG, electricity from NG, and LPG);
- Use of woody biomass-based ethanol greatly reduced GHG emissions;
- Corn-based ethanol could increase GHG emissions;
- Use of solar energy via electricity or hydrogen nearly eliminated GHG emissions; and
- Use of nuclear energy via electricity or hydrogen greatly reduced GHG emissions.

Delucchi's was the most comprehensive and extensive study of energy-cycle GHG emissions. The study has been widely cited. A substantial amount of input data for GREET 1.0 — the first version of the GREET model — was derived from Delucchi's 1991 study.

2.2 National Renewable Energy Laboratory et al. 1991, 1992

The National Renewable Energy Laboratory (NREL), with assistance from Oak Ridge National Laboratory and Pacific Northwest National Laboratory, conducted an analysis that compared fuel-cycle emissions of biomass-based ethanol with those of reformulated gasoline (RFG) (NREL et al. 1991, 1992). The NREL study compared three fuels: RFG, E10 (mixture of 10% ethanol and 90% gasoline by volume), and E95 (mixture of 95% ethanol and 5% gasoline by volume). In its study, NREL assumed that E10 would be used by the year 2000 and E95 would be used by 2010. The researchers further assumed that ethanol would be produced from municipal solid waste (MSW) in 2000 and from biomass such as grasses and trees in 2010; production of ethanol from corn was excluded.

For the MSW-to-ethanol cycle in 2000, NREL selected one site: Chicago/Cook County. For the biomass-to-ethanol cycle in 2010, NREL selected five sites with distinctly different climatic, soil, and other natural parameters: Peoria, Illinois; Lincoln, Nebraska; Tifton, Georgia; Rochester, New York; and Portland, Oregon.

In estimating emissions for RFG production, NREL assumed two refineries with different levels of crude quality, refining capacity, and refinery emissions. The NREL researchers specified the compositions of RFG by using the general requirements contained in the 1990 Clean Air Act Amendments. In 1994, EPA adopted a final rule on RFG requirements that was based on potential emission reductions rather than on component compositions (EPA 1994). Because of this rule, actual RFG specifications in the future may vary among companies and will certainly differ from NREL's assumed specifications. For example, the NREL researchers assumed that methyl tertiary butyl ether (MTBE) was the sole oxygenate for RFG. However, in practice, ethanol, ethyl tertiary butyl ether (ETBE), or MTBE can be used as oxygenates in RFG.

The NREL study included estimates of solid waste, water pollutant, and air pollutant emissions. The air pollutants studied were VOCs, CO, NO_x, SO_x, CO_2, and particulate matter (PM). The researchers also calculated petroleum displacement from using E10 and E95.

NREL concluded that using MSW-based E10 in 2000 would cause very little change in fuel-cycle emissions when compared with using RFG because the major part of E10 is still gasoline. On the other hand, using biomass-based E95 in 2010 would reduce CO_2 emissions by 90% to 96% and reduce NO_x, SO_x, and PM emissions considerably. However, NREL found that use of E95 could increase VOC and CO emissions. On a per-mile basis, the study estimated that E10 would help displace 6% of fossil fuel use; E95 would displace 85%.

NREL researchers estimated significantly larger reductions in CO_2 emissions as a result of using ethanol than Delucchi did, primarily because the assumptions made by NREL favored ethanol. For example, NREL assumed high energy efficiencies and low emissions from ethanol fuel cycles, a high allocation of upstream ethanol cycle emissions to other by-products, a large electricity credit earned in ethanol plants, and favorable emission reductions for E10 and E95. NREL used EPA’s Mobile 4.1 model to estimate emissions from RFG-fueled baseline vehicles.

2.3 Bentley et al. 1992

Bentley et al. prepared a study for the Idaho National Engineering and Environmental Laboratory (INEEL) to estimate fuel-cycle CO_2 emissions from electric vehicles (EVs), fuel-cell vehicles (FCVs), and internal combustion engine vehicles (ICEVs) powered by different fuels (Bentley et al. 1992). The researchers included the following fuel cycles in their study: petroleum to gasoline, NG to methanol, NG to CNG, NG to hydrogen, corn to ethanol, and electricity generation from various fuels. While the study did not include an in-depth analysis of upstream fuel-cycle emissions (energy efficiencies and CO_2 emissions for upstream stages were derived primarily from other studies), it did present detailed projections of likely vehicle configurations, vehicle drivetrains, and component efficiencies.

