GREET® Life-Cycle Analysis of Transportation Fuels and Vehicle Technologies

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The GREET® (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) Model

GREET.net

GREET 1 (Fuel Cycle)  GREET 2 (Materials)  Stochastic

GREET Application only implements methodology

GREET Data Service  GREET Software Server

Regular Updates

GREET.Net separates datasets and methodology

VEHICLE CYCLES (GREET 2 Series)

Vehicle cycle modelling for vehicle manufacturing

GREET 1 model:
Fuel-cycle modeling of vehicle/fuel systems

Stochastic Simulation Tool
GREET development has been supported by several DOE Offices since 1995

- Vehicle Technology Office (VTO)
- Bioenergy Technology Office (BETO)
- Fuel-Cell Technology Office (FCTO)
- Geothermal Technology Office (GTO)
- Energy Policy and Systems Analysis (EPSA)

GREET has been in public domain and free of charge - Updated annually

Examples of major uses of GREET

- US EPA used GREET for RFS and vehicle GHG standard developments
- CARB developed CA-GREET for its Low-Carbon Fuel Standard compliance
- DOE, USDA, and the Navy use GREET for R&D decisions
- DOD DLA-Energy uses GREET for alternative fuel purchase requirements
- Auto industry uses it for R&D screening of vehicle/fuel system combinations
- Energy industry (especially new fuel companies) uses it for addressing sustainability of R&D investments
- Universities uses GREET for education on technology sustainability of various fuels
There are 30,000 registered GREET users globally.
GREET outputs include energy use, greenhouse gases, criteria pollutants and water consumption for vehicle and energy systems

- **Energy use**
  - Total energy: fossil energy and renewable energy
    - Fossil energy: petroleum, natural gas, and coal (they are estimated separately)
    - Renewable energy: biomass, nuclear, hydro-power, wind, and solar energy

- **Greenhouse gases (GHGs)**
  - CO$_2$, CH$_4$, N$_2$O, and black carbon
  - CO$_2$e of the three (with their global warming potentials)

- **Air pollutants**
  - VOC, CO, NO$_x$, PM$_{10}$, PM$_{2.5}$, and SO$_x$
  - They are estimated separately for
    - Total (emissions everywhere)
    - Urban (a subset of the total)

- **Water consumption**

- **GREET LCA functional units**
  - Per mile driven
  - Per unit of energy (million Btu, MJ, gasoline gallon equivalent)
  - Other units (such as per ton-mi for transportation modes)
GREET includes more than 100 fuel production pathways from various energy feedstock sources.

**Feedstock**
- **Petroleum**
  - Conventional
  - Oil Sands
- **Coal**
- **Natural Gas**
  - North American
  - Non-North American
  - Shale gas
- **Renewable Natural Gas**
  - Landfill Gas
  - Animal Waste
  - Waste water treatment
  - Coke Oven Gas
  - Petroleum Coke
  - Nuclear Energy

**Fuel**
- **Gasoline**
- **Diesel**
- **Jet Fuel**
- **Liquefied Petroleum Gas**
- **Naphtha**
- **Residual Oil**
- **Hydrogen**
  - Fischer-Tropsch Diesel
  - Fischer-Tropsch Jet
  - Methanol
  - Dimethyl Ether

**Feedstock**
- **Corn**
- **Sugarcane**
- **Soybeans**
  - Palm
  - Rapeseed
  - Jatropha
  - Camelina
  - Algae

**Fuel**
- **Ethanol**
- **Butanol**
- **Biodiesel**
- **Renewable Diesel**
- **Renewable Gasoline**
- **Hydroprocessed Renewable Jet**

**Cellulosic Biomass**
- **Switchgrass**
- **Willow/Poplar**
- **Crop Residues**
- **Forest Residues**
- **Miscanthus**

**Fuel**
- **Ethanol**
- **Hydrogen**
- **Methanol**
- **Dimethyl Ether**
  - Fischer-Tropsch Diesel
  - Fischer-Tropsch Jet
  - Pyro Gasoline/Diesel/Jet
- **Electricity**

**Fuel**
- **Residual Oil**
- **Coal**
- **Natural Gas**
- **Biomass**
- **Other Renewables**
**GREET includes all transportation subsectors**

- **Road transportation**
  - Light-duty vehicles
  - Medium-duty vehicles
  - Heavy-duty vehicles
  - Various powertrains: Internal Combustion Engines, Electrics, Fuel cells

- **Air transportation**
  - Globally, a fast growing sector with GHG reduction pressure
  - Interest by DOD, ICAO, FAA, and commercial airlines
  - GREET includes
    - Passenger and freight transportation
    - Various alternative fuels blended with petroleum jet fuels

- **Rail transportation**
  - Interest by FRA, railroad companies
  - Potential for CNG/LNG to displace diesel

- **Marine transportation**
  - Desire to control air pollution in ports globally
  - Interest by EPA, local governments, IMO
  - GREET includes
    - Ocean and inland water transportation
    - Baseline diesel and alternative marine fuels
GREET examines more than 80 on-road vehicle/fuel systems for both LDVs and HDVs

