GREET Life-Cycle Analysis of Vehicle/Fuel Systems

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Reductions of Oil Use and GHG Emissions Are Major Goals for the U.S. Transportation Sector

- Three general approaches to achieve these goals
  - Vehicle technology improvements
  - Alternative fuels
  - Reduction in vehicle miles traveled

- Alternative transportation fuels
  - Natural gas-based fuels: CNG, LNG, LPG, methanol, DME, FT diesel
  - Coal-based fuels: methanol (in 1980s), FT diesel (under exploration)
  - Biofuels: corn/cellulosic ethanol, soybean biodiesel
  - Hydrogen produced from different energy sources

- Advanced vehicle technologies
  - Improvement of conventional engine technologies
  - Hybrid electric vehicles: both grid independent and plug-in hybrids
  - Fuel cell vehicles
  - Battery-powered electric vehicles
  - Dieselization vs. hybridization: Europe vs. North America
Sales of Hybrid Electric Vehicles Has Been Strong in the U.S.
Well-to-Wheels Analysis of Vehicle/Fuel Systems Covers Activities for Fuel Production and Vehicle Use
**The GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) Model**

- Argonne began GREET development in 1995 with DOE support
- Includes emissions of greenhouse gases
  - $\text{CO}_2$, $\text{CH}_4$, and $\text{N}_2\text{O}$ (and optional GHGs such as VOC, CO, and NO$_x$)
- **Estimates emissions of six criteria pollutants**
  - VOC, CO, NO$_x$, SO$_x$, PM$_{10}$, and PM$_{2.5}$
  - Total and urban separately
- **Separates energy use into**
  - All energy sources (fossil and non-fossil)
  - Fossil fuels (petroleum, natural gas, and coal combined)
    - Petroleum
    - Coal
    - Natural gas
- **GREET is in public domain**
  - Available at [http://www.transportation.anl.gov/software/GREET/](http://www.transportation.anl.gov/software/GREET/) (or simply Google GREET on the Web)
  - At present, there are more than 3,500 registered GREET users worldwide
  - The most recent GREET version was released in August 2007
Fuel Production Pathways from Various Energy Feedstocks (Well-to-Pump) in GREET

- **Petroleum:**
  - Conventional Oil Sands
  - Gasoline
  - Diesel
  - LPG
  - Naphtha
  - Residual oil

- **Natural Gas:**
  - NA
  - Non-NA
  - CNG
  - LNG
  - LPG
  - Methanol
  - Dimethyl Ether
  - FT Diesel and Naphtha
  - Hydrogen

- **Coke Oven Gas**
  - Hydrogen

- **Nuclear**
  - Hydrogen

- **Coal**
  - Hydrogen
  - FT Diesel
  - Methanol
  - Dimethyl Ether

- **Cellulosic Biomass:**
  - Switchgrass
  - Fast growing trees
  - Crop residues
  - Forest residues
  - Ethanol
  - Hydrogen
  - Methanol
  - Dimethyl Ether
  - FT Diesel

- **Residual Oil**
  - Coal
  - Natural Gas
  - Nuclear
  - Biomass
  - Other Renewables

- **Electricity**

- **Corn**
  - Butanol
  - Ethanol

- **Sugar cane**
  - Ethanol

- **Soybeans**
  - Biodiesel
GREET WTP Analysis Includes Key Production and Transportation Activities

WTP Efficiency: Gasoline 80%; Diesel 83%

- Petroleum Recovery (97%)
- Petroleum Transport and Storage (99%)
- Petroleum Refining to Gasoline (84.5-86%, Depending on Oxygenates and Reformulation) and Low-S Diesel (87%)
  - Transport, Storage, and Distribution of Gasoline (99.5%)
  - Gasoline and Diesel at Stations
- MTBE or EtOH for Gasoline
- NG to MeOH
- Corn
- NA NG Recovery (97.5%)
- NA NG Refining to Gasoline and Diesel
- Compressed G.H2 at Stations
- Transport, Storage, and Distribution of Gasoline (99.5%)
- Gasoline and Diesel at Stations

NA NG-based H2 56%  nNA NG-based H2 52%

- NA NG Recovery (97.5%)
- NA NG Processing (97.5%)
- LNG Production (88.0%)
- LNG Transport via Ocean Tankers (98.5%)
- NG Transport via pipelines
- LNG Gasification in Ports
- G.H2 Production at Stations (67%)
- G.H2 Compression at Stations (89% & 94.0% for NG & Electric)
- Compressed G.H2 at Stations
- Natural Gas to Compressed Hydrogen
GREET Includes More Than 75 Vehicle/Fuel Systems

