Life-cycle Analysis of Vehicle/Fuel Systems Using the GREET Model

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LIFE CYCLE ASSESSMENT METHODS TO SUPPORT INDIA’S EFFORTS TO DECARBONISE TRANSPORT WORKSHOP UNDER THE DTEE AND NDC-TIA PROJECTS
April 13 2021
The GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model Framework

- Argonne has been developing the GREET life-cycle analysis (LCA) model since 1995 with annual updates and expansions
- It is available at greet.es.anl.gov
~ 43,800 Registered GREET Users Globally
**GREET includes a suite of models and tools**

- **GREET coverage**
  - GREET1: fuel cycle (or WTW) model of vehicle technologies and transportation fuels
  - GREET2: vehicle manufacturing cycle model of vehicle technologies

- **Modeling platform**
  - Excel
  - .net

- **GREET derivatives**
  - ICAO-GREET by ANL, based on GREET1
  - China-GREET by ANL, with support of Aramco
  - CA-GREET by CARB, based on GREET1
  - AFLEET by ANL: alternative-fuel vehicles energy, emissions, and cost estimation
  - EverBatt by ANL: energy, emissions, and cost modeling of remanufacturing and recycling of EV batteries

**GREET applications by agencies**

- CA-GREET3.0 built based on and uses data from ANL GREET
- Oregon Dept of Environ. Quality Clean Fuel Program
- EPA RFS2 used GREET and other sources for LCA of fuel pathways; GHG regulations
- National Highway Traffic Safety Administration (NHTSA) fuel economy regulation
- FAA and ICAO AFTF using GREET to evaluate aviation fuel pathways
- GREET was used for the US DRIVE Fuels Working Group Well-to-Wheels Report
- LCA of renewable marine fuel options to meet IMO 2020 sulfur regulations for the DOT MARAD
- US Dept of Agriculture: ARS for carbon intensity of farming practices and management; ERS for food environmental footprints; Office of Chief Economist for bioenergy LCA
GREET sustainability metrics include energy use, criteria pollutants, greenhouse gases, and water consumption

- **Energy use**
  - Total energy: fossil energy and renewable energy
  - Fossil energy: petroleum, natural gas, and coal
  - Renewable energy: biomass, nuclear energy, hydro-power, wind power, and solar energy

- **Air pollutants**
  - VOC, CO, NOx, PM$_{10}$, PM$_{2.5}$, and SOx
  - Estimated separately for total and urban (a subset of the total) emissions

- **Greenhouse gases**
  - CO$_2$, CH$_4$, N$_2$O, black carbon, and albedo
  - CO$_{2e}$ of the five (combined with their global warming potentials)

- **Water consumption**
  - Addressing water supply and demand (energy-water nexus)

- **GREET LCA functional units**
  - Per service unit (e.g., mile driven, ton-mile, passenger-mile)
  - Per unit of output (e.g., million Btu, MJ, gasoline gallon equivalent)
  - Per units of resource (e.g., per ton of biomass)
GREET covers many groups of energy systems

**Petroleum Sector:**
- Conventional oil
- Shale oil
- Oil Sands

**Natural Gas Sector:**
- Conventional NG
- Shale gas

**Gasoline**
- Diesel
- Jet fuel
- Liquefied petroleum gas
- Naphtha
- Residual oil

**Electric Systems:**
- Electricity generation at US plant level
- Aggregate to national, NERC, and state level
- With CCS, if applicable

**Renewable Energy/Fuels:**
- Ethanol
- Biodiesel
- Renewable diesel
- Renewable gasoline
- Renewable jet fuel
- Renewable natural gas

**Natural gas**
- Coal
- Residual oil
- Biomass
- Nuclear
- Hydro
- Wind
- Solar

**Renewable Hydrogen via electrolysis:**
- Wind
- Solar
- Nuclear

**E-Fuels:**
- Gasoline
- Diesel
- Jet fuel
- Methanol

**1st Gen Feedstocks:**
- Corn
- Sorghum
- Soybeans
- Rapeseeds
- Sugarcane
- Palm

**2nd Gen Feedstocks:**
- Dedi. energy crops
- Crop residues
- Forest residues
- MSW
- Animal wastes
- Algae

**Renewable Hydrogen via electrolysis:**
- Wind
- Solar
- Nuclear

**CO₂ Sources:**
- Ethanol plants
- NG SMR plants
- Cement plants
- Etc.

Besides energy systems, GREET also includes plastics and products.
GREET includes key propulsion technologies for light-duty and heavy-duty vehicles

Conventional Spark-Ignition Engine Vehicles
- Liquid and gaseous fuels

Spark-Ignition, Direct-Injection Engine Vehicles
- Liquid and gaseous fuels

Compression-Ignition, Direct-Injection Engine Vehicles
- Liquid fuels

Hybrid Electric Vehicles (HEVs)
- Spark-ignition engines:
  - Compression-ignition engines

Plug-in Hybrid Electric Vehicles (PHEVs)
- Spark-ignition engines:
  - Compression-ignition engines

Battery-Powered Electric Vehicles
- Various electricity generation sources

Fuel Cell Vehicles
- Hydrogen and on-board hydrocarbon reforming to hydrogen
GREET includes all transportation subsectors
(It is now expanded to include LCA of buildings and building technologies)

- Road
  - Light-duty vehicles
  - Medium-duty vehicles
  - Heavy-duty vehicles
  - Various powertrains: Internal combustion, Battery electric, Fuel cells

- Air
  - Globally, a fast growing sector with GHG reduction pressure.
  - GREET includes
    - Passenger and freight transportation of various alternative fuels blended with petroleum jet fuels

