Update to Transportation Parameters in GREET^{TM}

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1. Introduction

The Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET^{TM}) model contains data that allows users to calculate the energy intensity and emissions associated with transportation and distribution of both the final fuel product that is often the focus of an analysis and of the inputs to the life cycle of that fuel. For example, in the case of corn ethanol, GREET contains parameters for both the transportation and distribution of the final ethanol product and for inputs to its life cycle such as fertilizer. In this memo, we document updates to the energy intensity and emissions associated with four modes of transport: locomotives, pipelines, heavy-duty trucks, and ocean-going vessels. We also document GREET data for barges. Locomotive, pipeline, and heavy-duty truck emission factors were determined for year 2013, but are entered for 2010 in GREET. All emission factors are reported in grams per million Btu (mmBtu) on a lower heating value (LHV) basis. We also report updates to the transportation distances and mode shares of many of the commodities within GREET.

2. Emissions and Energy Intensity of Transportation of Goods by Locomotive

Energy Intensity

The energy intensity for goods transport by rail reflects data reported to the Surface Transportation Board of the United States Department of Transportation (DOT) by Class I Railroads (DOT 2013a). In 2012, there were seven Class I railroads, which are defined as having 2011 operating revenue in excess of $433.2 million dollars (AAR 2013). The Class I railroads are: BNSF railway, CSX Transportation, Grand Trunk Corporation, Kansas City Southern Railway, Norfolk Southern Combined Railroad Subsidiaries, Soo Line Corporation, and Union Pacific Railroad. In total, operating line haul and yard locomotives of these seven railroads in 2012 consumed 3.5 billion gallons of fuel. In that year, these seven companies reported moving 1.7 billion ton-miles of freight. The corresponding fuel economy of these railroads in aggregate is 472 ton-miles/gallon. We converted this value to an energy basis with the lower heating value (LHV) of low sulfur diesel fuel in GREET, 129,488 Btu/gallon. The resulting energy intensity used in GREET is 274 Btu/ton-mile.

Emissions

Emission factors for locomotives were based on a 2009 United States Environmental Protection Agency (EPA) technical document (EPA 2009). Emission factors were determined on a g/bhp-hr basis and converted to a g/gallon basis using a factor that relates fuel consumption and the usable engine power. EPA (2009) provides NO_x, PM_{10}, and hydrocarbon (HC) emission factors over time from 2006 to 2040. Of these emission factors, we selected values for 2013, 2020, and 2030 for use in GREET. CO emission factors were provided but assumed not to change over time because regulations were designed to cap CO emissions at pre-control levels rather than reduce them. EPA noted that recent testing data indicated that control technologies that serve to reduce PM and HC emissions also seem to reduce CO emissions, so the estimates they provided may be too high.

SO_x emissions were calculated on the basis of the sulfur content of #2 diesel fuel that locomotives consume. The sulfur concentration of this fuel currently must not exceed 500 ppm. We assumed this sulfur content in calculating SOx emissions from locomotives for 2013. By 2014, locomotive fuels must comply with a more stringent sulfur standard of 15 ppm, which was the value used in calculating SOx emissions from locomotives in 2020 and 2030. Equation 1 was used to calculate SO_x emission factors.

$$EF_{SOx} = \rho \times C_S \times R_S \times [S] \qquad [1]$$

Where

EF_{SOx} = SO_x emission factor [g/gal];
ρ = fuel density [3,167 g/gal];
C_s = fraction of sulfur converted to SO_x [97.8%][1];
R_s = the mass ratio of SO_2 to S based on molecular weight (2); and
[S] = the sulfur content of the fuel.

Similarly, CO_2 emissions are calculated based on the fuel's carbon content.

$$EF_{CO2} = \rho \times R_C \times [C] \qquad [2]$$

Where

EF_{CO2} = CO_2 emissions factor [g/gal];
ρ = fuel density [3,167 g/gal];
R_c = the mass ratio of CO_2 to C based on molecular weight [3.67]; and
[C] = the sulfur content of the fuel [86.5%].

