NOTATION

ACRONYMS AND ABBREVIATIONS

AFV	alternative-fuel vehicle
CARB	California Air Resources Board
CH_4	methane
CNG	compressed natural gas
CNGV	compressed natural gas vehicle
CO	carbon monoxide
CO_2	carbon dioxide
CPGEM	**C**riteria **P**ollutant, **G**reenhouse Gas, and **E**nergy **M**odel
EIA	Energy Information Administration
EPA	U.S. Environmental Protection Agency
ETAE	ethyl tertiary amyl ether
ETBE	ethyl tertiary butyl ether
EV	electric vehicle
E10	mixture of 10% ethanol and 90% gasoline (by volume)
E85	mixture of 85% ethanol and 15% gasoline (by volume)
E95	mixture of 95% ethanol and 5% gasoline (by volume)
E100	neat ethanol
FCV	fuel-cell vehicle
GHG	greenhouse gas
GREET	**G**reenhouse Gases, **R**egulated **E**missions, and **E**nergy Use in **T**ransportation
GRI	Gas Research Institute
GV	gasoline vehicle
GWP	global warming potential
HC	hydrocarbon
HEV	hybrid electric vehicle
ICEV	internal combustion engine vehicles
INEL	Idaho National Engineering Laboratory
IPCC	Intergovernmental Panel on Climate Change
LNG	liquefied natural gas
LPG	liquefied petroleum gas
LSD	low-sulfur diesel
MSW	municipal solid wastes
MTBE	methyl tertiary butyl ether
MY	model year
M85	mixture of 85% methanol and 15% gasoline (by volume)
M100	neat methanol
Na/S	sodium/sulfur

NG	natural gas
NMOG	nonmethane organic gases
NO_x	nitrogen oxides
N_2O	nitrous oxide
NREL	National Renewable Energy Laboratory
PM	particulate matter
PM_{10}	particulate matter measuring 10 microns or less
RFG	reformulated gasoline
ROG	reactive organic gas
SCAQMD	South Coast Air Quality Management District
SO_x	sulfur oxides
SO_2	sulfur dioxide
TAME	tertiary amyl methyl ether
T&D	transportation and distribution
T&S	transportation and storage
T&S&D	transportation, storage, and distribution
VMT	vehicle miles traveled
VOC	volatile organic compound

UNITS OF MEASURE

Btu	British thermal unit
Btu/mi	Btu per mile
Btu/10^6 Btu	Btu per million Btu
g/10^6 Btu	grams per million Btu
g/gal	grams per gallon
g/mi	grams per mile
kWh	kilowatt hours
MPG	miles per gallon

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DEVELOPMENT AND USE OF THE GREET MODEL TO ESTIMATE FUEL-CYCLE ENERGY USE AND EMISSIONS OF VARIOUS TRANSPORTATION TECHNOLOGIES AND FUELS

by

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ABSTRACT

This report documents the development and use of the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model. The model, developed in a spreadsheet format, estimates the full fuel-cycle emissions and energy use associated with various transportation fuels for light-duty vehicles. The model calculates fuel-cycle emissions of five criteria pollutants (volatile organic compounds, carbon monoxide, nitrogen oxides, sulfur oxides, and particulate matter measuring 10 microns or less) and three greenhouse gases (carbon dioxide, methane, and nitrous oxide). The model also calculates the total fuel-cycle energy consumption, fossil fuel consumption, and petroleum consumption using various transportation fuels. The GREET model includes 17 fuel cycles: petroleum to conventional gasoline, reformulated gasoline, clean diesel, liquefied petroleum gas, and electricity via residual oil; natural gas to compressed natural gas, liquefied petroleum gas, methanol, 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; and landfill gases to methanol. This report presents fuel-cycle energy use and emissions for a 2000 model-year car powered by each of the fuels that are produced from the primary energy sources considered in the study.

1 INTRODUCTION

Transportation technologies — powered by various transportation fuels — are being promoted to help solve urban air pollution problems, limit climate change impacts caused by greenhouse gas (GHG) emissions, and reduce U.S. dependence on imported oil. To completely evaluate the energy and emission effects of these transportation technologies, one must consider emissions and energy use from upstream fuel production processes as well as from vehicle operations. This 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.

Various studies have been conducted to estimate fuel-cycle emissions and energy use for various transportation technologies; the estimates developed by researchers are subject to assumptions regarding technology development, emission controls, primary fuel sources, fuel production processes, and many other factors. Tools for calculating emissions and energy use are needed to test the effects of these assumptions on fuel-cycle emissions. Comprehensive tools to compare the fuel-cycle emissions and energy use of various technologies and to conduct sensitivity analyses of various assumptions are rarely available. It is difficult, then, to compare and reconcile the results of different studies and to conduct a comprehensive evaluation of fuel-cycle emissions and energy use.

This report describes the development of a fuel-cycle model called the **G**reenhouse Gases, **R**egulated **E**missions, and **E**nergy Use in **T**ransportation (GREET) model. The model calculates, for a given fuel/transportation technology combination, the fuel-cycle emissions of five criteria pollutants — volatile organic compounds (VOC), carbon monoxide (CO), nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate matter measuring 10 microns or less (PM_{10}) — and three greenhouse gases — carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The GREET model also calculates total fuel-cycle energy consumption, fossil fuel consumption, and petroleum consumption according to the fuel/transportation technology combination. The model can be used both to compare the fuel-cycle emissions and energy use of various transportation technologies and to test the emission and energy effects of the various assumptions used to estimate emissions and energy use. Our report presents the fuel-cycle emissions and energy use of various transportation technologies, as calculated by using the GREET model.

