Multimodal LCA Data in The GREET Model

Mohsen Mehrabiyan, Ph.D. Student

West Virginia University

1. The GREET (Greenhouse gasses, Regulated Emissions, and Energy use in Transportation) Model

LCA is a major step to holistically evaluate sustainability of technologies and policies. LCA for vehicle/fuel systems is a comprehensive method used to assess the environmental impacts associated with all the stages of a vehicle's life, from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling. This includes assessing the impact of fuel production and consumption.

The GREET is a tool developed by the Argonne National Laboratory, primarily used for evaluating the energy and environmental impacts of various vehicle technologies and fuels. The purpose of GREET is to provide a comprehensive, life-cycle analysis (LCA) of energy and emission impacts associated with different types of vehicles and fuels. The GREET model is particularly important in policy-making and research, as it helps to understand the full environmental impact of different transportation options. It's used to compare the environmental performance of traditional internal combustion engine vehicles with alternative options like electric vehicles, hybrids, and fuel cell vehicles, considering both direct emissions from the vehicles and indirect emissions from fuel production and vehicle manufacturing.

There are two modules in the GREET model:

1) GREET Fuel-Cycle (WTW) Model (GREET1): It assesses the energy and emission impacts associated with various vehicle fuel cycles. **A fuel cycle encompasses all the steps from fuel extraction or production (like petroleum refining or biofuel production) to the delivery and use of the fuel in a vehicle.** GREET1 analyzes different types of fuels, including conventional gasoline, diesel, biofuels (like ethanol and biodiesel), natural gas, hydrogen, and electricity.
2) GREET Vehicle-Cycle Model (GREET2): It evaluates the energy and environmental impacts of vehicle manufacturing, operation, and disposal. It considers the entire lifecycle of a vehicle, including the extraction and processing of materials used in the vehicle, the vehicle assembly process, and the eventual recycling or disposal of the vehicle.

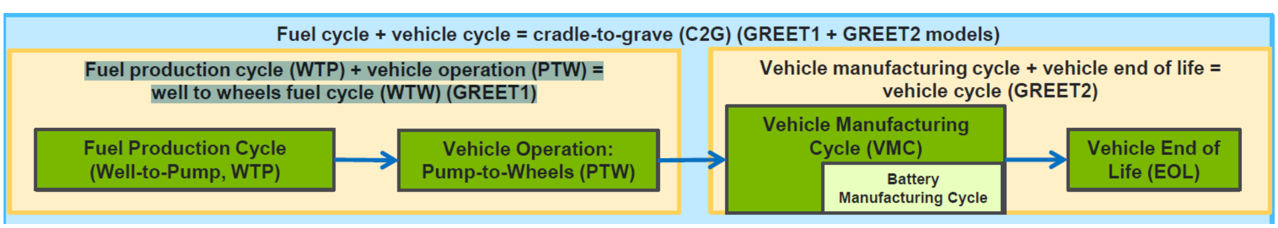

Figure 1. The Well-to-Wheel (WTW) LCA method in the GREET model.

1.1. GREET Sustainability Metrics

GREET evaluates a broad range of sustainability metrics, including energy usage, air pollutants, greenhouse gasses (GHGs), and water consumption. We focus particularly on GHG. GHGs are gasses in the Earth's atmosphere that trap heat, contributing to the greenhouse effect and warming the planet and are emitted from various sources, including:

- Burning fossil fuels for energy production (CO_2).
- Agricultural activities, such as livestock farming and rice cultivation (CH_4 and N_2O).
- Industrial processes, including manufacturing and cement production (CO_2 and other fluorinated gasses).
- Land-use changes, such as deforestation and urbanization (CO_2).
- Impact on Climate: Increased concentrations of GHGs lead to higher temperatures, altering weather patterns, melting polar ice caps, and causing sea levels to rise. Climate change impacts ecosystems, biodiversity, agriculture, water resources, and human health.
- The "CO2e" likely refers to the carbon dioxide equivalent (CO2e) values associated with five different greenhouse gasses, each with their respective global warming potentials (GWPs).

Table 1. GREET sustainability metrics.

