

# *Life Cycle Inventory Energy Consumption and Emissions for Biodiesel versus Petroleum Diesel Fueled Construction Vehicles*

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## **ABSTRACT**

Substitution of soy-based biodiesel fuels for petroleum diesel will alter life cycle emissions for construction vehicles. A life cycle inventory was used to estimate fuel cycle energy consumption and emissions of selected pollutants and greenhouse gases. Real-world measurements using a portable emission measurement system (PEMS) were made for five backhoes, four front-end loaders, and six motor graders on both fuels from which fuel consumption and tailpipe emission factors of CO, HC, NO<sub>x</sub>, and PM were estimated. Life cycle fossil energy reductions are estimated at 9% for B20 and 42% for B100 versus petroleum diesel based on the current national energy mix. Fuel cycle emissions will contribute a larger share of total life cycle emissions as new engines enter the in-use fleet. The average differences in life cycle emissions for B20 versus diesel are: 3.5% higher for NO<sub>x</sub>; 11.8% lower for PM, 1.6% higher for HC, and 4.1% lower for CO. Local urban tailpipe emissions are estimated to be 24% lower for HC, 20% lower for CO, 17% lower for PM, and 0.9% lower for NO<sub>x</sub>. Thus, there are environmental trade-offs such as for rural versus urban areas. The key sources of uncertainty in the B20 LCI are vehicle emission factors.

## **INTRODUCTION**

Life cycle inventories (LCI) are used to compare fuels, taking into account energy consumption and emissions for fuel production and use. LCI methods include process flow diagrams, matrix representations of product systems, and input-output methods (8-11). Process flow diagrams are the most commonly used. An example is the “Greenhouse Gases, Regulated Emissions, and Energy use in Transportation” (GREET) model of Argonne National Laboratory (13). Over half of U.S. biodiesel is made from soybean oil (“soyoil”). Biodiesel can be used in a diesel engine without major modifications (1). Biodiesel is typically blended in a 20:80 percent volume ratio with petroleum diesel (PD), known as B20. B20 has been shown to have lower tailpipe emissions of particulate matter (PM), carbon monoxide (CO), and hydrocarbons (HC) for years. Nitrogen oxides (NO<sub>x</sub>) have been a focus of policy debate as to whether biodiesel can create lower NO<sub>x</sub> emissions. Both engine dynamometer tests conducted by the United States Environmental Protection Agency (USEPA) and chassis dynamometer tests conducted by the National Renewable Energy Laboratory (NREL) have shown a slight increase of NO<sub>x</sub> emissions from tailpipes when using B20 (2, 3). However, real-world in-use measurements using a portable emission measurement system (PEMS) have shown an average decrease in vehicle tailpipe emissions of NO<sub>x</sub>, PM, CO, and HC when comparing B20 and PD over 35 onroad and nonroad heavy duty diesel vehicles used in the construction industry (4-7). Even though tailpipe emissions

contribute significantly to life cycle emissions, none of the previous life cycle studies apply in-use data for the LCI (10, 13, 17, 18).

Production of soy-based B100 blendstock includes: soybean farming, soyoil extraction, and biodiesel production. Most U.S. soyoil extraction plants use a solvent to remove the oil from the soybeans (17). These plants are the most significant source of biodiesel life cycle HC emissions (13). In November 2004, EPA promulgated New Source Performance Standards (NSPS) applicable to the solvent extraction process (18). The standards require reduction of emissions of air toxics and volatile organic compounds (VOCs) from vegetable oil production facilities. Previous life cycle studies have not considered the EPA new emission standards applicable to soyoil plants as is done herein (10, 13, 17, 18).

An updated and modified LCI is developed here in order to improve the evaluation of the benefits of biodiesel and to assess the tailpipe emissions of selected types of construction vehicles. The key improvements include: update of combustion emission factors based on 2006 US national average emission rates; comparison of Pre-NSPS and NSPS-compliant soyoil plants; the use of PEMS data for real-world tailpipe emission factors; and comparisons based on 15 nonroad diesel vehicles. The key research questions addressed here are: (1) What are the best estimates of energy use and emissions associated with fuel production and tailpipe emissions for PD and B20; (2) What is the uncertainty in these estimates; (3) What are the key sources of uncertainty; and (4) What are the emissions implications of the use of biodiesel fuel for nonroad construction vehicles?

## **METHODOLOGY**

The key elements of the methodology include:

- Defining the system boundaries of the LCI;
- Quantifying the fuel life cycles of PD and biodiesel;
- Quantifying tailpipe emissions of backhoes, front-end loaders, and motor graders; and
- Applying the LCI model to quantify energy use, emissions, and uncertainties.

### **System Boundary**

An LCI involves quantification of energy use, raw material requirements, and air pollutant emission throughout the life cycle of a product. The generally accepted system components for PD production include crude oil recovery, crude oil transport, crude oil refining, diesel transport, and vehicle operation. The generally accepted system components for biodiesel production include soybean agriculture, soyoil production, soyoil transport, biodiesel production, biodiesel transport, and vehicle operation. Fossil energy is consumed for operating farm equipment and for manufacturing, procuring, and distributing fertilizers, herbicides, and pesticides (13, 19-21). Most soybeans are transported to an oil production plant within 75 miles of the farming area (10). The average distance in the U.S. from a soyoil production plant to a biodiesel plant has been reported as 600 miles (13). At a biodiesel plant, biodiesel is produced by transesterification which converts soyoil to biodiesel. More recently new plants have been built reflecting the possibility of shorter haul distances. We investigated an alternative 40 mile distance and found that in either distance

the energy use from transport itself was 0.58% or less making this transport segment a negligible contributor to LCI energy consumption.