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

Delucchi conducted 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 (NMOG). Besides emissions and energy use of 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 a 1985 Energy Information Administration (EIA) survey 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.

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 improvements in energy efficiency 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 mostly 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 is by far the most comprehensive study of energy-cycle GHG emissions. For the last several years, the study has been widely cited, and the model has been widely used. Although still credible, the emissions and energy consumption assumed by Delucchi need to be revised. At the time of the study, Delucchi used EPA's Mobile4.1 model to estimate GV emissions. Most researchers now believe that Mobile4.1 significantly underestimates actual on-road emissions. (Mobile5a — the successor of Mobile4.1 — is also believed to underestimate actual on-road emissions, but to a lesser extent.) Delucchi assumed emission reductions of AFVs relative to baseline GVs primarily on the basis of AFV emission tests conducted in the mid and late 1980s.

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 Laboratory, conducted an analysis of fuel-cycle emissions of biomass-based ethanol compared 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 in 2000 would be produced from municipal solid wastes (MSW), and in 2010 from biomass such as grasses and trees; 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 is based on potential emission reductions rather than on component compositions (U.S. EPA 1994). Because of this rule, actual RFG specifications in the future may vary among companies and will be 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), tertiary amyl methyl ether (TAME), ethyl tertiary amyl ether (ETAE), or MTBE can be used as an oxygenate 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 using E10 and E95.

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

NREL researchers estimated significantly larger CO_2 emission reductions by using ethanol than Delucchi did, primarily because the assumptions made by NREL favored ethanol. For example, NREL assumed high energy efficiencies and low emissions of 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 emissions reduction for E10 and E95. NREL used EPA's Mobile4.1 to estimate emissions of RFG-fueled baseline vehicles.

2.3 BENTLEY ET AL. — 1992

Bentley et al. of A.D. Little prepared a study for the Idaho National Engineering Laboratory (INEL) 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 drivetrain, 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 the SIMPLEV — a computer model developed at INEL to simulate vehicle fuel economy. In using SIMPLEV, Bentley et al. 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 over 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 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 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. So 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 emissions. The study revealed that, with the average electric generation mix in the United States, EVs and HEVs reduced

CO_2 emissions relative to 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 U.S. average generation mix, where over 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 compared with use of petroleum-based fuels. Use of diesel and vegetable oils produced the highest 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 was conducted using only Swedish data of 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 Mobile5a 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. Emission of NO_x 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, but under high-speed driving cycles, CO_2 emissions from EVs could increase because the EV energy benefit (relative to GVs) was reduced. SO_x emissions in Denver increased when using EVs 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 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 [ROG], 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 emissions 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. Over 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, fuel-cycle emissions in California were significantly lower than those in the United States as a whole.

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 is problematic, because the safety margin between emission standards and emission certification levels can be as large as 50% — meaning that certification levels can be 50% lower than applicable standards. Furthermore, neither emission standards nor emission certification levels represent actual on-road emissions. Because of emission control deteriorations 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 made 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 and M85 had relatively high NO_x emissions. EVs had the highest NO_x emissions, and CNGVs had the lowest.

ICEVs powered by conventional gasoline, RFG, LPG, E85, and M85 had similar ROG and CO emissions rates. CNGVs had significantly lower emissions, and EVs had the lowest emissions. In California, EVs were shown to have lower emissions for NO_x as well as for ROG and CO. CNGVs produced the lowest NO_x emissions.

The extremely low emissions 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 lowest 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 emissions from EVs were generally lower than those for CNGVs, all-location emissions of NO_x from EVs were slightly higher than those from CNGVs. However, EVs always generated lower all-location ROG and CO emissions than CNGVs.

2.8 ACUREX — 1995

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). In its study, Acurex 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 involved 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 of 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, average generation mix in the South Coast Air Basin, U.S. average generation mix, and 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 information about per-mile emissions from vehicles in 2010. Vehicles powered by LNG, CNG, LPG, and hydrogen generated the lowest CO_2 emissions; followed by vehicles powered by M100, M85, E85, and diesel; then by gasoline-powered vehicles. EVs had the highest CO_2 emissions. In fact, EV CO_2 emissions were more than twice as high as those for GVs.

For NO_x emissions occurring within the South Coast Air Basin, vehicles powered by CNG, hydrogen, LPG, electricity, and diesel generated the lowest 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 emissions (emissions from LNG-powered vehicles were five times as high as emissions from GVs).

Vehicles powered by hydrogen, LNG, electricity, CNG, M100, and diesel generated the lowest ozone reactivity-adjusted NMOG emissions; followed by vehicles powered by E85 and M85; then by GVs. LPG vehicles generated the highest 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 as studies have found that fine particulates may have already caused significant damages to human health. Researchers' ability to apply the Acurex framework for California to other regions in the United States remains unclear.

2.9 SUMMARY

Of the eight studies discussed in Section 2, those conducted by Delucchi and Acurex are the most comprehensive, although neither study included PM_{10} and SO_x emissions. 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 the framework can be used to estimate emissions for other U.S. regions.

Because of the different assumptions regarding upstream energy conversion efficiencies, technology pathways, emission control intensities, and vehicular emissions used in the studies, different studies of the same technology may generate significantly different emission results. The limitations of the previous studies and available models reveal a need to develop a user-friendly model so that different transportation technologies can be compared by using systematic assumptions.