GREET sustainability metrics				
Energy use	**Air pollutants**	**Greenhouse gasses**	**Water consumption**	**GREET LCA functional units***
Total energy: fossil energy (petroleum, natural gas) and renewable energy (biomass, nuclear energy, hydro-power, wind power and solar energy	VOC, CO, NOx, PM_{10} $PM_{2.5}$, and SOx They are estimated separately for -Total (emissions everywhere) -Urban (a subset of the total)	- CO_2, CH_4, N_2O, black carbon, and albedo - CO_{2e} of the five (with their global warming potentials)	Addressing water supply and demand (energy-water nexus)	-*Per service unit* (e.g., mile driven, tone*-mile, passenger-mile) -*Per unit of output* (e.g., million Btu*, MJ*, gasoline gallon equivalent) -*Per units of resourc*e (e.g., per ton of biomass)

A note on the units:

- "Per million Btu" refers to a quantity measured for each million British thermal units of output.
- "Ton" typically refers to the unit of weight measurement in the United States customary system and is equal to 2,000 pounds. On the other hand, "tonne" (also known as the metric ton) is equal to 1,000 kilograms or approximately 2,204.62 pounds.

- The "Joule (J)" is defined as the work done by a force of one newton acting through a distance of one meter. It's commonly used to measure various forms of energy such as mechanical, thermal, and electrical energy.

1.2. Energy Systems Covered in GREET WTW

See Table 2.

Table 2. Energy Systems Covered in GREET WTW.

Energy Systems			
Feedstock	**Fuel**	**Feedstock**	**Fuel**
Petroleum sector: • Conventional Oil • Oil Sands and Shale oil	• Gasoline, • Diesel, • LPG, • Naphtha, • Residual oil, • Jet fuel, • Liquefied petroleum gas	**Electric Systems:** • Natural gas, • Coal, • Residual oil, • Biomass, • Nuclear, • Hydro, • Wind, • Solar	• Electricity generation at US plant level, • Aggregate to national, NERC, and state level • With CCS, if applicable
Natural Gas sector: • Conventional NG • Shale gas	• NG end use in electric, industrial and residential sectors • Transportation sector: CNG, LNG • Alternative fuels: LPG, methanol, DME, FT diesel, FT jet	**Renewable Energy/Fuels:** • 1st Gen Feedstocks: Corn, Sorghum, Soybeans, Rapeseeds, Sugarcane, Palm • 2nd Gen Feedstocks: Dedicated energy crops, Crop residues, Forest residues, MSW, Animal wastes, Algae	• Ethanol, • Biodiesel, • Renewable diesel, • Renewable gasoline, • Renewable jet fuel, • Renewable natural gas

Hydrogen economy: 1. Natural gas, 2. Biomass, 3. Coal, 4. Petroleum coke, 5. Coke oven gas, 6. Electrolysis with electricity 7. Nuclear energy	• Gaseous hydrogen, • Liquid hydrogen, • With CCS	**Electro Fuels:** 1. Gasoline, 2. Diesel, 3. Jet fuel, 4. Methanol	• CO2 Sources: Ethanol plants, NG SMR plants, Cement plants Etc. • Renewable Hydrogen via electrolysis: Wind, Solar, Nuclear

1.3. GREET LCA Functional Units

Table 3. GREET LCA Functional Units

Vehicles		**Service & Energy Functional Unit**						
HDV: Combination Long-Haul and Short-Haul Trucks	**Per vehicle distance traveled or Cargo distance transported**	**Energy Unit**	***Btu***	***mBtu***	***mmBtu***	***J***	***kJ***	***MJ***
			1	10^{-3}	10^{-6}	1055.05585	1.0550559	0.001055056
		Emission Unit	***g***	***Kg***	***tonne***	***lb***	***oz***	***ton***
			1	10^{-3}	10^{-6}	0.0022	0.0352	1.10E-06
		Service Functional Unit for HDV	***Mile***	***KM***	-	-	-	-
			1	1.609	-	-	-	-
Rail		**Service Functional Unit for Rail**	***ton or passenger mi***	***lb or passenger mi***	***tonne or passenger km***	***kg or passenger km***	-	-
		Freight	1	2000	1.451	1451	-	-
		Passenger	1	1	1.6	1.6	-	-
Marine		**Energy Functional Unit**	***Btu***	***mBtu***	***mmBtu***	***J***	***kJ***	***MJ***
			10^{6}	10^{3}	1	10,5505,585	1,055,055.9	1,055.05585
	Per Energy in Fuels	**Energy Unit**	***Btu***	***mBtu***	***mmBtu***	***J***	***kJ***	***MJ***
			1	10^{-3}	10^{-6}	1055.05585	1.0550559	0.001055056
		Emission Unit	***g***	***Kg***	***tonne***	***lb***	***oz***	***ton***
			1	10^{-3}	10^{-6}	0.0022	0.0352	1.10E-06

1.4. Types of Fuel

See Table 4.