## Fuel Life Cycle

The fuel cycle energy use and air emissions were calculated based on GREET (20), run in Microsoft EXCEL, for which the following information was updated:

- Combustion source emission factors (e.g., for coal-fired utility and industrial boilers based on 2006 US national average emission rates) and emission factors for Pre-NSPS and NSPS-compliant soyoil plants;
- Vehicle tailpipe emission rates (based on real-world measurement data for PD and B20); and
- Biogenic HC emissions during soybean farming (estimated based on measurements of air-surface exchange rates of HC compounds (22)).

Emission factors for each combustion source were updated based on U.S. national average emission rates (9, 23):

$$EF_{i,j,k} = \frac{E_{i,j,k}}{EC_{j,k}} \quad (1)$$

where

$$EF_{i,j,k} = \text{Emission factor of pollutant } i, \text{ fuel } j, \text{ and combustion technology } k \left( \frac{lb}{10^6 Btu} \right)$$

$$E_{i,j,k} = \text{U.S. total emissions for pollutant } i, \text{ fuel } j, \text{ and combustion technology } k \text{ (} lb \text{)}$$

$$EC_{j,k} = \text{U.S. total energy consumption of fuel } j \text{ for combustion technology } k \text{ (} 10^6 Btu \text{)}$$

Fuel life cycle emissions were estimated based on energy consumption and emission factors for each combustion technology:

$$EM_{i,l} = EF_{i,j,k} \times EC_{j,k,l} \quad (2)$$

where

$$EM_{i,l} = \text{Emissions of pollutant } i \text{ and stage } l \text{ (g/gallon fuel throughput)}$$

$$EF_{i,j,k} = \text{Emission factor of pollutant } i, \text{ fuel } j \text{ and combustion technology } k \text{ (g/Btu)}$$

$$EC_{j,k,l} = \text{Energy consumption of fuel } j, \text{ combustion technology } k \text{ and stage } l \text{ (Btu/gallon fuel throughput)}$$

Emissions during the transport of raw materials and fuel products were estimated based upon distances traveled and gram-per-mile emission factors in GREET (24).

## Vehicle Tailpipe Emissions

Tailpipe emissions data were collected for five backhoes, four front-end loaders, and six motor graders using a PEMS. Each vehicle was tested once on PD and once on B20. The vehicle characteristics are given in Table 1.

The PEMS used in this study was the OEM-2100 “Montana” system manufactured by Clean Air Technologies International, Inc. (25). This system consists of: (a) two parallel five-gas analyzers; (b) a PM measurement system; (c) an engine sensor array for measuring engine RPM, manifold absolute pressure, and intake air temperature; (d) a global position system (GPS); and (e) an

on-board computer. PM measurements are based on a light scattering method, which is analogous to opacity.

The PEMS light scattering-based PM measurement is adequate for relative comparisons between PD and B20. However, in order to estimate the absolute value of PM emission factors, the NONROAD model was used to estimate PM emission factors based on PD (10). The PM emission factors for B20 ( $EF_{B20}$ ) are estimated as:

$$EF_{B20} = EF_{PD} \times \frac{Opacity_{B20}}{Opacity_{PD}} \quad (3)$$

where

- $EF_{B20}$  = PM emission rate for B20 (g/gallon);
- $EF_{PD}$  = PM emission rate for PD (g/gallon);
- $Opacity_{B20}$  = Opacity for B20 based on PEMS measurements; and
- $Opacity_{PD}$  = Opacity for PD based on PEMS measurements;

## Study Design

The fuel life cycle scenarios include: baseline PD; B20 produced from a Pre-NSPS soyoil plant; and B20 produced from an NSPS soyoil plant. The vehicle emissions scenarios include: baseline PD in-use measurement data based on PEMS (4, 7); B20 in-use measurement data based on PEMS (4, 7); estimated B20 vehicle emissions based on EPA's engine dynamometer data (2); and estimated B20 vehicle emissions based on NREL's chassis dynamometer data (3). Because there are several possible configurations, seven scenarios were used for LCI analysis, as listed in Table 2. The baseline scenario is for PD with in-use PEMS measurement data for tailpipe emissions. For the B20 LCI, each vehicle has two fuel cycle scenarios and three vehicle emissions scenarios, which include 6 scenarios in total. In order to represent real-world activities, two or three duty cycles were observed for each type of vehicle during PEMS measurements. For example, backhoe loaders have three different duty cycles: (1) load a truck; (2) material handling; and (3) mass excavation. The tailpipe emissions used in the LCI model were averaged over those duty cycles.

## Uncertainty Analysis

Uncertainty in life cycle assessment arises from a lack of knowledge regarding the true value of any one or more of the inputs (23, 24). Monte Carlo simulation was used to quantify uncertainty in LCI models (25, 26). The GREET model includes default probability distributions to account for uncertainty of each input in the fuel life cycle (27). Probability distributions of uncertainty in combustion emission factors were assigned based upon previous studies and professional judgment. As an example for coal-fired power plants, the 95% range of uncertainty in  $NO_x$  emission factors is  $\pm 25\%$  of the mean (28). As another example, the range of uncertainty relative to the mean for AP-42 emission factors for natural-gas-fired engines are  $-34\%$  to  $+47\%$  for  $NO_x$  and  $-33\%$  to  $+37\%$  for HC, respectively (32). For other combustion sources, the relative uncertainty ranges are judged to be  $\pm 40\%$  for  $NO_x$ ,  $\pm 35\%$  for HC,  $\pm 30\%$  for CO, and  $\pm 30\%$  for PM. For vehicle tailpipe emissions, the relative uncertainty ranges are  $\pm 3\%$  for HC,  $\pm 8\%$  for CO,  $\pm 3\%$  for NO,  $\pm 2\%$  for  $CO_2$ , and  $\pm 5\%$  for PM, based on the precision of the PEMS data.