**Conventional Spark-Ignition Engine Vehicles**
- Gasoline
- Compressed natural gas, liquefied natural gas, and liquefied petroleum gas
- Gaseous and liquid hydrogen
- Methanol and ethanol

**Spark-Ignition, Direct-Injection Engine Vehicles**
- Gasoline
- Methanol and ethanol

**Compression-Ignition, Direct-Injection Engine Vehicles**
- Diesel
- Fischer-Tropsch diesel
- Dimethyl ether
- Biodiesel

**Fuel Cell Vehicles**
- On-board hydrogen storage
  - Gaseous and liquid hydrogen from various sources
  - On-board hydrocarbon reforming to hydrogen

**Battery-Powered Electric Vehicles**
- Various electricity generation sources

**Hybrid Electric Vehicles (HEVs)**
- Spark-ignition engines:
  - Gasoline
  - Compressed natural gas, liquefied natural gas, and liquefied petroleum gas
  - Gaseous and liquid hydrogen
  - Methanol and ethanol
- Compression-ignition engines
  - Diesel
  - Fischer-Tropsch diesel
  - Dimethyl ether
  - Biodiesel

**Plug-in Hybrid Electric Vehicles (PHEVs)**
- Spark-ignition engines:
  - Gasoline
  - Compressed natural gas, liquefied natural gas, and liquefied petroleum gas
  - Gaseous and liquid hydrogen
  - Methanol and ethanol
- Compression-ignition engines
  - Diesel
  - Fischer-Tropsch diesel
  - Dimethyl ether
  - Biodiesel
**GREET approach and data sources**

- **Approach: build LCA modeling capacity with the GREET model**
  - Build a consistent LCA platform with reliable, widely accepted methods/protocols
  - Address emerging LCA issues
  - Maintain openness and transparency of LCAs by making GREET publicly available
  - Primarily process-based LCA approach (the so-called attributional LCA); some features of consequential LCA are incorporated

- **Data sources**
  - Field data and open literature
  - Simulations with models such as ASPEN Plus for fuel production and ANL Autonomie and EPA MOVES for vehicle operations
  - Fuel producers and technology developers for fuels and automakers and system components producers for vehicles
  - Baseline technologies and energy systems: EIA AEO projections, EPA eGrid for electric systems, etc.
  - Consideration of effects of regulations already adopted by agencies
LCA GHG Emissions of Petroleum Fuels
LCA system boundary: petroleum to gasoline
Examined GHG emissions of Canadian oil sands covering all 27 major projects since 2008

Legend:
- Used as process fuel or feedstock
- Product output
- Flaring
- Transportation
- Co-produced electricity
- Co-produced steam
- Process flow
- Primary Process
- Associated process
Updated GHG emissions of oil sands for 4 major pathways

Oil sand operations are 3 to 6 times more carbon intensive than average US conventional crudes

http://pubs.acs.org/doi/abs/10.1021/acs.est.5b01255
ANL study covered 70% of U.S. refining capacity

- LP modeling of 43 large (>100k bbl/d) refineries in four PADD regions
  - Typical summer and winter days in 2010

<table>
<thead>
<tr>
<th>PADD Region</th>
<th>Crude Input to Refineries (1000 bbl/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>921</td>
</tr>
<tr>
<td>II</td>
<td>3,451</td>
</tr>
<tr>
<td>III</td>
<td>7,755</td>
</tr>
<tr>
<td>IV</td>
<td>574</td>
</tr>
<tr>
<td>V</td>
<td>2,337</td>
</tr>
<tr>
<td>Total</td>
<td>15,038</td>
</tr>
</tbody>
</table>
Developed linear regression model that correlates refinery overall efficiency with key refinery parameters

Efficiency = f(API, sulfur%, heavy product yield, refinery complexity index)

\[ \eta_{LHV} = 87.59 + 0.2008 \times API - 0.7628 \times S + 0.07874 \times HP - 0.1847 \times CI \]

\( \eta_{LHV} \) is the refinery’s overall efficiency (on an LHV basis) in %;
API is the API gravity of crude oil;
S is the sulfur content of crude oil in % by weight;
HP is the heavy products yield in % by energy;
Cl is the actual utilized Complexity Index of the refinery.
Refinery analysis - data are key for proper LCA

- Other feed/blends
- Process fuels
- Utilities
Refinery analysis - product yield by process unit

Yield Shares

- Atmospheric Distillation
- Vacuum Distillation
- FCC
- Coker
- Hydrocracker
- Reformer
- Naphtha HDT
- Diesel HDT
- FCC Feed/Resid HDT
- Alkylation
- Hydrogen Plant

Colors:
- Other
- Heavy
- Middle
- Light
- Gas
$\text{CO}_2e$ intensity of refinery fuels with data from 43 large U.S. refineries

![Box plot showing CO2e intensity for different fuels](image)

- Elgowainy et al. *Environmental Science and Technology*, 2014
- Forman et al. *Environmental Science and Technology*, 2014
- Han et al. *Fuel*, 2015
Sources of CO$_{2e}$ emissions associated with refinery fuels

- NG SMR
- FCC Coke Combustion
- Purch NG Combustion
- Fuel Gas Combustion

CO$_2$ Intensity (g CO$_2$/MJ)

- Gasoline
- Diesel
- Jet
- RFO
- LPG
- Coke
WTW GHG emissions of petroleum fuels is dominated by end use release of CO$_2$; refinery emissions is a distant second.