Assuming improvements in energy efficiency for both upstream fuel production processes and vehicle technologies over time, Bentley et al. estimated CO_2 emissions in three target years: 2001, 2010, and 2020. The study included three vehicle types: commuter cars, family cars, and minivans. Vehicle component energy efficiencies were projected from those of 1992 GVs. Actual on-road fuel economy of advanced vehicles was projected by using SIMPLEV — a computer model developed at INEEL to simulate vehicle fuel economy. In using SIMPLEV, Bentley and his colleagues made assumptions regarding aerodynamics coefficients, rolling resistance, weight reduction, and battery technologies on the basis of optimistic projections of technology advances and the characteristics of some prototype vehicles. To estimate

EV fuel-cycle emissions, the researchers established the following three scenarios regarding the electricity generation mix:

- The national average generation mix (under which coal-fired power plants generate more than 50% of total electricity);
- Advanced NG combustion technology providing electricity for EVs; and
- The newest NG combustion technology with the highest possible conversion efficiency providing electricity for EVs.

Bentley et al. assumed that the conversion efficiency for advanced NG combustion technology would increase from 43% in 1992 to 50% in 2020 and the efficiency for the newest NG technology would increase from 43% in 1992 to 57% in 2020.

The conclusions drawn from the Bentley et al. study included the following:

- Gasoline and methanol vehicles produce about the same amount of fuel-cycle CO_2 emissions;
- Compressed natural gas vehicles (CNGVs), EVs, and vehicles powered by ethanol (all of which produce about the same amount of CO_2 emissions) generate fewer CO_2 emissions than do GVs;
- EVs produce fewer emissions than CNGVs if electricity is generated from NG; and
- FCVs fueled with NG-based hydrogen generate fewer CO_2 emissions than do CNGVs.

2.4 Brogan and Venkateswaran 1992

Brogan and Venkateswaran (1992) estimated fuel-cycle energy use and CO_2 emissions of various transportation technologies. Their study included EVs, hybrid electric vehicles (HEVs), FCVs, and ICEVs powered with different fuels, for a total of 19 propulsion-system/fuel options. Their analysis was conducted for typical mid-size passenger cars to be introduced in 2001. They used technology projections for 2001, except for some advanced technologies such as FCVs and HEVs, for which they used technology assumptions from prototype or concept designs.

Brogan and Venkateswaran calculated CO_2 emissions by assuming that all carbon contained in a fuel was oxidized into CO_2; carbon contained in CO and hydrocarbon (HC) emissions was not considered. Upstream emissions of HC, CO, NO_x, and SO_x were estimated only for the fuel production stage (e.g., petroleum refining and electricity generation); emissions from primary energy production and distribution, transportation, and storage of fuels were ignored. It appears that the authors used emission standards of ICEVs to represent actual on-road emissions.

In estimating EV energy use, Brogan and Venkateswaran made optimistic assumptions about battery technologies. They specified a series, range-extended HEV design and assumed methanol-fueled ceramic gas turbines for the HEV design. They arbitrarily assumed that for HEVs, 75% of the road power demand would be met with grid electricity and 25% with on-board gas turbine generators. Performance characteristics remained constant among the 19 vehicle options, except for the EVs, for which the driving range was assumed to be shorter than the range for the other vehicle types. Vehicle component efficiencies were derived directly from the projections made in the Bentley et al. study.

Brogan and Venkateswaran concluded that ICEVs fueled with gasoline, methanol, CNG, and ethanol had higher primary energy consumption rates than electric propulsion technologies (i.e., EVs, HEVs, and FCVs). Ethanol vehicles were shown to have the lowest CO_2 emission rate. The study revealed that on the basis of the average electric generation mix in the United States, EVs and HEVs generated fewer CO_2 emissions than gasoline ICEVs. The results for HC, CO, NO_x, and SO_x emissions were inconclusive, because the study did not estimate these emissions for the complete fuel cycle.