Crystal Ball™, an add-in software to EXCEL™, was used to quantify uncertainty in the inputs and estimate uncertainty in the outputs of the LCI based on Monte Carlo simulation. Examples of selected key input assumptions are given in Table 3.

## RESULTS

The life cycle fossil energy consumption and emissions are quantified. The key sources of uncertainty are identified by Monte Carlo simulation. The spatial distribution of biodiesel life cycle emissions is evaluated to help assess the effect on urban and rural emissions.

### Petroleum Diesel and Biodiesel Life Cycle Inventory

An example of the results for the estimated life cycle energy consumption and emissions is shown in Figure 1 based on a Front-End Loader 1 (FL1 in Table 1) and on Scenarios 1, 2, and 5. For PD, the fuel cycle energy use contributes approximately 16% of the total life cycle energy consumption. While the operation of the vehicle itself consumes more energy than does the fuel cycle for producing the fuel, the amount of energy consumed during the fuel cycle is far from negligible. Crude oil refining contributes most to the fuel cycle energy consumption and to PM, CO, and CO<sub>2</sub> emissions. The results are similar for other vehicles. Sheehan et al (10) concluded that life cycle primary energy (or total energy) for PD and BD are similar because in their model they do not use an internal commodity flow loop system. Thus they under-estimated the energy consumption in the overall LCI (11). The results shown in this paper included loop calculations among different process energy, such as electricity, oil, etc. Thus, the BD LCI primary energy is higher than in Sheehan's study.

A NSPS-compliant soyoil plant consumes less energy than Pre-NSPS plants due to improved efficiency. However, the difference in total LCI energy consumption between NSPS and Pre-NSPS soyoil plants is less than 2%. The average differences between B20 versus PD LCI emissions per gallon of diesel equivalent are shown in Table 4. When comparing all six B20 scenarios versus PD, the average and range of difference in life cycle emissions are: 3.5% (+1.7 to +5.2%) higher for NO<sub>x</sub>; 11.8% (7.8 to 14.3%) lower for PM, +1.6% (9.9% to 16.3%) higher for HC, and 4.1% (-3.3% to +10.7%) lower for CO.

Even though tailpipe emissions are the largest contribution to LCI NO<sub>x</sub> emissions; for some scenarios, tailpipe NO<sub>x</sub> emissions decrease when using B20. Meanwhile high NO<sub>x</sub> emissions from the biodiesel fuel cycle result in overall LCI NO<sub>x</sub> increases. Hence, life cycle NO<sub>x</sub> emissions are slightly higher in all cases.

Life cycle PM emissions are lower. HC and CO emissions differences depend on the scenario. Life cycle HC emissions are higher for Scenario 2, 3, and 4, because of high HC emissions from Pre-NSPS soyoil plants. In general, LCI emissions of HC and CO are lower if NSPS-compliant soyoil plants are used.

EPA has set progressively more stringent Tier 1 to Tier 4 emission standards for engines used in construction vehicles. As the tailpipe emissions are reduced from newer engines (e.g. Tier 2 or

Tier 3), vehicle emissions will contribute less to the LCI, as shown in Table 5. Thus, over time, more attention should be focused on reducing fuel cycle as well as tailpipe emissions.

The distribution between fossil and renewable energy consumption for one diesel equivalent gallon of fuel is shown in Figure 2. The total energy consumed to produce B20 or B100 is higher than for PD, but less fossil energy is used. The fossil energy contribution to the B20 life cycle is 83%, versus 37% for pure B100 blend stock. The use of B20 instead of PD will reduce fossil energy consumption and CO<sub>2</sub> emissions by 9% based on NSPS soyoil plants. The reduction for B100 is 42%. These percentages could increase if the share of non-fossil energy resources in power generation and transportation increase.

### **Uncertainty**

The average, and 95 percent probability range, of the difference in LCI emissions for B20 versus PD over the 15 measured nonroad vehicles is shown in Table 4. Even in the face of uncertainty, LCI NO<sub>x</sub> emissions increase slightly even for scenarios in which tailpipe emissions decrease. For PM, the B20 LCI emissions are approximately 11.8 percent lower, with a robust finding that there is a decrease even when uncertainty is considered. For HC, the estimated increase in LCI emissions for Pre-NSPS soyoil plants is robust to uncertainty, whereas the estimated decrease for NSPS-compliant plants is robust except if the chassis dynamometer emissions data are assumed to be representative. For CO, the LCI emissions are lower for B20 except if EPA emission factor data are used. Overall, for an NSPS-compliant soyoil plant, there are small net increases in LCI NO<sub>x</sub> emissions and average decreases of varying proportions for PM, HC, and CO.

Since vehicle tailpipe emissions contribute to most of the life cycle emissions for B20 and PD, vehicle tailpipe emissions are the most sensitive inputs to the life cycle HC, CO, NO<sub>x</sub>, and PM emissions. The rank correlation of the uncertainty in the LCI emissions to the vehicle tailpipe emission uncertainty ranges from 59% to 97% percent, depending on the vehicle, pollutant, and scenario.