Table 4. Types of fuel for each vehicle.

Vehicle	Service functional units	Types of fuel	Description
HDV: Combination Long-Haul and Short-Haul Trucks	Per Ton-Mile	Diesel, Biodiesel, CNG, LNG, Electricity, Hydrogen, Renewable diesel	Adaptable, heavy-duty, transportation, logistics, efficiency
Rail	Per ton-mile or per passenger-mile	Diesel, LNG, LPG, DME, FTD, RD, H2 and electricity	Rail types: freight rails, intercity rails, computer rails and transit rails
Marine	Per million tonne-km or per defined trip	HFO, MOD, MGO, LNG, FTD, Pyrolysis oil, methanol, ammonia, …	Vessel types: bulk, container-large, tanker VLCC Regions: Pacific, Atlantic, Gulf of Mexico and Great Lakes
Aviation	Per passenger-km, per kg-km	Petroleum jet and sustainable aviation fuels (SAF)	Aircraft types (passenger and freight): single aisle, small twin aisle, large twin aisle

2. Heavy Duty Vehicles (HDVs)

The passage discusses two types of heavy-duty vehicles (HDVs) relevant to intermodal transportation: long-haul and short-haul trucks. Long-haul trucks are designed for long-distance transportation, often hauling semi-trailers or trailers, and are commonly used for interstate or cross-country routes. Short-haul trucks, on the other hand, are for transporting goods over shorter distances, typically regionally or locally, as they are not optimized for long journeys like long-haul trucks. Data is stored in the "HDV_WTW" tab in the "GREET1.xlsm" file. Metrics are available in Btu/mile, Gallon/mile, and g/mile. Btu/mile, Gallon/mile, and g/mile are metrics used to measure energy consumption and emissions of heavy-duty vehicles. Btu/mile quantifies energy usage per mile traveled, Gallon/mile measures fuel consumption per mile, and g/mile assesses emissions per mile, aiding in evaluating the efficiency and environmental impact of HDVs.

Table 5. Types of HDVs in GREET

HDV	Vehicle Technology	Fuel Technology
Long-haul/Short-haul Trucks	CIDI	Diesel
		Biodiesel
		Renewable
		DME
		LNG
Long-haul/Short-haul	SI	CNG
		LNG
Long-haul/Short-haul	Electric	Electricity
Long-haul	Co-optimized engine	Algae HTL
		Wastewater sludge HTL
Long-haul	MCCI	Waste feedstock
Short-haul	Fuel-cell	Gas H2, Liquid H2

2.1. Vehicle Propulsion Technologies

- **Compression-Ignition, Direct-Injection (CIDI) Engine Vehicles:** It utilize diesel fuel and inject it directly into highly compressed air in the combustion chamber, spontaneously igniting the mixture to generate power, known for their efficiency and torque, ideal for heavy-duty applications like trucks and buses.
    - Liquid fuels
- **Spark-Ignition (SI), Direct-Injection Engine Vehicles:** It is a type of vehicle propulsion technology employing engines where fuel is injected directly into the combustion chamber and ignited by a spark plug. They typically use gasoline and are known for their fuel efficiency and performance, making them suitable for a wide range of vehicles, including cars and motorcycles.
    - Liquid and gaseous fuels
- **Battery-Powered Electric Vehicles:** Battery-Powered Electric Vehicles utilize rechargeable batteries to power an electric motor, emitting zero tailpipe emissions and offering quiet operation and low maintenance, representing an eco-friendly and cost-effective transportation choice.
    - Various electricity generation sources
- **Co-Optimized Engine:** An engine design that is optimized simultaneously for maximum efficiency and minimum emissions. It integrates advanced technologies and fuel types to achieve better performance while reducing environmental impact.
- **Mixing-Controlled Compression Ignition (MCCI):** MCCI combines aspects of spark ignition and compression ignition engines, creating a homogeneous fuel-air mixture for controlled auto-ignition, enhancing fuel efficiency, and decreasing emissions.
- **Fuel Cell Vehicles:** FCVs use hydrogen fuel and oxygen to produce electricity in a fuel cell, emitting only water vapor, providing a clean and efficient transportation solution.
    - Hydrogen and on-board hydrocarbon reforming to hydrogen

