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GREET 1.5 — Transportation Fuel-Cycle Model

Volume 1: Methodology, Development, Use, and Results

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GREET — *G*reenhouse Gases, *R*egulated *E*missions, and *E*nergy Use in *T*ransportation

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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.