The *G*reenhouse Gases, *R*egulated *E*missions, and *E*nergy Use in *T*ransportation (GREET) Model Version 1.5

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1. Introduction

The transportation sector accounts for 27% of the 90 quadrillion Btu of energy consumed in the United States each year (Davis 1998). Petroleum-based fuels account for 97% of the transportation energy consumed — making the U.S. transportation sector vulnerable to potential world oil supply disruptions. In recent years, concern for potential global warming of anthropogenic greenhouse gas (GHG) emissions has rekindled a renewed interest in reducing GHG emissions. The U.S. transportation sector contributes about 26% of the U.S. total GHG emissions (U.S. Environmental protection Agency [EPA] 1998a). If the United States is to reduce its overall GHG emissions, it must reduce its transportation GHG emissions. The transportation sector is also a major contributor to urban air pollution problems. Nationwide, this sector accounts for 40% of volatile organic compounds, 77% of carbon monoxide, and 49% of nitrogen oxide emissions (EPA 1998b). The transportation shares of these emissions in urban areas are even higher.

Alternative transportation fuels and advanced vehicle technologies are being promoted to help reduce U.S. dependence on imported oil, decrease GHG emissions, and solve urban air pollution problems. To accurately 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.

Researchers have conducted studies to estimate fuel-cycle emissions and energy use associated with various transportation fuels and 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.

2. Development of the GREET Model

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 1995, with funding from the U.S. Department of Energy's (DOE's) Office of Transportation Technologies, Argonne began to develop a spreadsheet-based fuel-cycle model. The goal was to provide a transparent computer tool that would allow researchers to evaluate fuel-cycle energy and emission impacts of various transportation technologies. The first version of the model, named the **G**reenhouse Gases, **R**egulated **E**missions, and **E**nergy Use in **T**ransportation (GREET) fuel-cycle model, was completed and released in 1996 with a report documenting its development and use (Wang 1996). Since then, the model has been significantly expanded and improved.

The GREET model has evolved significantly since its introduction in 1996. Development and use of the latest version of the model, GREET 1.5, is described in a two-volume report (Wang 1999a, 1999b). For a given transportation fuel/technology combination, GREET 1.5 separately calculates: (1) the fuel-cycle consumption of (a) total energy (all energy sources), (b) fossil fuels (petroleum, natural gas, and coal), and (c) petroleum; (2) the fuel-cycle emissions of GHGs — primarily carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O); and (3) the fuel-cycle emissions of five criteria pollutants – volatile organic compounds (VOCs), carbon monoxide (CO), nitrogen oxides (NO_x), particulate matter with a diameter measuring 10 micrometers or less (PM_{10}), and sulfur oxides (SO_x). The model is designed to readily allow researchers to input their own assumptions and generate fuel-cycle energy and emission results for specific fuel/technology combinations.

The GREET model comprises three sub-models. The GREET one series sub-model estimates fuel-cycle energy use and emissions of light-duty vehicles (passenger cars and light-duty trucks). The GREET two series sub-model estimates vehicle-cycle energy use and emissions for light-duty vehicles. The GREET three series sub-model estimates fuel-cycle energy use and emissions of heavy-duty vehicles. Results of the GREET one series sub-model are summarized here. The current version of the GREET one series sub-model is GREET 1.5. GREET 1.5 estimates the full fuel-cycle emissions and energy use associated with various transportation fuels and advanced vehicle technologies applied to light-duty vehicles. The model includes both near- and long-term transportation fuels and vehicle technologies. Near-term options are those that are already available or will be available within the next few years, and long-term options are those that could become available in about ten years. Table 1 presents vehicle technology options that are included in GREET 1.5. Figure 1 shows fuel pathways included in GREET 1.5.