2.5 Ecotraffic, AB 1992

Researchers at Ecotraffic, AB, in Sweden estimated fuel-cycle emissions and primary energy consumption of various transportation fuels in Sweden (Ecotraffic, AB 1992). The Swedish study included the following fuel cycles: petroleum to gasoline, petroleum to diesel, petroleum to LPG, NG to CNG, NG to methanol, biomass to methanol, biomass to ethanol, rapeseed to vegetable oil, solar energy to hydrogen via electrolysis of water, NG to hydrogen, and electricity generation from various fuels. Fuel-cycle emissions of three criteria pollutants (HC, CO, and NO_x) and six GHGs (CO_2, CH_4, N_2O, NO_x, CO, and HC) were estimated for three vehicle types: cars, medium-duty trucks, and buses.

Ecotraffic estimated emissions of HC, CO, and NO_x from both upstream fuel production processes and vehicle operations by considering emission standards applicable to stationary sources and motor vehicles in Sweden. Emissions from the vehicles powered by diesel and gasoline were taken directly from laboratory emissions testing results. EV emissions were calculated for two electric generation mix scenarios. The first was the Swedish average electric generation mix, in which 50% of electricity is from hydropower, 45% is from nuclear energy, and the remaining 5% is from fossil fuels. Compared with the average generation mix in the United States, where more than 50% of electricity is generated from coal, the Swedish mix is very clean. In the second scenario, NG was the sole primary energy source for EV electricity generation.

Ecotraffic concluded that use of nonfossil fuels could result in a greater-than-50% reduction in GHG emissions when compared with use of petroleum-based fuels. Use of diesel and vegetable oils produced the greatest NO_x emissions. Because almost all electricity in Sweden is generated from hydropower and nuclear energy, use of EVs reduced emissions of criteria pollutants and GHGs dramatically. Because the study used only Swedish data on emissions and energy efficiencies, its conclusions may be applicable only to Sweden.

2.6 Wang and Santini 1993

Wang and Santini (1993) estimated fuel-cycle emissions of EVs and GVs in four U.S. cities (Chicago, Denver, Los Angeles, and New York) under different driving cycles. The study included emissions of HC, CO, NO_x, SO_x, and CO_2. An early version of EAGLES — a computer simulation model for vehicle fuel consumption developed at Argonne National Laboratory — was used to estimate GV fuel economy and EV electricity consumption under different driving cycles (Marr 1995). Considering city-specific electric generation mix and power plant emissions, Wang and Santini estimated power plant emissions attributable to EV use in each of the four cities. By using EPA's Mobile 5a model, they estimated in-use emissions of U.S. Tier 1 GVs. Petroleum refinery emissions attributable to GV use were included in the estimates.

Wang and Santini concluded that use of EVs reduced emissions of HC and CO by more than 98% in each of the four cities and under each of the six driving cycles studied. The amount of NO_x emitted from EVs depended on the stringency of NO_x control by power plants and on the type of power plants that provided electricity for EVs. In Chicago, Los Angeles, and New York, NO_x emissions were significantly reduced by using EVs, while in Denver, NO_x emissions were reduced only moderately. EV use reduced CO_2 emissions significantly under low-speed driving cycles; under high-speed driving cycles, Wang and Santini found that CO_2 emissions from EVs could increase because the EV energy benefit (relative to GVs) was reduced. In Denver, SO_x emissions increased when EVs were used because more than half of that city's electricity is generated from coal; emissions also increased in New York, where nearly half of electricity is generated from oil.

Although Wang and Santini assumed that sodium/sulfur (Na/S) batteries would be used for EVs, when estimating EV electricity consumption, they did not account for the loss of energy from the thermal management system that was necessary to maintain the high temperature required for Na/S batteries. They took into account emissions from power plants, refinery plants, and vehicle operations but did not consider emissions from other fuel-cycle stages.

2.7 Darrow 1994a, 1994b

Darrow conducted two separate studies: one for the Gas Research Institute (GRI) to analyze fuel-cycle emissions of alternative fuels (Darrow 1994a) and the other for Southern California Gas Company to compare fuel-cycle emissions from EVs and CNGVs (Darrow 1994b).