For CO<sub>2</sub> emissions and energy consumption, the uncertainty in the B20 and PD LCI was dominated by diesel refining efficiency with average rank correlation of 72% and 79%, respectively.

### **Spatial Distribution of Biodiesel Life Cycle Inventory Emissions**

Most of the current soybean yield in the U.S. is located in Iowa, Illinois, Minnesota, and Indiana (30). The spatial distribution of soybean yield, biodiesel plants, and ozone non-attainment areas are shown in Figure 3. Biodiesel fuel production occurs mostly in Midwest states and ozone non-attainment areas are located mostly in California or the Northeast. Fuel cycle emissions most frequently occur in rural air basin, whereas tailpipe emissions most frequently occur in urban areas. Figure 4 differentiates the portion of HC, CO, NO<sub>x</sub>, and PM emissions that would typically occur in urban areas, many of which are in non-attainment for ozone. On average for all tested vehicles, the B20 local urban emissions from local fuel transport and vehicle tailpipe emissions are 24.3%

lower for HC, 20.2% lower for CO, 16.9% lower for PM and 0.9% lower for NO<sub>x</sub> compared to PD local emissions, based on NCSU data.

The largest portion of biodiesel fuel cycle HC emissions are from soyoil plants. The new NSPS standard is expected to significantly reduce these HC emissions. If biodiesel fuel production occurs in the same airsheds as tailpipe emissions, local urban HC, CO, and PM emissions would be decreased, but there may be an increase or a decrease in NO<sub>x</sub> depending on vehicle tailpipe NO<sub>x</sub> emissions. The air quality benefits of using biodiesel will depend on the geographic locations of the fuel production and of the vehicles consuming the fuel and on prevailing baseline air quality conditions. It is likely that the reduction in tailpipe emissions from use of B20 will occur in airsheds where air quality is a significant problem, whereas the emissions associated with the fuel cycle may occur in rural areas where air quality (e.g., ozone, PM) problems may be less pressing. However, highly localized air quality problems in rural area can be severe in some cases. Biodiesel is a promising alternative to diesel, but there are environmental trade-offs. Nonetheless, soy-based B20 offers promising environmental benefits in terms of reduced tailpipe emissions as well as reductions in fuel cycle emissions of selected pollutants. Further studies are needed to improve confidence in vehicle emission factors, which were a key source of uncertainty in LCI emissions, are needed. Further study to characterize the speciation of HC and PM will also be useful.

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## **SUPPORTING INFORMATION AVAILABLE**

Text, tables, and figures are available pertaining to: review of previous life cycle models and applications; detailed method of calculating energy consumption and emissions; point estimate and uncertainty input assumptions, PD and biodiesel LCI results; data on emissions from existing and new soyoil plants, and results of uncertainty analysis. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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Table 1. Characteristics of Tested Vehicles

Vehicle ID <sup>1</sup>	Chassis Characteristics				Engine Characteristics				
	Manufacturer	Year	Model <sup>2</sup>	GVW (lbs)	Tier	Displacement (liter)	Cylinders	Horsepower	Cumulative Engine Operating Hours
BH1	CATERPILLAR	2004	420D	22,000	2	4.0	4	97	78
BH2	JCB	1997	215	16,540	0	4.2	4	90	11,528
BH3	JCB	2001	2.15E-01	16,540	1	4.2	4	90	2,792
BH4	CASE	1999	590SL	19,578	1	3.9	4	99	3,874
BH5	CATERPILLAR	2004	420D	22,000	2	4.0	4	97	740
FL1	HYUNDAI	2002	HL740-TM3	29,000	1	5.9	6	130	3,645
FL2	HYUNDAI	2002	HL740-TM3	29,000	1	5.9	6	130	9,345
FL3	CASE	2002	621B XT	28,000	1	5.9	6	126	3,569
FL4	HYUNDAI	2005	HL740-TM7	29,000	2	5.9	6	133	446
MG1	VOLVO	2001	G720VHP	37,000	1	8.27	6	195	4,367
MG2	VOLVO	2004	G720B	37,000	2	7.1	6	195	841
MG3	VOLVO	2001	G720VHP	37,000	1	8.27	6	195	3,044
MG4	DRESSER	1990	850	37,000	0	8.27	6	167	440
MG5	CHAMPION	1993	G720	37,000	0	8.27	6	160	4,554
MG6	VOLVO	2007	G930	37,000	3	7.2	6	198	3

<sup>1</sup> BH = Backhoe

FL = Front-End Loader

MG = Motor Grader

<sup>2</sup> All tested vehicles are turbocharged.