Table 1. Near- and Long-Term Vehicle Technology Options In GREET 1.5

Near-Term Options	Long-Term Options
Gasoline vehicles:	SI vehicles:
Federal reformulated gasoline	Dedicated compressed natural gas
California reformulated gasoline	Dedicated liquefied natural gas
E10	Dedicated liquefied petroleum gas
CIDI vehicles: diesel	Dedicated E90
Compressed natural gas vehicles:	Dedicated M90
Bi-fuel	SIDI vehicles:
Dedicated fuel	Federal reformulated gasoline
Dedicated liquefied petroleum gas vehicles	California reformulated gasoline
Flexible-fuel vehicles:	E90
E85	M90
M85	CIDI vehicles:
Electric vehicles	Reformulated diesel
Grid-connected HEVs: Calif. Reformulated gasoline	Dimethyl ether
Grid-independent HEVs:	Fischer-Tropsch diesel
Federal reformulated gasoline	Biodiesel
Diesel	Grid-independent HEVs:
	Federal reformulated gasoline
	Compressed natural gas
	Liquefied natural gas
	Liquefied petroleum gas
	E90
	M90
	Reformulated diesel
	Dimethyl ether
	Fischer-Tropsch diesel
	Biodiesel
	Grid-connected HEVs:
	California reformulated gasoline
	Compressed natural gas
	Liquefied natural gas
	Liquefied petroleum gas
	E90
	M90
	Reformulated diesel
	Dimethyl ether
	Fischer-Tropsch diesel
	Biodiesel
	Electric vehicles
	Fuel-cell vehicles:
	Hydrogen
	Methanol
	Gasoline
	Ethanol
	Compressed natural gas

Notes for Table 1:

HEVs = hybrid electric vehicles; CIDI = compression-ignition, direct-injection; SI = spark ignition; SIDI = spark-ignition, direct-injection; E90 = mixture of 90% ethanol and 10% gasoline by volume; E85 = mixture of 85% ethanol and 15% gasoline by volume; E10 = mixture of 10% ethanol and 90% gasoline by volume; M90 = mixture of 90% methanol and 10% gasoline by volume; M85 = mixture of 85% methanol and 15% gasoline by volume.