2.2. Fuel Technologies for HDVs

- **Diesel:** Commonly used in trucks and buses, diesel fuel is derived from crude oil and known for its efficiency but emits pollutants like nitrogen oxides and particulate matter.
- **Biodiesel:** Made from renewable sources like vegetable oils, biodiesel emits fewer pollutants and greenhouse gasses, offering an environmentally friendly alternative to diesel.
- **Renewable Diesel:** Similar to petroleum diesel, renewable diesel is derived from renewable feedstocks, offering reduced emissions and improved performance in cold weather.
- **Dimethyl Ether (DME):** Produced from natural gas, biomass, or waste, DME burns cleanly with minimal emissions, suitable for diesel engines with minor modifications.
- **Compressed Natural Gas (CNG) / Liquefied Natural Gas (LNG):** Derived from natural gas, CNG and LNG are cleaner-burning alternatives to diesel and gasoline, domestically abundant and cost-effective.
- **Electricity:** Powering vehicles like electric cars and hybrids, electricity offers zero tailpipe emissions, with sustainability depending on renewable energy sources.
- **Hydrogen:** Produced from various sources, hydrogen fuels fuel cell vehicles with zero emissions except water vapor, offering long-range driving but facing challenges in infrastructure and cost.
- **Algae HTL:** Algae HTL converts algae into liquid fuel for long-haul trucks through high temperature and pressure, yielding bio-crude oil. This eco-friendly process utilizes algae's carbon absorption, offering a sustainable alternative to fossil fuels, potentially cutting emissions and reducing oil dependence in trucking.
- **Wastewater sludge HTL:** Wastewater sludge HTL for long-haul truck fuel involves converting sewage sludge into liquid fuel through hydrothermal liquefaction (HTL), offering a sustainable alternative energy source. This process utilizes high temperature and pressure to break down organic matter in sludge, producing bio-crude oil that can be refined for use in long-haul trucks, potentially reducing reliance on traditional fossil fuels and addressing waste management challenges.

3. Rail

Rail transportation encompasses various types of rails serving different purposes. Freight rails primarily facilitate the transportation of goods, carrying heavy cargo across long distances efficiently. Intercity rails connect cities and regions, offering long-distance passenger services, often at higher speeds and with fewer stops. Commuter rails cater to daily commuters within metropolitan areas, providing convenient transport between suburbs and urban centers. Transit rails, including subways and light rails, operate within cities, offering mass transit options for short to medium-distance travel, crucial for urban mobility and reducing congestion. Each type plays a vital role in the broader rail network, serving distinct needs for both passengers and freight.

Table 6. Types of rail freight transportation in GREET.

Rail	Vehicle Technology	Fuel Technology
Freight Rails	Diesel-Electric locomotives	Diesel
		LNG
		LPG
		DME
		FTD
		Biodiesel (BD20)
		Renewable Diesel II
		Renewable Gasoline
		Gaseous Hydrogen
		Electricity

3.1.Vehicle Propulsion Technologies

- **Diesel-Electric:** Diesel-electric propulsion employs a diesel engine to generate electricity, powering electric motors linked to the wheels, offering flexible power distribution and suitability for diverse loads and terrains. These locomotives are prevalent in both freight and passenger rail services, especially in regions without electrification infrastructure.
- **Electric:** Electric propulsion systems, utilizing overhead wires or a third rail, supply power to trains, offering increased energy efficiency and environmental benefits with zero emissions. These systems are widely adopted in urban commuter rail networks and high-speed rail systems.
- **Hybrid:** Hybrid propulsion systems combine multiple power sources, such as diesel engines and batteries, to drive trains. These systems offer increased efficiency and reduced emissions compared to traditional diesel-only propulsion. Hybrid trains are particularly useful for routes that alternate between electrified and non-electrified sections.
- **Battery electric:** These trains rely solely on onboard batteries, resulting in quiet, emission-free operation and charging flexibility through various methods such as overhead wires, ground-based infrastructure, or regenerative braking, making them increasingly favored for routes where electrification is impractical or costly.