EPA did not have detailed emission factors for N_2O or CH_4. They suggest two possible approaches to dealing with this data gap. First, one could either scale N_2O emission factors based on NO_x emission factors and CH_4 emission factors based on HC emission factors. Alternatively, one could assume N_2O and CH_4 emission factors are similar to those for peer

[1] EPA (2009) indicated that up to 5% of sulfur is further oxidized to sulfate and forms PM. PM emission factors account for contribution from sulfur.

diesel engines, such as in Category 2 marine vessels. Given the uncertainty associated with these emission factors, we have conservatively assumed they stay constant at (relatively low) 2013 levels into the future.

Emission factors were provided for both line haul and yard locomotives. We calculated an average emission factor based on the share of fuel consumption nationally for these two types of locomotives. EPA (2009) reported line haul locomotives consume about 90% of locomotive fuel and yard engines consume about 10%. All emission factors were converted from g/gal to g/mmBtu with the LHV of nonroad diesel fuel, 129,488 Btu/gal.

We have also developed an emission factor for black carbon from locomotives based on information in EPA's Report to Congress, which estimates that black carbon emission factors are 0.75 of the $PM_{2.5}$ emission factors (EPA 2012).

Locomotive emission factors are in Table 1 and on the EF_TS tab in the Excel version of GREET.

Table 1 Locomotive emission factors (g/mmBtu)*

	VOC	CO	NO_x	PM_{10}	$PM_{2.5}$	CH_4	N_2O	Black Carbon
2013	58	207	1,140	30	29	6.8	2.1	22
2020	35	207	833	19	19	6.8	2.1	14
2030	19	207	460	8.9	8.6	6.8	2.1	6.5

*SO_x and CO_2 emission factors are calculated in GREET from sulfur and carbon balance, respectively

3. Emissions and Energy Intensity of Transportation of Goods by Pipeline

Analysis of transportation and distribution by pipeline was conducted separately for natural gas pipelines and pipelines carrying other materials, mostly petroleum products and alternative liquid fuels. In the case of natural gas pipelines, engines may operate on either natural gas or electricity. In all other cases, electricity powers the pipeline motors. New emission factors were developed for natural gas-powered engines as described below. When motors run on electricity, existing GREET emission factors for the power sector are used.

Energy Intensity

The energy intensity of natural gas movement by pipeline was calculated from several data sources. First, the amount of natural gas consumed for the operation of natural gas pipelines was determined from the Energy Information Administration's (EIA) Annual Energy Outlook (AEO) to be 0.61 quadrillion Btu in 2009[2] (EIA 2012). The Transportation Energy Data Book (DOE/ORNL 2013) reported that 3,037 million kWh of electricity was consumed in 2009 to operate natural gas pipelines. In total then, 620 trillion Btu[2] were used to convey natural gas in pipelines in 2009. In that same year, the ton-miles of natural gas transported was 341,282

[2] High heating value (HHV) basis

(DOT/BTS 2012). Converting the energy consumption per ton-mile with a ratio of natural gas HHV to LHV yields a total energy consumption of 1,641 Btu/ton mile. The natural gas-driven engine share of this total energy consumption is 98%; electricity-driven engines count for the remaining 2% of energy consumption based on the above-described data.

Energy intensities were also developed for moving other commodities by pipeline. The amount of electricity consumed in operating natural gas pipelines in 2009 was subtracted from total pipeline electricity use in the same year (240 trillion Btu). As a result, we calculated that 67,332 million kWh was used to operate non-natural gas pipelines in 2009. The majority of these pipelines is used to move petroleum products. In 2009, 568,400 million ton-miles of petroleum products were transported. The resulting energy intensity for petroleum product transport in pipelines is 404 Btu/ton mile. This value was adopted for the movement of any liquid product in pipelines including petroleum products (e.g., gasoline, jet fuel) and biofuels (e.g., ethanol, biodiesel).