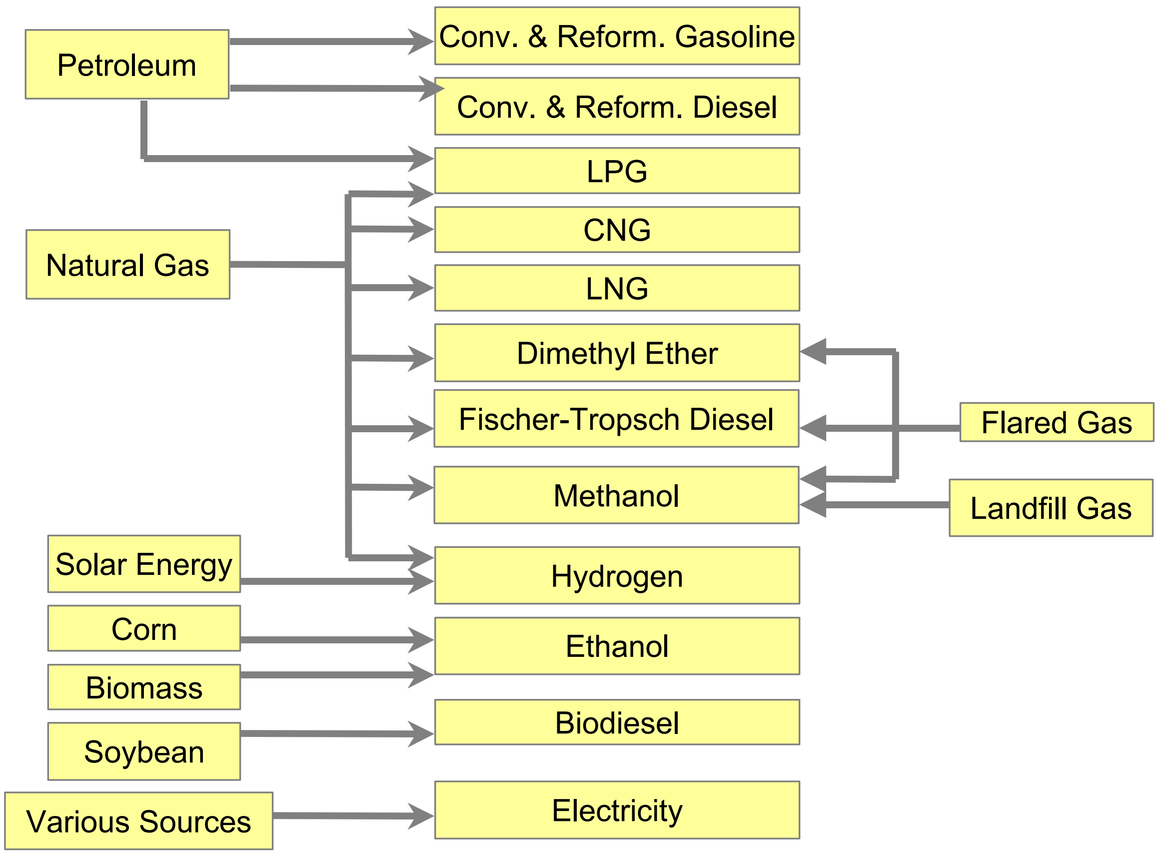

Figure 1. Fuel-Cycle Pathways Included in GREET 1.5

3. Computer System Requirements and Model Structure

GREET 1.5 is a multidimensional spreadsheet model developed in Microsoft Excel 97. In order to run the model, Microsoft Excel 97 must be installed on a user's computer. The size of GREET 1.5 is about 2.4 megabytes of memory. If a user receives the model in a zipped format, it must be unzipped by means of a zip/unzip software. The model can then be stored on a computer, and then opened and run in Excel 97 or higher version such as the version in the Microsoft Office 2000 Suite.

GREET1.5 is designed with the circular calculation feature in Excel. Before running the model, a user must ensure that the circular feature in Excel is turned on. This setting is already incorporated in GREET 1.5; however, if a user already has a different Excel file open with the circular calculation feature off, opening GREET 1.5 with the feature off will prevent the model from executing circular calculations. It is recommended that a user always opens GREET 1.5 before any other Excel files in order to prevent this problem from happening.

With the circular calculation feature, if a cell in GREET 1.5 is assigned an invalid value (such as a symbolic input to a numerical value-required cell), the model will generate non-repairable error messages in many cells. It is recommended that a user maintains the original GREET 1.5 copy on a computer as a backup and uses an operational copy for calculations.

Within GREET 1.5, some cells present default assumptions used for fuel-cycle energy and emission calculations, while others are logic calculations. A user has the option to change any of the default assumptions. The cells that contain critical assumptions are colored yellow so the user can easily distinguish these assumptions from logic calculations and can change key assumptions as needed. When a user completes all inputs for key assumptions, the user needs to press the F9 key on the computer key board to calculate results based on the new assumptions.

GREET 1.5 consists of 15 sheets; each of these is briefly described below.

Overview. This sheet presents a brief summary of each of the following sheets in GREET. It is intended to introduce the functions of each sheet. It is highly recommended that first-time users read this sheet before proceeding with GREET calculations.

EF. In this sheet, emission factors (EF) are presented for individual combustion technologies that burn natural gas, residual oil, diesel, gasoline, crude oil, liquefied petroleum gas, coal, and biomass. These emission factors are used in other sheets of GREET 1.5 to calculate emissions associated with fuel combustion in various upstream stages.

Fuel_Specs. This sheet presents specifications for individual fuels. Lower and higher heating values, fuel density, carbon weight ratio, and sulfur weight ratio are specified for each fuel. The parametric values for these fuel specifications are needed to estimate energy consumption and emissions, as well as for conversions among mass, volume, and energy content. Global warming potentials for individual GHGs, which are used in GREET to convert emissions of GHGs into CO_2-equivalent emissions, also are presented in this sheet.

Petroleum. This sheet is used to calculate upstream energy use and emissions of petroleum-based fuels. Six petroleum-based fuels are included in GREET: conventional gasoline, reformulated gasoline, conventional diesel, reformulated diesel, liquefied petroleum gas, and residual oil. Although residual oil is not a vehicle fuel, it is included here for calculating upstream energy use and emissions associated with producing transportation fuels and electricity.