In his GRI study, Darrow included the following fuel cycles: petroleum to conventional gasoline, petroleum to RFG, petroleum to LPG, NG to CNG, NG to methanol, NG to LPG, corn to ethanol, and electricity generation from various fuels. Fuel-cycle emissions for five criteria pollutants (reactive organic gases [ROGs], NO_x, CO, SO_x, and PM_{10}) and three GHGs (CO_2, CH_4, and N_2O) were included in the study.

Darrow analyzed fuel-cycle emissions for the United States and California in two target years: 1994 and 2000. For the United States, he analyzed emission data from various areas of the country and aggregate U.S. data on emissions and energy efficiencies. For California, Darrow included emissions occurring only within the state. More than 50% of electricity in the United States is generated from coal, while natural gas, hydropower, and nuclear are the primary sources of electricity in California. Consequently, overall fuel-cycle emissions in California were significantly lower than those in the United States.

As the basis for his study, Darrow used a typical minivan powered by various fuels. For vehicular emissions, Darrow assumed federal Tier 1 standards for all ICEV types except CNGVs, for which the extremely low certification emission levels of the Chrysler CNG minivan were used. This assumption is problematic, because the difference between emission standards and emission certification levels can be as large as 50% — certification levels can be 50% lower than applicable standards. Furthermore, neither emission standards nor emission certification levels represent actual on-road emissions. Because of the deterioration of emission control systems over the life of the vehicle, lifetime average emission rates are much higher than emission standards and emission certification levels. It is also questionable to compare a very clean CNG van to other vehicles, which Darrow assumed would meet Tier 1 standards. The Chrysler CNG van is designed to achieve the lowest possible emissions. The vehicle's specialized catalyst formation, high catalyst loading, and engine modification are designed to reduce engine-out NO_x emissions. If the same intense emission control measures were applied to other vehicle types, their emissions would certainly be lower.

In the United States, Darrow showed that the fuel-cycle NO_x emissions generated from ICEVs powered by conventional gasoline, RFG, and LPG were similar. ICEVs powered by E85 (mixture of 85% ethanol and 15% gasoline by volume) and M85 (mixture of 85% methanol and 15% gasoline by volume) had relatively high NO_x emission rates. EVs had the most NO_x emissions, and CNGVs had the fewest.

ICEVs powered by conventional gasoline, RFG, LPG, E85, and M85 had similar ROG and CO emission rates. CNGVs had significantly fewer emissions, and EVs had the fewest emissions. In California, EVs were shown to have fewer emissions of NO_x, ROG, and CO. CNGVs produced the fewest NO_x emissions.

The extremely low emission levels from CNGVs estimated by Darrow for both the United States and California were caused by his use of the extremely low certification emission levels of the Chrysler CNG minivan for CNGVs. In fact, Darrow showed that, when Tier 1 standards were applied to CNGVs as well as to other vehicle types, CNGVs usually demonstrated few emission reduction benefits; the emission rates from CNGVs were about the same as those from LPGVs.

Darrow presented GHG emissions from various transportation fuels but did not provide the details for his GHG emission calculations. He showed that EVs and vehicles powered by E85 and M85 had high CO_2-equivalent emissions; gasoline and CNG ICEVs produced GHG emissions at an equal rate, and LPGVs generated the fewest GHG emissions.

In his study for Southern California Gas Company (Darrow 1994b), Darrow compared fuel-cycle emissions from CNGVs and EVs. By using the data and assumptions that he applied in his study for GRI, he concluded that in Southern California, while in-basin emission rates from EVs were generally lower than those for CNGVs, all-location emission rates of NO_x from EVs were slightly higher than those from CNGVs. However, EVs always generated fewer all-location ROG and CO emissions than did CNGVs.

2.8 Acurex 1996

Acurex Environmental Corporation conducted a study for the California Air Resources Board (CARB) to estimate the fuel-cycle emissions of RFG, clean diesel, and alternative transportation fuels (Acurex 1995). The Acurex study included the following fuel cycles: petroleum to conventional gasoline, petroleum to RFG, petroleum to clean diesel, NG to LPG, NG to methanol, NG to CNG, NG to LNG, coal to methanol, biomass (including corn, woody and herbaceous biomass) to methanol, biomass to ethanol, electricity generation from various fuels, and hydrogen from electricity via electrolysis of water. The study examined three criteria pollutants (NO_x, NMOG, CO) and two GHGs (CO_2 and CH_4). NMOG emissions from different fuel production processes and from vehicles using different alternative fuels were adjusted to account for their ozone-forming potentials.