Emission Factors

Based on industry experience in this sector, it is assumed that natural gas pipelines will primarily use spark ignition internal combustion engines rated at about 1,000 brake horse power hour (bhp-hr). Key documents used in the development of base year (2013) emission factors assume a distribution between four-stroke lean burn (4SLB) and rich burn (4SRB) engines of 75% and 25%, respectively (EPA 2000, EPA 2005, EPA 2008a, EPA 2008b). EPA 2005 and 2008a are the supporting information for regulations that affect emissions of carbon monoxide (CO), nitrogen oxides (NO_x) and volatile organic carbon (VOC). These documents report different baseline emission factors depending on whether the engine is lean burn or rich burn. The emission factors developed for CO, NO_x, and VOC reflect the baseline emission factors assumed in these regulations as of 2013, which predates New Source Performance Standard (NSPS) requirements that will come into effect in 2020 and 2030.

For 2020 emission factors, the percentages of engines in use that would be either subject to the Stage 1 New Source Performance Standards (NSPS), subject to the Stage 2 NSPS standards, or not subject to either of these (i.e., would still have the baseline emission factors) were estimated. Stage 1 standards apply to engines manufactured between January 1, 2009 and January 1, 2010. Stage 2 standards apply to engines manufactured since January 1, 2010. Since the NSPS emission limits only apply to new or reconstructed units, it is important to have an estimate of the annual population turnover. Based on information in the regulatory dockets (EPA 2005, EPA 2008a), we assume that 5% of the reciprocating internal combustion engine (RICE) population will be a new unit, either through replacement or new additions, in any given year. Therefore, about 35% of the population in 2020 would consist of new units from the date of the 2013 baseline. We would further anticipate that some of these units in the population would be subject to the NSPS Stage 1 requirements, while many more will be subject to the Stage 2 NSPS requirements, depending on their construction date. Due to the two-year applicability range of the NSPS Stage 1 starting in 2008, we estimate that about 6% of RICE units will be subject to Stage 1 requirements, and 29% will be subject to the NSPS Stage 2 requirements by 2020, while the remainder, built before either standard came into effect, still emit at baseline levels.

In 2030, the RICE will include more units that were constructed after the January 1, 2010 NSPS Stage 2 applicability date, so that it is estimated that 79% of RICE units will be subject to Stage 2. The 6% of RICE units that were subject to Stage 1 in 2020 will still be in operation. Additionally, 15% of RICE units will have been constructed prior to January 1, 2008 that will not subject to NSPS.

Due to the NSPS regulations, the CO, VOC, and NO_x emissions decline in the future, while emissions of the non-regulated pollutants remain essentially the same as the 2013 baseline. The only exception is CO_2 emissions, which are affected by the difference in CO reductions in 2020 and 2030. (CO undergoes catalytic oxidation to CO_2 to meet NSPS requirements.) Table 3 lists emission factors adopted in GREET for RICE operating on natural gas pipelines. Base year (2013) emissions were determined from information in EPA guidance documents and regulations. Future year emission factors adjust 2013 factors based upon the above-described changes in RICE population.

Table 2 Natural gas pipeline emission factors (g/mmBtu)*

	2013	2020	2030
VOC	154[a]	137	110
CO	499[a]	441	333
NO_x	791[a]	572	248
PM_{10}	1.0[b]	1.0	1.0
$PM_{2.5}$	1.0[b]	1.0	1.0
CH_4	408[b]	408	408
N_2O	41[c]	41	41
Black Carbon	0.40[d]	0.40	0.40

[a] U.S. EPA 2008a
[b] U.S. EPA 2000
[c] U.S. EPA 2008a
[d] U.S. EPA 2012
* SO_x and CO_2 emission factors are calculated in GREET from sulfur and carbon balance, respectively

4. Emissions and Energy Intensity of Transportation of Goods by Heavy-Duty Truck

U.S. EPA's Motor Vehicle Emission Simulator (MOVES) model, version 2010b, was used to develop both energy intensity and emission factors for heavy-duty (HD) trucks for this GREET update. In this analysis, we only examined these parameters for 2013. Scenarios for calendar years 2020 and 2030 were not run at this time, because MOVES 2010b does not account for the new EPA/National Highway Traffic Safety Administration (NHTSA) fuel economy standards for heavy-duty vehicles, which take effect starting in 2014. GREET will be updated with new future year emission factors for HD trucks upon release of a revised MOVES model.