**Conventional Spark-Ignition Vehicles**
- Conventional gasoline, federal reformulated gasoline, California reformulated gasoline
- Compressed natural gas, liquefied natural gas, and liquefied petroleum gas
- Gaseous and liquid hydrogen
- Methanol and ethanol

**Compression-Ignition Direct-Injection Hybrid Electric Vehicles: Grid-Independent and Connected**
- Conventional diesel, low sulfur diesel, dimethyl ether, Fischer-Tropsch diesel, E-diesel, and biodiesel

**Battery-Powered Electric Vehicles**
- U.S. generation mix
- California generation mix
- Northeast U.S. generation mix
- User-selected generation mix

**Spark-Ignition Hybrid Electric Vehicles: Grid-Independent and Connected**
- Conventional gasoline, federal reformulated gasoline, California reformulated gasoline
- Compressed natural gas, liquefied natural gas, and liquefied petroleum gas
- Gaseous and liquid hydrogen
- Methanol and ethanol

**Fuel Cell Vehicles**
- Gaseous hydrogen, liquid hydrogen, methanol, federal reformulated gasoline, California reformulated gasoline, low sulfur diesel, ethanol, compressed natural gas, liquefied natural gas, liquefied petroleum gas, and naphtha

**Compression-Ignition Direct-Injection Vehicles**
- Conventional diesel, low sulfur diesel, dimethyl ether, Fischer-Tropsch diesel, E-diesel, and biodiesel

**Spark-Ignition Direct-Injection Vehicles**
- Conventional gasoline, federal reformulated gasoline, and California reformulated gasoline
- Methanol and ethanol
GREET Includes Some of the Potential Biofuel Production Pathways

**Oils for Biodiesel/Renewable Diesel**
- Soybeans
  - Rapeseed
  - Palm oil
  - Jatropha
  - Waste cooking oil
  - Animal fat

**Sugar Crops for EtOH**
- Sugar cane
  - Sugar beet
  - Sweet sorghum

**Starch Crops for EtOH**
- **Corn**
  - Wheat
  - Cassava
  - Sweet potato

**Butanol Production**
- **Corn**
  - Sugar beet

**Cellulosic Biomass for EtOH**
- **Corn stover**, rice straw, wheat straw
- **Forest wood residue**
  - Municipal solid waste
- **Energy crops**
  - Black liquor

**Cellulosic Biomass via Gasification**
- **Fischer-Tropsch diesel**
- **Hydrogen**
- Methanol

The feedstocks that are underlined are already included in the GREET model.
GREET Ethanol Life-Cycle Analysis Includes Activities from Fertilizer to Ethanol at Refueling Stations

- Agricultural chemical production
  - Agricultural chemical transportation
    - Corn farming
    - Crop residue collection
    - Switchgrass farming
    - Fast growing tree farming
    - Forest residue collection
    - Sugar cane farming
      - Sugar cane ethanol production
      - Co-produced electricity
    - Cellulosic ethanol production
      - Ethanol transportation
        - Ethanol blending at bulk terminal
        - Ethanol blends at refueling station
      - Animal feed
  - Corn ethanol production
  - Fast growing tree farming
  - Forest residue collection
  - Sugar cane farming
  - Switchgrass farming
  - Crop residue collection
  - Corn farming
  - Animal feed
Key Issues for Biofuel Life-Cycle Analysis

- Nitrogen fertilizer production: primarily from natural gas and a small amount from coal
- Conversion of fertilizer in farms
  - Nitrogen fertilizer: N2O emissions from N nitrification and denitrification
  - Lime: CO2 emissions from lime stone (CaCO3) to lime (CaO) in fields for stabilizing soil acidity
- Energy use for farming
- Open field burning in sugarcane plantations
- Nitrogen cycle and resultant N2O emissions
- Energy use in biofuel plants
  - The amount of process fuels for steam production
  - The type of process fuels
- Co-products of biofuel plants
- Land use change from biofuel production and resulted CO2 emissions
**Fuel-Cycle GHG Emission Shares for Corn-Based Ethanol**

**Shares of GHG Emissions for Corn Ethanol: Total of 5,795 grams/gallon (with Co-Product Credits)**
- Ethanol Transportation: 2%
- Corn Farming: 16%
- Corn Transportation: 3%
- EtOH Production: 35%
- Farming Machinery: 2%
- Other Chemicals: 11%
- Nitrogen: 31%