3.2. Fuel Technologies for Rails:

Diesel: A widely used fuel in freight rail technology, known for its energy density and efficiency in locomotive engines, offering high torque and long-range capabilities, albeit with emissions concerns requiring advancements in emissions control technology.

LNG (Liquefied Natural Gas): Emerging as a cleaner alternative to diesel, LNG reduces emissions of particulate matter and nitrogen oxides, while offering potential cost savings and lower greenhouse gas emissions, necessitating infrastructure investments for storage and refueling.

LPG (Liquefied Petroleum Gas): Offering lower emissions compared to diesel, LPG is a versatile fuel for freight rail, with potential for reduced maintenance costs and cleaner combustion, but requiring investment in specialized infrastructure for storage and handling.

DME (Dimethyl Ether): A promising alternative fuel for freight rail, DME offers low emissions of particulate matter and sulfur, with potential for simplified engine design and lower infrastructure costs, but requiring investment in production facilities and refueling infrastructure.

FTD (Fischer-Tropsch Diesel): Derived from synthesis gas, FTD offers lower emissions than conventional diesel, with potential for renewable feedstocks and reduced greenhouse gas emissions, but requiring advancements in production technology and infrastructure development.

Biodiesel (BD20): Blending diesel with biodiesel reduces emissions of particulate matter and sulfur, offering a renewable alternative for freight rail, albeit with potential for reduced energy density and infrastructure challenges related to storage and distribution.

Renewable Diesel II: A second-generation biofuel offering reduced emissions and compatibility with existing diesel infrastructure, Renewable Diesel II holds promise for reducing greenhouse gas emissions in freight rail operations, but requires scaling up production and distribution networks.

Renewable Gasoline: A renewable alternative to conventional gasoline, offering lower emissions and compatibility with existing infrastructure, Renewable Gasoline presents an opportunity for cleaner freight rail operations, contingent on advancements in production technology and supply chain logistics.

Gaseous Hydrogen: With zero emissions at the point of use, hydrogen holds potential for clean freight rail operations, but requires significant investments in production, storage, and distribution infrastructure, along with advancements in fuel cell technology.

Electricity: Electrification of railroads offers zero-emission operation and high efficiency, particularly when sourced from renewable energy, presenting a sustainable solution for freight rail, but requiring substantial infrastructure investments and coordination with energy providers

4. Marine

Marine vessels serve diverse cargo transport needs, with bulk carriers optimized for bulk cargo like coal and grain, boasting sturdy construction and open cargo holds for efficient loading. In contrast, container ships excel in transporting standardized shipping containers, facilitating seamless intermodal transport of various goods from electronics to clothing through stacked containers secured on deck, playing a crucial role in global trade and logistics.

4.1. Key Variables: 1) Fuel and Engine Types **2)** Trip and Vessel Characteristics **3)** Emissions Regulations

Main Engine type: 1) SSD: Slow Speed Diesel; **2) MSD:** Medium Speed Diesel; **3) ST:** Steam Turbine; **4) GT:** Gas Turbine

Aux. Engine type: 1) MSD: Medium Speed Diesel; **2)** HSD: High Speed Diesel

Fuel Emissions: 1) Fuel only: shows the well to wake results for the fuel only; **2)** With pilot oil: for certain fuels, pilot oil is required to create high-temperature and high-pressure environment for robust ignition

4.2. Greet Marine Models

- Marine Fuel Pathways incl. Fossil, Renewable, Fossil/Biomass Blends
- Relevant Environmental Metrics incl. GHGs, Energy use, CAPs, Water use
- Standardization enables apples-to-apples comparison across fuel and technology pathways, and capacity to 'drill down' on the LCA results

4.3. Functional Units: Energy: 1) Based (Impacts per unit MJ) **2)** Service Based (Impacts per Trip, Tonne Km)

Table 7. Trip Characteristics in GREET

Marine Vessels	Travel	Region	Fuel Technology
Container-Large	Domestic	Pacific	HFO, MDO, MGO, LNG, BD, and …
		Atlantic	
		Gulf of Mexico	
		Great Lakes	

** Container-large vessels are ocean-faring ships designed to transport large quantities of standardized cargo containers, facilitating global trade by efficiently moving goods between ports worldwide. They are characterized by their immense size and capacity, often featuring multiple decks stacked with containers.