ERG ran the moves model to generate values for both energy intensity and emission factors to be used in GREET. MOVES provides results for the following vehicle categories (MOVES "source types").

- Light-commercial truck (32)
- Short-haul single unit trucks (52)
- Long-haul single unit trucks (53)
- Short-haul combination trucks (61)
- Long-haul combination trucks (62)

GREET, however, contains data for two specific types of HD diesel vehicles (HDDV), Class 6 (19,500 – 26,000 lbs. gross vehicle weight rating (GVWR)) and Class 8B (> 60,000 lbs. GVWR). Therefore, a post-processor developed by Eastern Research Group was applied to the model outputs, applying weighting factors passenger truck, single unit, and combo trucks source to the types listed above to determine estimated emission rates for class 6 and 8b diesel vehicles (results for classes 7 and 8a were also obtained but are not used in GREET).

The ERG post-processor combines the emissions and activity output from the MOVES model with the MOVES "sizeweightfraction" table. For a given combination of source type and model year, this table contains the fraction of vehicles apportioned across the weight classes. Given the weight class, the post-processor then determines what portion of emissions and activity is attributable to a given range of vehicle weights, and subsequently, maps those weights (along with fuel type) back to the vehicle weight classes, which are based on GVWR. This transformation is achieved with a separate lookup table which is derived from Appendix B, Table 3 of the EPA's MOBILE6.2 User's Guide. For each calendar year, source type and pollutant, the *sizeweightfraction* is multiplied by the emissions (in grams) and activity (in miles) to obtain an *EmissionFrac* and *ActivityFrac*, respectively. Finally, the *EmissionFrac* and *ActivityFrac* are summed by year, pollutant, fuel type, and MOBILE6 weight class (e.g., HDDV8b). This provides total emissions and activity independent of the MOVES source type or vehicle model year. The post-processor then divides the aggregated emissions and energy consumed by the activity to arrive at g/mi emission factors and Btu/mile energy intensities.

Energy Intensity

On-road diesel trucks currently use ultra-low sulfur diesel fuel (ULSD). The sulfur concentration of ULSD must not exceed 15 ppm, which is the value used in EPA's MOVES model.

ERG used the above-described post-processing procedure to calculate Btu/mile factors for each truck class. Energy intensity on a miles per diesel gallon basis was calculated using an LHV energy content of 129,488 Btu/gallon of low sulfur diesel. Class 6 and 8b energy consumption were calculated to be 10.4 and 5.3 miles per diesel gallon, respectively.

Emissions

Emissions were calculated from MOVES output with the ERG post-processer as previously described. The resulting emission factors are reported in Table 4.

Table 3 HD truck emission factors* (g/mile)

	Class 6	Class 8b
VOC	0.40	0.76
CO	1.8	3.0
NO_x	3.7	11
PM_{10}	0.26	0.52
$PM_{2.5}$	0.20	0.45
CH_4	0.05	0.16
N_2O	3.0×10^{-3}	2.0×10^{-3}

* SO_x and CO_2 emission factors are calculated in GREET from sulfur and carbon balance, respectively

5. Ocean Going Vessels and Barges

In October 2013, GREET1_2013 was released with a new marine vessel module. Documentation of that model (Adom et al. 2013) is available on the GREET website. In this document we report key parameters from the model that are used in transportation and distribution calculations for commodity movement. Brake specific fuel consumption for Category 3 vessels (those with displacement exceeding 3,000 L/cylinder and main engine power greater than 3,000 kw) is 145 g/bhphr of operation when the vessels use residual oil and 138 g/bhphr of operation when burning marine distillate fuel. The vessels travel between 14 and 21 nautical miles/hour. For general commodity transport, we adopt the average of these speeds, 18 nautical miles/hour (20 miles per hour). The load factor of the engine during transport is 0.83. Payload data were not updated in GREET at this time, but will be for the next release. The data and methodology underpinning GREET values for the energy intensity of commodity transport by barge is He and Wang (2000). These values were not updated for the 2013 GREET release.