Table 2. Scenarios Included in Life Cycle Inventory Case Studies

Scenario	Fuel Cycle	Vehicle Emissions Data	Descriptive Label
1	Petroleum Diesel	In-Use Measurement	Diesel
2	Pre-NSPS Soyoil Plant	In-Use Measurement	Pre-NSPS, In-Use
3	Pre-NSPS Soyoil Plant	Engine Dynamometer	Pre-NSPS, Engine
4	Pre-NSPS Soyoil Plant	Chassis Dynamometer	Pre-NSPS, Chassis
5	NSPS Soyoil Plant	In-Use Measurement	NSPS, In-Use
6	NSPS Soyoil Plant	Engine Dynamometer	NSPS, Engine
7	NSPS Soyoil Plant	Chassis Dynamometer	NSPS, Chassis

Table 3. Examples of Best Estimates and Uncertainty Assumptions for Key Inputs for Front-End Loader 1

Petroleum Diesel Life Cycle Inventory			B20 Biodiesel Life Cycle Inventory		
Description and units	Best Estimate	Distribution and parameters <sup>a</sup>	Description and units <sup>a</sup>	Best Estimate	Distribution and parameters <sup>a</sup>
Crude Oil Recovery Efficiency, %	97.7 <sup>c</sup>	T:96.0-99.0 (98.0)	Soybean Use; soybean use per lb. of soyoil throughput	5.9 <sup>c</sup>	N: 5.3-6.5
Refining Efficiency	89.0 <sup>c</sup>	N: 88.0-90.0	Soyoil Use; soyoil use per lb of biodiesel throughput	1.04 <sup>c</sup>	N: 5.74-6.06
Tailpipe HC Emission, g/gal D.E. <sup>b</sup>	18 <sup>d</sup>	N: 17.1-18.9	Tailpipe HC Emission, g/gal D.E. <sup>b</sup>	7.5 <sup>d</sup>	N: 7.1-7.9
Tailpipe CO Emission, g/gal D.E. <sup>b</sup>	16.3 <sup>d</sup>	N: 15.0-17.6	Tailpipe CO Emission, g/gal D.E. <sup>b</sup>	8.7 <sup>d</sup>	N: 8.0-9.4
Tailpipe NO <sub>x</sub> Emission, g/gal D.E. <sup>b</sup>	110 <sup>d</sup>	N: 106.7-113.3	Tailpipe NO <sub>x</sub> Emission, g/gal D.E. <sup>b</sup>	113 <sup>d</sup>	N: 109.6-116.4
Tailpipe PM Emission, g/gal D.E. <sup>b</sup>	6.9 <sup>d</sup>	N: 6.6-7.3	Tailpipe PM Emission, g/gal D.E. <sup>b</sup>	5.3 <sup>d</sup>	N: 5.0-5.6

<sup>a</sup> T = triangular distribution; N = normal distribution. For the triangular distribution, the range of minimum to maximum is shown with the mode given in parentheses. For normal distributions, the 2.5<sup>th</sup> and 97.5<sup>th</sup> percentile are given.

<sup>b</sup> Selected cases are converted to a per gallon of petroleum diesel equivalent basis. Per gallon diesel equivalent (D.E.) on an energy basis is 128,500 Btu/gallon.

<sup>c</sup> Based on GREET 1.6 Model.

<sup>d</sup> Based references (4,7).

Table 4. Average Percentage Difference <sup>a</sup> (%) of Life Cycle Inventory Emissions for B20 versus Petroleum Diesel per Gallon of Diesel Equivalent

Scenario		Average Percentage Difference (%) of LCI Emissions for B20 versus Petroleum Diesel LCI (95% Probability Range) <sup>b</sup>			
		NO <sub>x</sub>	PM	HC	CO
(2)	Pre-NSPS, In-Use	<b>+2.5</b> (+1.5 to +4.2)	<b>-14.0</b> (-15.7 to -12.2)	<b>+4.3</b> (+2.1 to +6.5)	<b>-5.2</b> (-8.4 to -2.0)
(3)	Pre-NSPS, Engine	<b>+5.2</b> (+4.3 to +6.0)	<b>-7.5</b> (-8.5 to -6.6)	<b>+7.6</b> (+5.9 to +9.3)	<b>+3.3</b> (+0.6 to +5.5)
(4)	Pre-NSPS, Chassis	<b>+3.9</b> (+3.0 to +4.6)	<b>-13.5</b> (-14.4 to -12.7)	<b>+16.3</b> (+14.5 to +18.1)	<b>-2.3</b> (-4.9 to -0.3)
(5)	NSPS, In-Use	<b>+1.7</b> (+0.9 to +3.4)	<b>-14.3</b> (-15.7 to -12.6)	<b>-9.9</b> (-12.6 to -6.7)	<b>-10.7</b> (-13.9 to -6.8)
(6)	NSPS, Engine	<b>+4.5</b> (+3.8 to +5.3)	<b>-7.8</b> (-8.2 to -7.2)	<b>-6.6</b> (-8.9 to -3.8)	<b>-2.1</b> (-4.6 to +0.8)
(7)	NSPS, Chassis	<b>+3.2</b> (+2.5 to +3.9)	<b>-13.7</b> (-14.2 to -13.2)	<b>-2.1</b> (-4.4 to +0.8)	<b>-7.8</b> (-10.2 to -4.8)
<b>Average</b>		<b>+3.5</b>	<b>-11.8</b>	<b>+1.6</b>	<b>-4.1</b>

<sup>a</sup> Based on average of 15 vehicles

<sup>b</sup> Based on simulation in Crystal Ball for 10,000 trials

Table 5. Proportion of Vehicle Tailpipe Emissions to Total Life Cycle Inventory Emissions Based on Vehicle Types and Engine Tier (NCSU In-Use Measurement data)