Acurex established a framework for estimating fuel-cycle emissions in California between 1990 and 2010. Emission regulations applicable to this timeframe in California were taken into account. In particular, Acurex considered the reductions in stationary source emissions brought about by the adoption of emission regulations by the South Coast Air Quality Management District (SCAQMD). Given the uncertainties involved in emission controls and fuel economy improvements from the present to 2010, Acurex established three scenarios in 2010 to reflect varying degrees of stationary emission controls and vehicle fuel economy.

Acurex produced an HC speciation profile for NMOG emissions from each fuel-cycle stage and for each vehicle type to estimate ozone reactivity-adjusted NMOG emissions. The speciated NMOG emissions were then multiplied by the maximum incremental ozone reactivity factors developed by CARB to calculate ozone reactivity-adjusted NMOG emissions. Only NMOG emissions occurring within California were taken into account in fuel-cycle NMOG emission calculations.

In calculating EV emissions, Acurex used four sets of electric generation mix: a marginal generation mix for EVs in California, an average generation mix in the South Coast Air Basin, a U.S. average generation mix, and a worldwide average generation mix. The worldwide average generation mix may have little meaning because EVs will not be introduced worldwide.

The Acurex study revealed the following about per-mile emissions from vehicles in 2010. Vehicles powered by LNG, CNG, LPG, and hydrogen would generate the fewest CO_2 emissions; followed by vehicles powered by M100 (100% methanol by volume), M85, E85, and diesel; then by gasoline-powered vehicles. EVs had the highest CO_2 emissions. In fact, the CO_2 emission rates of EVs were more than twice as high as those of GVs.

For NO_x emissions occurring within the South Coast Air Basin, vehicles powered by CNG, hydrogen, LPG, electricity, and diesel generated the fewest emissions; followed by vehicles powered by E85, M85, and RFG; then by vehicles powered by M100. Vehicles powered by LNG produced the highest in-basin NO_x emission rates (emission rates from LNG-powered vehicles were five times as high as those from GVs).

Vehicles powered by hydrogen, LNG, electricity, CNG, M100, and diesel generated the lowest rate of ozone reactivity-adjusted NMOG emissions; followed by vehicles powered by E85 and M85; then by GVs. LPG vehicles generated the highest rates of ozone-adjusted NMOG emissions.

In its study, Acurex thoroughly characterized emissions of various fuel production processes in California, especially in the South Coast Air Basin. Acurex collected extensive emissions data, and its established fuel-cycle framework will serve as a useful tool to estimate fuel-cycle emissions in California. However, the study did not include PM_{10} and SO_x emissions. PM_{10} and other fine particulates have increasingly become a concern since studies have found that fine particulates may have already caused significant damage to human health. Researchers' ability to apply the Acurex framework for California to other regions in the United States remains unclear.

2.9 Delucchi 1997

In 1997, Delucchi issued a report documenting revisions made to his 1991 study (Delucchi 1997). With newly available data, Delucchi updated many of his parametric assumptions and used new methodologies to account for energy use and emissions associated with fuel-cycle stages.

Comparison of the GREET model and the Delucchi model reveals that, in many cases, the GREET model takes its parametric assumptions from model users, while the Delucchi model calculates parametric values that are determined by certain assumptions. For example, the value used by GREET to calculate relative differences in vehicle fuel economy between AFVs and GVs is determined outside of GREET by comparing testing data from AFVs and GVs. The Delucchi model calculates a relative change in fuel economy for AFVs by taking into account potential differences in engine efficiency, vehicle weight, and so on.

2.10 Argonne National Laboratory et al. 1998

Between 1993 and 1996, DOE commissioned a multi-national laboratory study to assess energy and emission impacts of using EVs relative to GVs (Argonne National Laboratory et al. 1998a,b). The study, called the Electric Vehicle Total Energy Cycle Analysis (EVTECA), assessed EV impacts in four metropolitan areas (Chicago, Houston, Los Angeles, and Washington, D.C.) where air quality improvements were needed and where patterns of vehicle use, electric generation, and baseline gasoline quality varied. The study characterized EVs equipped with four battery types typical of battery technologies being studied around 1994: advanced lead-acid, nickel-cadmium, nickel-metal hydride, and sodium-sulfur. The study assumed that EV technologies would penetrate passenger car and van markets. GV fuel economy and EV electricity consumption rates between 1998 and 2010 were simulated by means of an Argonne vehicle model. The estimated per-mile EV electricity use rate, together with total daily travel and recharge requirements and total EV market penetration, was used to determine the total daily electricity demand by EVs in each of the four areas. High and low EV market penetration scenarios were assumed for each area.