High C-content of RFO and coke increase their life-cycle emissions.

WTW = well-to-wheels.
LCA of Vehicle Manufacturing
GREET 2 simulates vehicle cycle energy use and emissions from material recovery to vehicle disposal

- Raw material recovery
- Material processing and fabrication
- Vehicle component production
- Vehicle assembly
- Vehicle disposal and recycling
Developing a materials inventory for vehicles

Vehicle Components
- Body
- Powertrain
- Transmission
- Chassis
- Electric traction motor
- Generator
- Electronic controller

Battery
- Startup (Pb-Acid)
- Electric-drive
  - Ni-MH
  - Li-ion

Fluids
- Engine oil
- Power steering fluid
- Brake fluid
- Transmission fluid
- Powertrain coolant
- Windshield fluid
- Adhesives

ASCM
Dismantling Reports
Engineering Calculations
Other literature

1. Automotive System Cost Model, IBIS Associates and Oak Ridge National Laboratory
Key Parameters for Material Production

- Both steel and aluminum are modeled step-by-step from ore mining to part stamping
- Other metals are examined in three stages
  - Mining
  - Primary (virgin) production
  - Secondary (recycled) production
- Non-metals only examined production
Life Cycles of 60+ materials are included in GREET2

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Number in GREET</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferrous Metals</td>
<td>3</td>
<td>Steel, stainless steel, iron</td>
</tr>
<tr>
<td>Non-Ferrous Metals</td>
<td>12</td>
<td>Aluminum, copper, nickel, magnesium</td>
</tr>
<tr>
<td>Plastics</td>
<td>23</td>
<td>Polypropylene, nylon, carbon fiber reinforced plastic</td>
</tr>
<tr>
<td>Vehicle Fluids</td>
<td>7</td>
<td>Engine oil, windshield fluid</td>
</tr>
<tr>
<td>Others</td>
<td>17</td>
<td>Glass, graphite, silicon, cement</td>
</tr>
<tr>
<td>Total</td>
<td>62</td>
<td></td>
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</tbody>
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Key issues in vehicle-cycle analysis

- Use of virgin vs. recycled materials
- Vehicle weight and lightweighting
- Vehicle lifetime, component rebuilding/replacement
**GREET Examination of Vehicle Materials**

**GHG intensity of lightweight automotive materials vary significantly**

<table>
<thead>
<tr>
<th>Material</th>
<th>GHG Emissions (g CO2e/lb)</th>
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<tbody>
<tr>
<td>Magnesium</td>
<td>25,553</td>
</tr>
<tr>
<td>CFRP</td>
<td>9,430</td>
</tr>
<tr>
<td>Wrought Aluminum</td>
<td>4,598</td>
</tr>
<tr>
<td>Cast Aluminum</td>
<td>1,312</td>
</tr>
<tr>
<td>Steel</td>
<td>1,821</td>
</tr>
</tbody>
</table>

GHG Emissions (g CO2e/lb)
Material Burdens and Life Cycle Analysis

- We have examined the GHG burden of materials
  - Addressed the potential trade off between fuel cycle and vehicle cycle
  - Tailpipe GHG reduction vs. increased material embedded GHG burden
Al-intensive Light-duty Truck Case Study

F150 Super Crew 4WD 3.5L Specifications

<table>
<thead>
<tr>
<th></th>
<th>MY 2014</th>
<th>MY 2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curb Weight (lbs)</td>
<td>5615</td>
<td>4937</td>
</tr>
<tr>
<td>Fuel economy (MPG)</td>
<td>17 (15/21)</td>
<td>19 (17/23)</td>
</tr>
<tr>
<td>Al content (lbs)</td>
<td>545</td>
<td>1080</td>
</tr>
</tbody>
</table>

Vehicle lifetime miles: 180,000

Findings
- The high Al/steel substitution ratio (~0.44) observed in F150 leads to a net vehicle cycle GHG reduction of 3.5%.
- Fuel cycle GHG decreases by 9.9% as a result of improved fuel economy.
- Lightweighting reduces life-cycle GHG by 10%.
Example of C2G analysis with GREET

- Current and future (2030) vehicle-fuel pathways
  - GHG emissions
  - Levelized cost of driving for each pathway (at volume)
  - Cost of avoided GHG emissions relative to a conventional gasoline vehicle
  - Technology readiness level (TRL) assessment
- Fuel cycle and vehicle cycle
- Report published June 2016

https://greet.es.anl.gov/publication-c2g-2016-report
C2G GHG Emissions for current and future vehicle-fuel pathways

Large GHG reductions for light-duty vehicles are challenging and require consideration of the entire lifecycle, including vehicle manufacture, fuel production, and vehicle operation.

Note: Vehicle efficiency gain contributes to GHG reduction in all future pathways.
Please visit
http://greet.es.anl.gov

- GREET models
- GREET documents
- LCA publications
- GREET-based tools and calculators

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