Table 8. Marine Fuel Technology in GREET

Broad Coverage of Marine Fuel Options		
Fossil	**HFO**	HFO w/Scrubber
		HFO (2.7% Sulfur)

		HFO (0.5% Sulfur)
		HFO (0.1% Sulfur)
	MDO	MDO (1.92% Sulfur)
		MDO (0.5% Sulfur)
		MDO (0.1% Sulfur)
	MGO	MGO (1% Sulfur)
		MGO (0.5% Sulfur)
		MGO (0.1% Sulfur)
	LNG	Liquefied Natural Gas
	MeOH	Methanol (NG), Methanol (Coal)
	FTD	FT Diesel (NG)
	NH3	Ammonia, (H2 from SMR NG)
Fossil + Biomass	**FTD**	FT, Diesel (Biomass & Coal)
		FT, Diesel (Biomass & NG)
	RD	Renewable Diesel, (Yellow Grease & HFO)
Dedicated Biomass & Wastes	**SVO**	Straight Vegetable Oil, (Soybean
	Bio-Oil	Pyrolysis Oil, (Woody Biomass)
	FTD	FT Diesel (Biomass)
	BD	Biodiesel (Soybean Oil)
	RD	Renewable Diesel, (Yellow Grease)
	MeOH	Methanol (RNG)
		Methanol (Biomass)
		Methanol (Black Liquor)
		Methanol (Flare Gas)
Other Renewables	**eFuels**	eMethanol (Ind. Waste CO2) eFT Fuel (Ind. Waste CO2)

	NH3	Green Ammonia (H2 From Low Carbon Sources)

4.4.Fuel Technologies for Marine:

- **HFO (Heavy Fuel Oil):** A traditional marine fuel with high viscosity and sulfur content, HFO is commonly used in large vessels but faces environmental concerns due to emissions.
- **MDO (Marine Diesel Oil) & MGO (Marine Gas Oil):** Refined products with lower sulfur content compared to HFO, MDO and MGO are utilized in various marine engines for better environmental compliance.
- **LNG (Liquefied Natural Gas):** An increasingly popular marine fuel due to its lower emissions and compliance with stringent environmental regulations, LNG offers cleaner combustion and reduced greenhouse gas emissions.
- **MeOH (Methanol):** A potential alternative marine fuel derived from natural gas or biomass, Methanol offers lower sulfur emissions but requires investment in infrastructure for widespread adoption.
- **NH3 (Ammonia):** Considered as a future marine fuel, Ammonia has zero carbon emissions when produced from renewable sources, though challenges remain in terms of handling, storage, and infrastructure development.
- **FTD (Fischer-Tropsch Diesel):** A synthetic marine fuel with low sulfur content and reduced emissions, FTD holds promise for cleaner marine operations but requires investment in production facilities and supply chain infrastructure.
- **RD (Renewable Diesel):** Derived from renewable sources, Renewable Diesel offers a cleaner alternative to conventional fuels with lower emissions and compatibility with existing marine engines.
- **SVO (Straight Vegetable Oil):** Used in some niche applications, Straight Vegetable Oil requires engine modifications and faces challenges related to availability and sustainability of feedstocks.
- **Bio-Oil:** A renewable marine fuel derived from biomass, Bio-Oil offers reduced emissions compared to conventional fuels, but scalability and cost competitiveness remain key challenges.
- **BD (Biodiesel):** A renewable marine fuel produced from organic materials, Biodiesel can reduce greenhouse gas emissions but requires careful consideration of feedstock sourcing and engine compatibility.
- **eFuels:** Synthetic fuels produced using renewable energy sources, eFuels have the potential to significantly reduce greenhouse gas emissions in marine transportation but currently face challenges related to cost and scalability.