6. Transportation Distances and Mode Shares

As part of this GREET update, we revisited the distances for domestic transport of commodities that GREET contains by mode and the share for each mode (barge, truck, pipeline, rail) for each commodity. We did not update international transport distances. We relied on data from the U.S. DOT Federal Highway Administration's Freight Analysis Framework (FAF^3) model (U.S. DOT 2011) to develop these distances. FAF^3 is built with data from the 2007 Commodity Flow Survey and other data. It estimates tonnage, value and domestic ton-miles by commodity type and mode. It forecasts these estimates to 2040 and can provide region-specific estimates. The FAF^3 output does not exactly match commodity types in GREET, in many cases the model output is more general than the specific commodity types GREET includes. We assigned FAF^3 commodity types to GREET commodities as shown in Table 4.

Table 4 FAF^3 categories used to update transportation distances in GREET for various commodities

FAF^3 Output	GREET commodity
Coal	Coal for power plant, coking plant, central hydrogen plant, Fischer-Tropsch diesel (FTD) plant, methanol plant, and dimethyl ether plant
Coal n.e.c.	Natural gas
Crude petroleum	Conventional crude for use in U.S. refinery
Gasoline	U.S. conventional gasoline, pyrolysis fuels[a], U.S. reformulated gasoline,
Fuel oils	Residual oil for stationary use and as a marine fuel, diesel fuel[b], low-sulfur diesel, crude naphtha, conventional jet fuel, ultra low-sulfur jet fuel, and FT jet and marine fuel from North American (NA) and non-NA (NNA) natural gas, NNA fuel gas, biomass, and coal, biodiesel
Fertilizers	Ammonia as a fertilizer and as an intermediate product, urea, nitric acid, ammonium nitrate, sulfuric acid, phosphoric rock, phosphoric acid, K_2O, herbicides, insecticides

[a] Gasoline, marine, and aviation
[b] For ground transportation and marine vehicles

Transportation distances for the commodities in Table 5 were updated based on data from the FAF^3 model. If GREET values for a commodity were not updated from the previous release (GREET1_2012), it is not included in Table 5. Transport distances for cellulosic biofuel feedstocks are developed and documented in Wang et al. (2013).

Table 5 Updated domestic transportation distances (D, miles) by mode and mode share (%)

Commodity	Barge		Pipeline		Rail		Truck	
	%	D	%	D	%	D	%	D
Conventional crude oil for use in U.S. refinery	24%	750	76%	420				
U.S. conventional and reformulated gasoline	31%	340	67%	120	2%	150		
Fuel oil[a]	49%	200	46%	110	5%	490		
Residual oil to refueling station							100%	100
Natural gas for stationary combustion use			100%	680[3]				
Fertilizers and agrochemicals[b] domestic production to bulk terminal	9%	790			91%	780		
Fertilizers and agrochemicals[b] from bulk terminal to mixer							100%	240
Ethanol as a transportation fuel produced in the U.S.	13%	520			79%	800	8%	80
Coal	2%	320	93%	740			5%	150

[a] Conventional and low sulfur diesel, crude naphtha, Fischer-Tropsch Diesel, Fischer-Tropsch (FT) Naphtha, conventional and ultra-low sulfur jet fuel, FT jet and marine fuels, biodiesl, renewable diesel, residual oil for stationary use and as a marine fuel. Domestic production to bulk terminal

[b] Ammonia, urea, nitric acid, ammonium nitrate, sulfuric acid, phosphoric rock, K_2O, herbicides, insecticides

[3] Based on U.S. ton-miles of natural gas freight via pipeline in 2009 as reported by DOT's Bureau of Transportation Statistics (BTS), special tabulation, Table 1-50, and tons of dry natural gas production in the same year as reported by Energy Information Agency (EIA).

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