**Shares of GHG Emissions for Corn Ethanol: Total of 7,171 grams/gallon (without Co-Product Credits)**
- Ethanol Transportation: 2%
- Corn Farming: 13%
- Corn Transportation: 2%
- EtOH Production: 48%
- Farming Machinery: 1%
- Other Chemicals: 9%
- Nitrogen: 25%
The Type of Energy, As Well As the Amount of Energy, Is Important When Addressing Energy Effects

Btu required for 1 Btu available at fuel pump

- From Biomass
- From Coal and Natural Gas
- From Petroleum

Fossil Btu = 1.22
Fossil Btu = 0.77
Fossil Btu < 0.1

Energy in the Fuel

- Gasoline: Petroleum Btu = 1.1
- Corn Ethanol: Petroleum Btu = 0.09
- Cellulosic Ethanol: Petroleum Btu = 0.07
Most Recent Studies Show Positive Net Energy Balance for Corn Ethanol

Energy balance here is defined as Btu content in a gallon of ethanol minus fossil energy used to produce a gallon of ethanol.
From Corn to Sugar Cane to Cellulosic Biomass, GHG Emission Avoidance Is Increased

<table>
<thead>
<tr>
<th></th>
<th>Sugar cane</th>
<th>Cellulosic ethanol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>3.1%</td>
<td></td>
</tr>
<tr>
<td>Current</td>
<td>-19%</td>
<td></td>
</tr>
<tr>
<td>NG</td>
<td>-28%</td>
<td></td>
</tr>
<tr>
<td>DGS</td>
<td>-39%</td>
<td></td>
</tr>
<tr>
<td>Biomass</td>
<td>-52%</td>
<td></td>
</tr>
<tr>
<td>Sugar Cane EtOH</td>
<td>-76%</td>
<td>-76%</td>
</tr>
<tr>
<td>Forest residual EtOH</td>
<td>-76%</td>
<td></td>
</tr>
<tr>
<td>Switchgrass EtOH</td>
<td>-85%</td>
<td></td>
</tr>
</tbody>
</table>

GHG Emission Reductions by Ethanol Relative to Gasoline (per Energy Unit Basis)
Potential Land Use Change by Large-Scale Biofuel Production Needs to Be Examined

1. **Primary land use change and secondary land use change**: the latter is much more difficult to assess

2. No comprehensive simulations of land use change at the national and global level have been done yet, especially for a biofuel future; agricultural community now begins to address this

3. Soil carbon content and vegetation carbon content in different land use patterns

4. U.S. annual corn ethanol production could be increased from current 6 billion gallons a year to 15 billion gallons in 2015
   - Besides increases in per-acre corn yield, where will additional amount of corn for ethanol production be from?
   - In 2007, U.S. corn farming acres have increased by 12 million through switch from soybean to corn farming; what is the long-term effect of such switch?
   - U.S. has been exporting 20% of its total annual corn production; what is the effect of reduction in U.S. corn export on global corn/grain market?

5. Brazil has 12.4 million acres of sugar cane plantations. It can increase sugar cane plantations to 25 million acres in the near future
   - Sugar cane farming is in South Central Brazil; what is the current farming practice and vegetation for the additional sugar cane acres?
   - Will the increase in sugar cane farming acres force farming of corn, soybean, and cattle to the Amazon rainforest region?

6. Palm oil production in Malaysia has caused conversion of some tropical forest and pit soil into palm tree farming; what is the environmental and GHG consequences?
Trade-Offs Between Petroleum Reductions and GHG Reductions Among Fischer-Tropsch Diesel Types

Per-Mile Ratio Relative to Gasoline Vehicle

- Petroelum Ratio
- GHG Ratio

- BTL, Trees
- BTL, Forest Residues
- Diesel
- GTL
- CTL, High Effi., CCS
- CTL, Low Effi., CCS
- CTL, High Effi.
- CTL, Low Effi.
Argonne Examined Nine Vehicle/Fuel Systems in a Study

<table>
<thead>
<tr>
<th>Vehicle Option</th>
<th>Fuel Option</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Gasoline vehicle</td>
<td>Gasoline: corn-derived ethanol as oxygenate</td>
</tr>
<tr>
<td>2 Diesel vehicle</td>
<td>Low sulfur diesel: 15 ppm S</td>
</tr>
<tr>
<td>3 E85 flexible fuel vehicle</td>
<td>E85: corn-derived ethanol</td>
</tr>
<tr>
<td>4 E85 flexible fuel vehicle</td>
<td>E85: herbaceous biomass-derived ethanol</td>
</tr>
<tr>
<td>5 Gasoline hybrid</td>
<td>Gasoline: corn-based ethanol as oxygenate</td>
</tr>
<tr>
<td>6 Diesel hybrid</td>
<td>Low sulfur diesel, 15 ppm S</td>
</tr>
<tr>
<td>7 Electric vehicle</td>
<td>Average U.S. electricity generation mix(^a)</td>
</tr>
<tr>
<td>8 Electric vehicle</td>
<td>California electricity generation mix(^b)</td>
</tr>
<tr>
<td>9 Fuel cell vehicle</td>
<td>Gaseous H(_2), distributed NG steam methane reforming</td>
</tr>
</tbody>
</table>