Vehicle Type	Fuel Cycle <sup>a</sup>	Engine Tier	Tailpipe Emissions as a Percentage of Life Cycle Inventory					
			NO <sub>x</sub>	PM	HC	CO	CO <sub>2</sub>	Fossil CO <sub>2</sub>
Backhoe	Petroleum Diesel	Tier 0	95.6	98.6	93.6	98.4	84.6	84.6
		Tier 1	95.5	97.7	89.9	96.7	84.6	84.6
		Tier 2	95.4	94.7	90.9	88.8	84.6	84.6
	B20 Pre-NSPS	Tier 0	92.7	98.0	75.7	94.8	79.4	72.9
		Tier 1	91.6	96.2	63.9	90.3	79.4	72.9
		Tier 2	92.0	90.7	54.6	70.6	79.4	72.9
	B20 NSPS	Tier 0	93.4	98.1	83.9	96.0	80.9	73.5
		Tier 1	92.4	96.3	74.5	92.6	80.9	73.5
		Tier 2	92.7	91.1	66.4	76.2	80.9	73.5
Front-End Loader	Petroleum Diesel	Tier 1	96.2	95.5	93.7	90.9	84.6	84.6
		Tier 2	95.2	90.7	84.3	91.1	84.6	84.6
	B20 Pre-NSPS	Tier 1	93.4	92.0	66.1	69.7	79.4	72.9
		Tier 2	91.7	86.6	53.2	73.5	79.4	72.9
	B20 NSPS	Tier 1	94.0	92.3	76.6	75.6	80.9	73.5
		Tier 2	92.4	87.1	65.6	78.8	80.9	73.5
Motor Grader	Petroleum Diesel	Tier 0	96.5	98.0	94.0	95.7	84.6	84.6
		Tier 1	95.8	95.1	94.0	91.2	84.6	84.6
		Tier 2	95.3	89.2	92.0	89.1	84.6	84.6
		Tier 3	93.4	83.7	85.6	86.0	84.6	84.6
	B20 Pre-NSPS	Tier 0	93.9	96.7	77.1	86.5	79.4	72.9
		Tier 1	92.7	92.0	74.6	77.6	79.4	72.9
		Tier 2	92.3	82.7	66.5	73.1	79.4	72.9
		Tier 3	89.1	75.8	53.2	57.6	79.4	72.9
	B20 NSPS	Tier 0	94.4	96.8	84.9	89.6	80.9	73.5
		Tier 1	93.3	92.3	83.0	82.2	80.9	73.5
		Tier 2	93.0	83.3	76.9	78.5	80.9	73.5
		Tier 3	90.0	76.5	65.6	64.6	80.9	73.5

<sup>a</sup> PD = Petroleum diesel fuel cycle;  
 B20 Pre-NSPS = B20 fuel cycle with Pre-NSPS soyoil plants; and  
 B20 NSPS = B20 fuel cycle with NSPS soyoil plant.