- Rail
  - Freight transportation
  - GREET includes
    - Diesel
    - Electricity
    - CNG/LNG

- Marine
  - The sector is under pressure to reduce air emissions and GHG emissions. GREET includes
    - Ocean and inland water transportation
    - Baseline diesel and alternative marine fuels

(Globally, a fast growing sector with GHG reduction pressure. GREET includes Passenger and freight transportation of various alternative fuels blended with petroleum jet fuels)
GREET LCA modeling framework

- Build LCA modeling capacity
- Build a consistent LCA platform with reliable, widely accepted methods/protocols
- Address emerging LCA issues
- Access to primary data sources and conduct detailed analysis
- Document sources of data, modeling and analysis approach, and results/conclusions
- Maintain openness and transparency of LCAs by making GREET and its documentation publicly available
- Primarily process-based LCA approach (the so-called attributional LCA); some features of consequential LCA are incorporated
**GREET relies on a variety of data sources**

**Baseline technologies and systems**
- Energy Information Administration’s data and its Annual Energy Outlook projections
- EPA eGrid for electric systems
- US Geology Services for water data

**Field operation data**
- Oil sands and shale oil operations
- Ethanol plants energy use
- Farming data from USDA

**Simulations with models**
- ASPEN Plus for fuel production
- ANL Autonomie for fuel economy
- EPA MOVES for vehicle emissions, EPA AMPD for stationary emissions
- LP models for petroleum refinery operations
- Electric utility dispatch models for marginal electricity analysis

**Collaboration with other national laboratories**

**Industry inputs**
- Fuel producers and technology developers on fuels
- Automakers and system components producers on vehicles
Life cycle of petroleum fuels

- GREET covers from petroleum recovery to fuel use (combustion) by including all energy inputs and emissions for each stage.
Petroleum product well-to-wheels results

- WTW GHG emissions of petroleum fuels are dominated by end use release of CO₂; refinery direct/indirect emissions a distant second.

Jet, RFO, and coke are less processed fuels, thus lower energy intensities.

High C-content of RFO and coke increases their WTW GHG emission intensities.
GREET results inform various DOE offices and programs

(DOE EERE December 23, 2016, Record 16008)

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Low/high band: sensitivity to uncertainties associated with projected fuel economy values and selected fuel pathway parameters
Comparative life-cycle GHG emissions of a mid-size global average car by powertrain, 2018 (tonnes per vehicle lifetime)

Li-Ion battery LCA result regional variation: country specific GHG emissions

Source: Kelly et al., Mitigation and Adaptation Strategies for Global Change, 2019.

“Other” includes graphite, copper, electrolyte, PVDF, plastics, steel, insulation, and coolant. “Other Cathode” includes process energy use and non-Ni/Co reagents.
WTW GHG emission comparison of ICEV, HEV, BEV, and PHEV in China

- WTW GHG intensities of BEVs and PHEVs are higher than gasoline ICEVs in 7 and 10 northern provinces due to the GHG-intensive coal-based electricity and cold weather.

- Gasoline HEVs have lower WTW GHG emissions than BEVs in 18 provinces, and PHEVs in 26 provinces.

A variety of biofuel production pathways are covered in GREET

- Grains, sugars, and cellulosics
  - Fermentation, Indirect Gasification
  - Ethanol, butanol
  - Fermentation
  - Hydrothermal Liquefaction
  - Renewable diesel
  - Anaerobic Digestion
  - Renewable Natural gas
  - Combustion
  - Electricity

- Waste feedstock
  - Pyrolysis, Fermentation, Gasification (e.g., FT)
  - Drop-in hydrocarbon fuels
  - Gasification (e.g., FT), Alcohol to Jet, Sugar to Jet
  - Aviation and marine fuels
  - Hydroprocessing
  - Biodiesel

- Cellulosics
  - Hydroprocessing
  - Alcohol to Jet, Sugar to Jet

- Algae and oil crops
  - Transesterification
  - Biodiesel

- The highlighted options have significant volumes in LCFS and RFS
- Ethanol accounts for >15 billion gallons nationwide, and >1.1 billion gallons in CA
GREET system boundary for biofuel LCA: direct activities and indirect effects are included

Key factors determining biofuel LCA results

- LCA system boundary
- Feedstock types
- Conversion technologies: energy balance and materials inputs such as enzyme and catalyst
- Technology improvement over time
- Biorefineries with distinctly different products: co-product methods
- Direct and indirect land use changes
GREET life-cycle GHG emissions of ethanol: feedstock is the main driver

WTW GHG emissions, g CO$_2$e/MJ

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Feedstock is a significant contributor to corn ethanol LCA GHGs: 38% of corn ethanol CI, in addition to 11% from land use change GHGs.

Dry Milling Corn Ethanol w/ Corn Oil Extraction. DSG credit, -12.9 g CO$_2$e/MJ, is not included.
Argonne Previous and Ongoing Works in India

- **Previous works**
  - Developed detailed inventory of SO$_2$ and carbonaceous aerosol (i.e., black carbon and organic carbon) emissions from anthropogenic sources in India with a technology-based methodology. 
    
  
  - Developed unit-based NO$_x$ and SO$_2$ emission inventory for Indian thermal power sector and compared the emission estimates with the satellite observations of NO$_2$ and SO$_2$
    
  
  - Studied the transportation of black carbon from India to the Himalayas and Tibetan Plateau
    

- **Ongoing works (focus on the power and the coal sectors)**
  - Develop detailed unit-based energy and emission datasets for the entire power sector in India at the monthly level from 2005 to now
  
  - Develop coal transportation matrix from Indian coal producers to individual coal-fired power plants
  
  - Develop electricity transmission matrix among Indian power regions
Questions?

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