\(a\): U.S. mix consists of 48.7% coal, 22.5% NG, 17.6% nuclear, 2.6% residual oil, 1.3% biomass, and 7.3% others

\(b\): California mix consists of 21.0% coal, 42.0% NG, 15.6% nuclear, 0.6% residual oil, 1.5% biomass, and 19.3% others

**Baseline vehicle:** Gasoline vehicle

**Time frame:** 2015

**Vehicle type:** MY2010 vehicle (midsize passenger car platform)

**Examined items:** criteria air pollutants (VOC, CO, NO\(_x\), PM\(_{10}\), PM\(_{2.5}\), and SO\(_x\)) and GHGs (CO\(_2\), CH\(_4\) and N\(_2\)O).
On-Road Vehicle Fuel Economy Was Estimated with Argonne’s PSAT Model
Vehicle Emission Factors Are Simulated by MOBILE and EMFAC Based on the Assumption That 2010 Model-Year Vehicles Can Meet EPA Tier II Emission Standards

<table>
<thead>
<tr>
<th>Vehicle Technology</th>
<th>VOC: Exhaust</th>
<th>VOC: Evaporative</th>
<th>NO$_x$</th>
<th>PM$_{10}$: Exhaust</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline vehicle</td>
<td>Bin 3</td>
<td>Tier 2 Evap.</td>
<td>Bin 3</td>
<td>Bin 3</td>
</tr>
<tr>
<td>Diesel vehicle</td>
<td>Bin 4</td>
<td>Tier 2 Evap.</td>
<td>Bin 4</td>
<td>Bin 3</td>
</tr>
<tr>
<td>E85 flexible fuel vehicle</td>
<td>Bin 3</td>
<td>Estimate</td>
<td>Bin 3</td>
<td>Bin 3</td>
</tr>
<tr>
<td>Gasoline hybrid</td>
<td>Bin 2</td>
<td>Tier 2 Evap.</td>
<td>Bin 2</td>
<td>Bin 2</td>
</tr>
<tr>
<td>Diesel hybrid</td>
<td>Bin 3</td>
<td>Zero</td>
<td>Bin 3</td>
<td>Bin 3</td>
</tr>
<tr>
<td>H$_2$ fuel cell vehicle and electric vehicle</td>
<td>Bin 1</td>
<td>Zero</td>
<td>Bin 1</td>
<td>Bin 1</td>
</tr>
</tbody>
</table>

**Tier 2 Standards (PCs and LDTs, Fully in Effect in 2009, g/mi)**

<table>
<thead>
<tr>
<th></th>
<th>NMOG</th>
<th>CO</th>
<th>NO$_x$</th>
<th>PM</th>
<th>HCHO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bin 10</td>
<td>0.156/0.230</td>
<td>4.2/6.4</td>
<td>0.6</td>
<td>0.08</td>
<td>0.018/0.027</td>
</tr>
<tr>
<td>Bin 9</td>
<td>0.090/0.180</td>
<td>4.2</td>
<td>0.3</td>
<td>0.06</td>
<td>0.018</td>
</tr>
<tr>
<td>Bin 8</td>
<td>0.125/0.156</td>
<td>4.2</td>
<td>0.20</td>
<td>0.02</td>
<td>0.018</td>
</tr>
<tr>
<td>Bin 7</td>
<td>0.090</td>
<td>4.2</td>
<td>0.15</td>
<td>0.02</td>
<td>0.018</td>
</tr>
<tr>
<td>Bin 6</td>
<td>0.090</td>
<td>4.2</td>
<td>0.10</td>
<td>0.01</td>
<td>0.018</td>
</tr>
<tr>
<td>Bin 5</td>
<td>0.090</td>
<td>4.2</td>
<td>0.07</td>
<td>0.01</td>
<td>0.018</td>
</tr>
<tr>
<td>Bin 4</td>
<td>0.070</td>
<td>2.1</td>
<td>0.04</td>
<td>0.01</td>
<td>0.011</td>
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<tr>
<td>Bin 3</td>
<td>0.055</td>
<td>2.1</td>
<td>0.03</td>
<td>0.01</td>
<td>0.011</td>
</tr>
<tr>
<td>Bin 2</td>
<td>0.010</td>
<td>2.1</td>
<td>0.02</td>
<td>0.01</td>
<td>0.004</td>
</tr>
<tr>
<td>Bin 1</td>
<td>0.000</td>
<td>0.0</td>
<td>0.00</td>
<td>0.00</td>
<td>0.000</td>
</tr>
</tbody>
</table>
HEVs, EVs, and FCVs Could Achieve Moderate to Large Reductions in Total VOC Emissions Due to the Improved Vehicle Fuel Economy or Lower Emission Factors
Fuel Combustion in Vehicle Internal Combustion Engines Dominates WTW CO Emissions
WTP Stage Is the Dominant Source for Total NOx and All Vehicle/Fuel Systems Can Reduce Urban Emissions
PM$_{10}$ Emissions Depend Heavily on Process Energy Used in Fuel Production, and Those with Coal as Process Fuel Have High WTW PM$_{10}$ Emissions
Patterns of PM$_{2.5}$ Emissions among Various Systems Are Similar to Those for PM$_{10}$ Emissions
Pathways That Consume A Large Amount of Coal Have High WTW SOx Emissions
The Selected Vehicle/Fuel Systems Have Different Benefits in GHGs Emission Reductions