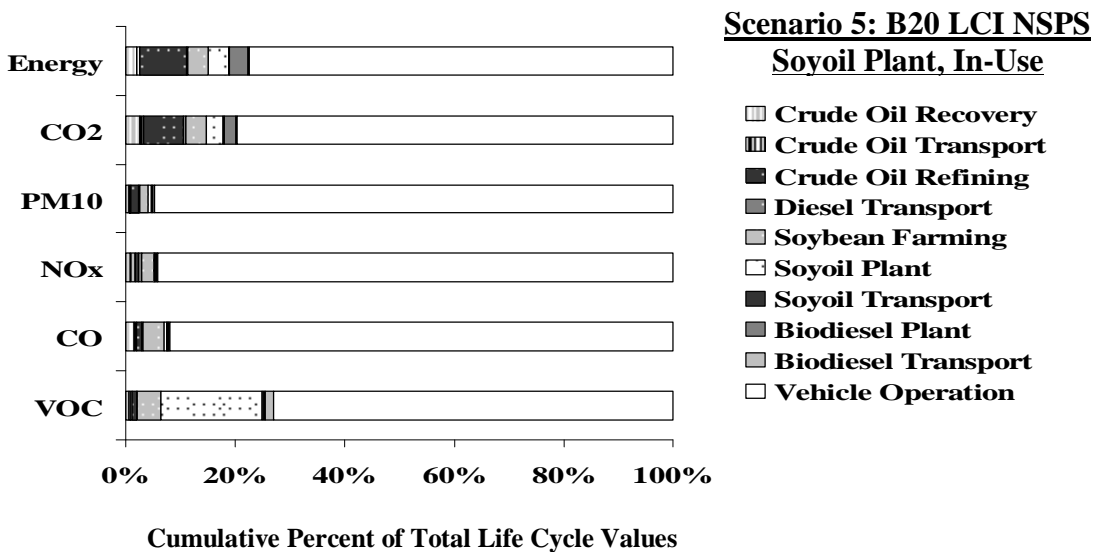
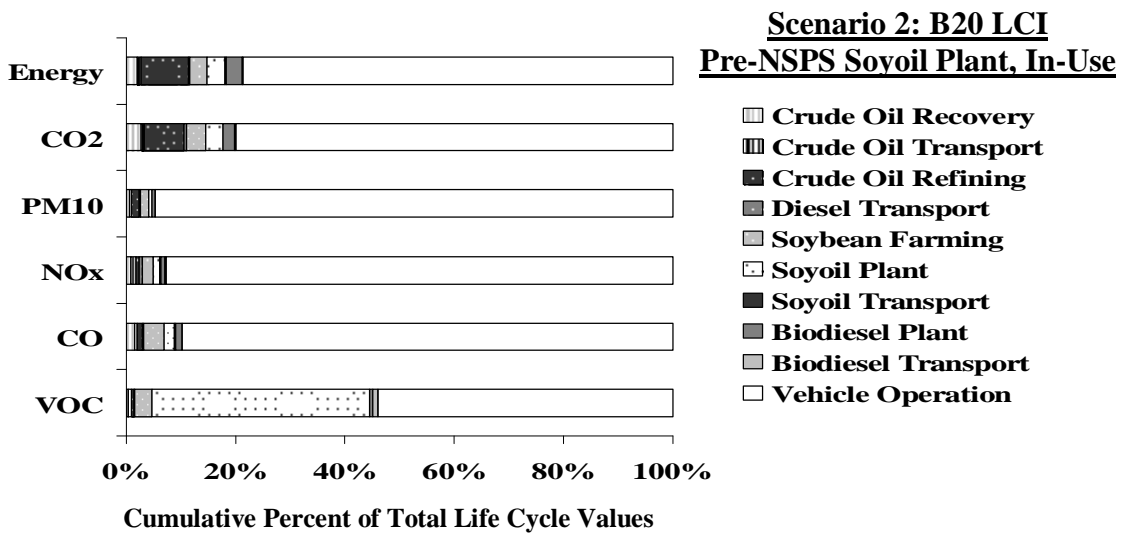
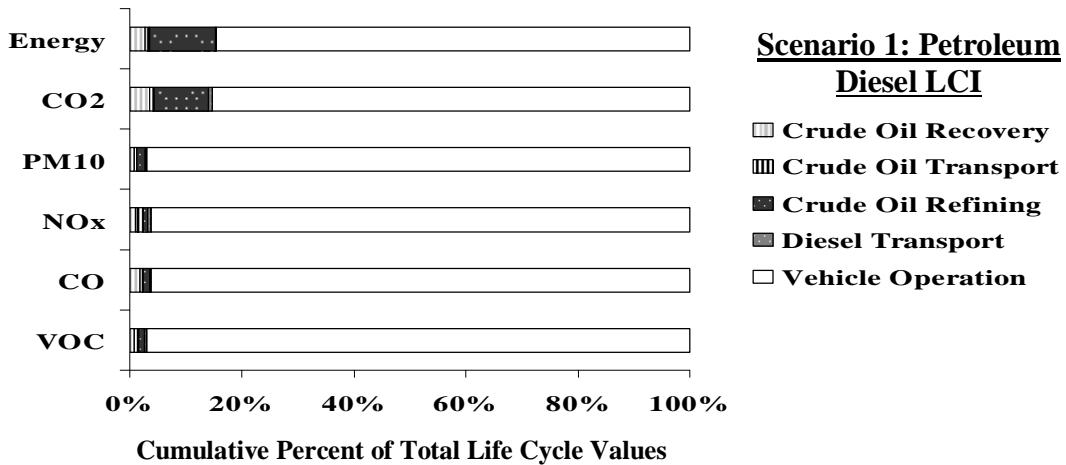
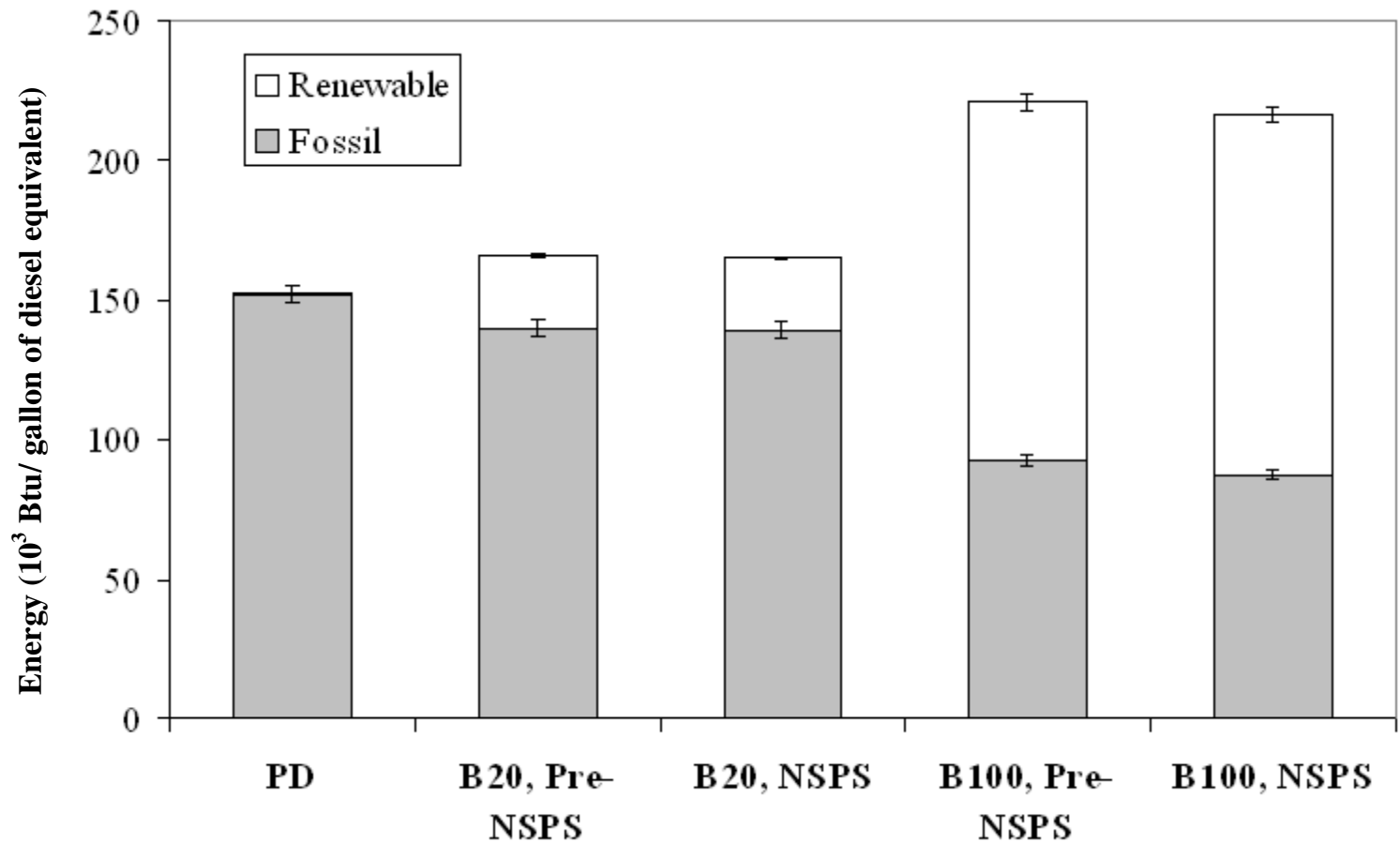