NG. This sheet presents calculations of energy use and emissions for natural gas (NG) -based fuels: compressed natural gas, liquefied natural gas, liquefied petroleum gas, methanol, dimethyl ether, Fischer-Tropsch diesel, and hydrogen. For convenience, the fuel cycle that consists of producing renewable hydrogen from solar energy via water electrolysis is also presented in this section. For hydrogen fuel-cycle pathways, hydrogen can be produced in either gaseous or liquid form; either form may be selected for simulation. Pathways from flared gas to methanol, dimethyl ether, and Fischer-Tropsch diesel are also presented in this sheet.

Ag_Inputs. This sheet presents calculations for agricultural chemicals (or agricultural inputs, Ag-Inputs), including synthetic fertilizers and pesticides. Three fertilizers are included: nitrogen, phosphate, and potash. Pesticides include herbicides and insecticides. This sheet also includes calculations of energy use and emissions associated with transportation of chemicals from manufacturing plants to farms.

EtOH. This sheet calculates energy use and emissions for fuel cycles that involve producing ethanol (EtOH) from corn, woody biomass, and herbaceous biomass.

BD. This sheet calculates energy use and emissions associated with producing biodiesel (BD) from soybeans.

Coal. This sheet is used to calculate energy use and emissions for coal mining and transportation. The results are used in other upstream calculation sheets.

Uranium. This sheet is used to calculate energy use and emissions for uranium mining, transportation, and enrichment. The results are used in the electricity sheet for calculating upstream energy use and emissions of nuclear electric power plants.

LF_Gas. This sheet presents energy use and emission calculations for the fuel cycle that consists of producing methanol from landfill gases (LF_Gas). We assumed in GREET that without methanol production, landfill gases would otherwise be flared. Flaring the gases generates significant emissions. The emissions offset by methanol production are taken into account as emission credits for methanol production; emissions from methanol combustion are taken into account during vehicle operation.

Electric. This sheet is used to calculate energy use and emissions associated with electricity generation for production of transportation fuels (where electricity is used) and for operation of electric vehicles and grid-connected hybrid electric vehicles.

Vehicles. This sheet is used to calculate energy use and emissions associated with vehicle operations. The sheet is constructed in three sections. In the first (scenario control) section, for methanol and ethanol flexible-fuel vehicles and dedicated methanol and ethanol vehicles, a user can specify the content of methanol or ethanol in fuel blends. For Fischer-Tropsch diesel and biodiesel blended with diesel, a user can specify the content of Fischer-Tropsch diesel or biodiesel in fuel blends. The split for vehicle miles traveled between grid electricity operation and vehicle engine operation for grid-connected hybrid electric vehicles also is presented in the control section.

The second section of the *Vehicles* sheet presents fuel economy and emission changes associated with alternative-fueled vehicles and advanced technology vehicles relative to baseline gasoline or diesel vehicles. Because fuel economy and emissions of baseline vehicles are different for near- and long-term technology options, fuel economy and emission changes for near- and long-term technologies are presented separately in this section.

The third section calculates energy use and emissions associated with vehicle operations for individual vehicle types. The fuel economy of baseline gasoline vehicles is input in this section.

Results. The sheet is constructed in two sections. Fuel-cycle energy use and emissions for each vehicle type are calculated in the first section. For each vehicle type, energy use and emissions are calculated for three stages: feedstock (including recovery, transportation, and storage), fuel (including production, transportation, storage, and distribution), and vehicle operation. Shares of energy use and emissions by each of the three stages are also calculated in this section. For the five criteria pollutants, both urban emissions (emissions occurring in urban areas) and total emissions (emissions occurring everywhere) are calculated in this section.

In the second section of this sheet, changes in fuel-cycle energy use and emissions by individual alternative-fueled vehicle type are calculated. The changes by fuel/vehicle technologies are calculated against conventional gasoline vehicles fueled with conventional (for near-term options) or reformulated gasoline (for long-term options).

Graphs. This sheet graphically presents shares of energy use and emissions by feedstock, fuel, and vehicle operations for each vehicle type. Furthermore, it shows energy use and emissions reductions by individual vehicle technologies relative to baseline gasoline vehicles.

4. Sponsorship

Development of the GREET model was supported by the Office of Technology Utilization and the Director's Office (Assessment and Planning) within the Office of Transportation Technologies, U.S. Department of Energy.

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