Cellulosic biomass-based EtOH achieves the best benefit in GHGs emission reduction.
Corn-based EtOH achieves a moderate benefit because it consumes a large amount of fossil fuel in EtOH plant.
Reduction in WTW GHGs of CIDI ICEs, HEVs, EVs, FCVs is primarily due to the improved vehicle fuel economy.
A 2001 Argonne Study Addressed WTW Emissions of Air Toxics from Motor Vehicles

- Four air toxics were examined
  - Acetaldehyde (CH₃CHO)
  - Benzene (C₆H₆)
  - 1,3-butadiene (C₄H₆)
  - Formaldehyde (HCHO)

- These toxics were chosen because mobile sources contribute to the bulk of these emissions in the U.S.
WTW VOC Emission Changes Relative to Gasoline Vehicles
(emissions of the four toxics are a fraction of VOC emissions)
WTW Formaldehyde Emission Changes

Changes in FM Emissions

GI DI DI HEV: CD
GI SI DI HEV: FRFG2
GC SI DI HEV: CA mix
EVEs CA mix
EVEs US NE mix
EVEs US mix
E85 FFV: corn
E50 FFV: corn
M85 FFV: NG
M50 FFV: NG
Dedi. LPGV: NG
Dedi. LPGV: crude
Dedi. CNGV
Bi-fuel, CNGV
CIDI: CD
GV: CARFG2, ETBE
GV: FRFG2, MTBE
WTW Acetaldehyde Emission Changes

Changes in AC Emissions

GI CIDI HEV: CD
GI SIDI HEV: FRFG2
GC SIDI HEV: CA mix
EVs CA mix
EVs US NE mix
EVs US mix
E85 FFV: corn
E50 FFV: corn
M85 FFV: NG
M50 FFV: NG
Dedi. LPGV: NG
Dedi. LPGV: crude
Dedi. CNGV
Bi-fuel, CNGV
CIDI: CD
GV: CARFG2, ETBE
GV: FRFG2, MTBE
WTW Benzene Emission Changes

Changes in BZ Emissions

-100%  -60%  -20%
GI CIDI HEV: CD
GI SIDI HEV: FRFG2
GC SIDI HEV: CA mix
EVs CA mix
EVs US NE mix
EVs US mix
E85 FFV: corn
E50 FFV: corn
M85 FFV: NG
M50 FFV: NG
Dedi. LPGV: NG
Dedi. LPGV: crude
Dedi. CNGV
Bi-fuel, CNGV
CIDI: CD
GV: CARFG2, ETBE
GV: FRFG2, MTBE

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WTW 1,3-Butadiene Emission Changes

Changes in BU Emissions

GI CIDI HEV: CD
GI SIDI HEV: FRFG2
GC SIDI HEV: CA mix
EVs CA mix
EVs US NE mix
EVs US mix
E85 FFV: corn
E50 FFV: corn
M85 FFV: NG
M50 FFV: NG
Dedi. LPGV: NG
Dedi. LPGV: crude
Dedi. CNGV
Bi-fuel, CNGV
CIDI: CD
GV: CARFG2, ETBE
GV: FRFG2, MTBE
Some of the Limitations of the 2001 Argonne Air Toxic Study

- Urban and rural emissions were not separated
- Secondary formation emissions were not considered
- Vehicle technologies were representative of late 1990s technologies