On the basis of the predicted electricity demand by EVs, NREL conducted electric utility simulations to determine marginal electric power plants for providing electricity for EVs and energy use and emissions in the electric utility sector induced by use of EVs. Additional electric generation capacity, which was required to meet EV electricity demand, was assumed to be provided by coal- and/or gas-fired advanced power plants. The comprehensive utility simulation showed that energy use and emissions associated with EVs varied from region to region and within regions depending on the assumptions that researchers made regarding the constraints associated with EV recharging, the type of electric generation capacity to be added, and the season of the year.

In addition to fuel-cycle energy use and emissions for both gasoline and electricity, the EVTECA study included energy use and emissions associated with the vehicle cycle. That is, researchers estimated energy use and emissions of material recovery, material fabrication, vehicle assembly, vehicle disposal/recycling, battery production, and battery disposal/recycling. The vehicle cycle analysis revealed that the manufacturing process for EVs would generate more criteria pollutant emissions than the manufacture of conventional vehicles, mainly because of EV battery production and recycling.

The EVTECA generated many results for the various combinations of cases. In general, the following conclusions were made on the basis of the study results:

- CVs use 15–40% more energy than EVs on a per-mile basis.
- Use of EVs reduced emissions of VOCs and CO by over 90% and emissions of CO_2 by 25–65%.
- All cases examined led to reductions in NO_x emissions, but the magnitude of reductions varied greatly between regions and depended primarily on the type of EV charging process assumed.
- EVs increased emissions of total suspended particulates and SO_x.
- Lead emissions increased significantly when lead-acid battery-equipped EVs were used.

2.11 Sheehan et al. 1998

In 1998, NREL completed a study for the U.S. Department of Agriculture and DOE to evaluate fuel-cycle energy and emission impacts of using biodiesel (BD) in place of petroleum diesel in urban buses (Sheehan et al. 1998). Although BD can be produced from several feedstocks, the study evaluated the production of BD from soybeans, the major pathway in the United States. In the study, the petroleum diesel fuel cycle included stages from petroleum recovery to diesel combustion on buses, and the BD cycle included stages from soybean farming to BD combustion on board diesel buses. The study included fossil energy use, petroleum use,

CO_2 emissions, and emissions of five criteria pollutants (NMHC, CO, NO_x, PM_{10}, and SO_x). The study also estimated, though less thoroughly, the amount of waste water and the amount of solid waste generated during production of BD.

The study included significant details regarding production locations for both feedstocks and fuel products and energy and emissions for each stage. A life-cycle model developed by Ecobalance, Inc. (a consulting company in Virginia) was used for the study, which provided a wealth of detailed information on energy use and emissions for each stage involved in the two fuel cycles.

The study resulted in the following conclusions. Use of pure BD can reduce petroleum use by over 95%, fossil energy use by about 70%, and CO_2 emissions by 78%. Emissions of PM, CO, and SO_x are reduced by 32%, 35%, and 8%, respectively. However, use of BD increases NO_x emissions by 13% and HC emissions by 35%. The increase in HC emissions is mainly caused by high levels of HC emissions during BD production.

2.12 Summary

Of the 11 studies discussed, those conducted by Delucchi and Acurex are the most comprehensive in terms of fuels and technologies. Through his study, Delucchi established a spreadsheet-based model to calculate GHG emissions. Acurex established a framework to calculate fuel-cycle emissions. But because the framework was designed for California only, it is not clear whether it can be used to estimate emissions for other U.S. regions. For a given fuel, the 1998 Argonne study was the most detailed on electric vehicles. The 1991 NREL study (NREL et al. 1991) was the most thorough study on cellulosic ethanol. The 1998 NREL study (Sheehan et al. 1998) was the most extensive study on BD.