Figure 1. Example of Life Cycle Inventory Results for Scenarios 1, 2, and 5



Note: 95% confidence intervals on the mean value are indicated.

Figure 2. Fossil and Total Energy Consumption for Petroleum Diesel, B20, and B100 Life Cycle Inventory per Gallon of Petroleum Diesel Equivalent

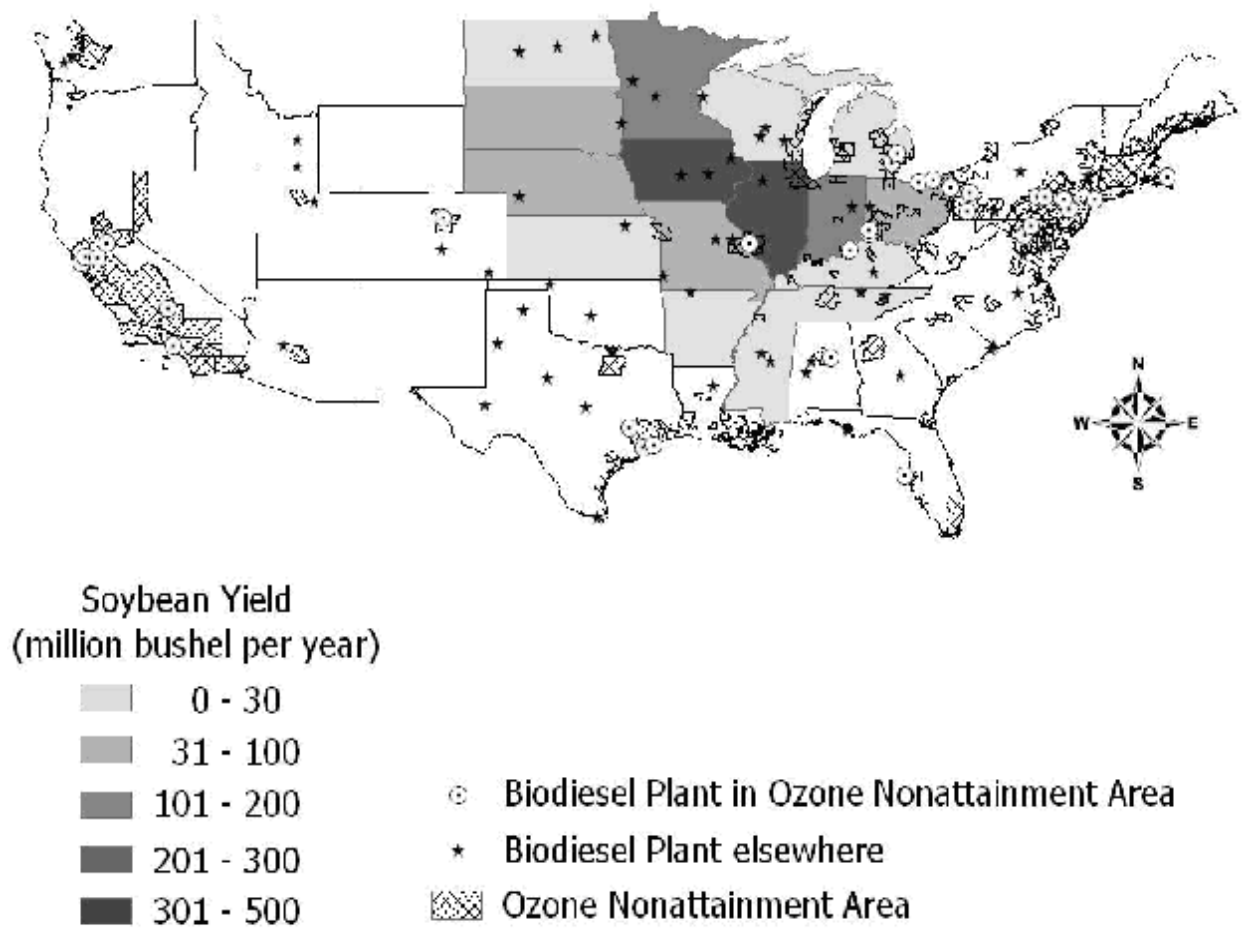


Figure 3. Geographic distribution of Soybean Yield, Biodiesel Plants and Air Quality Non-attainment Area in the U.S.

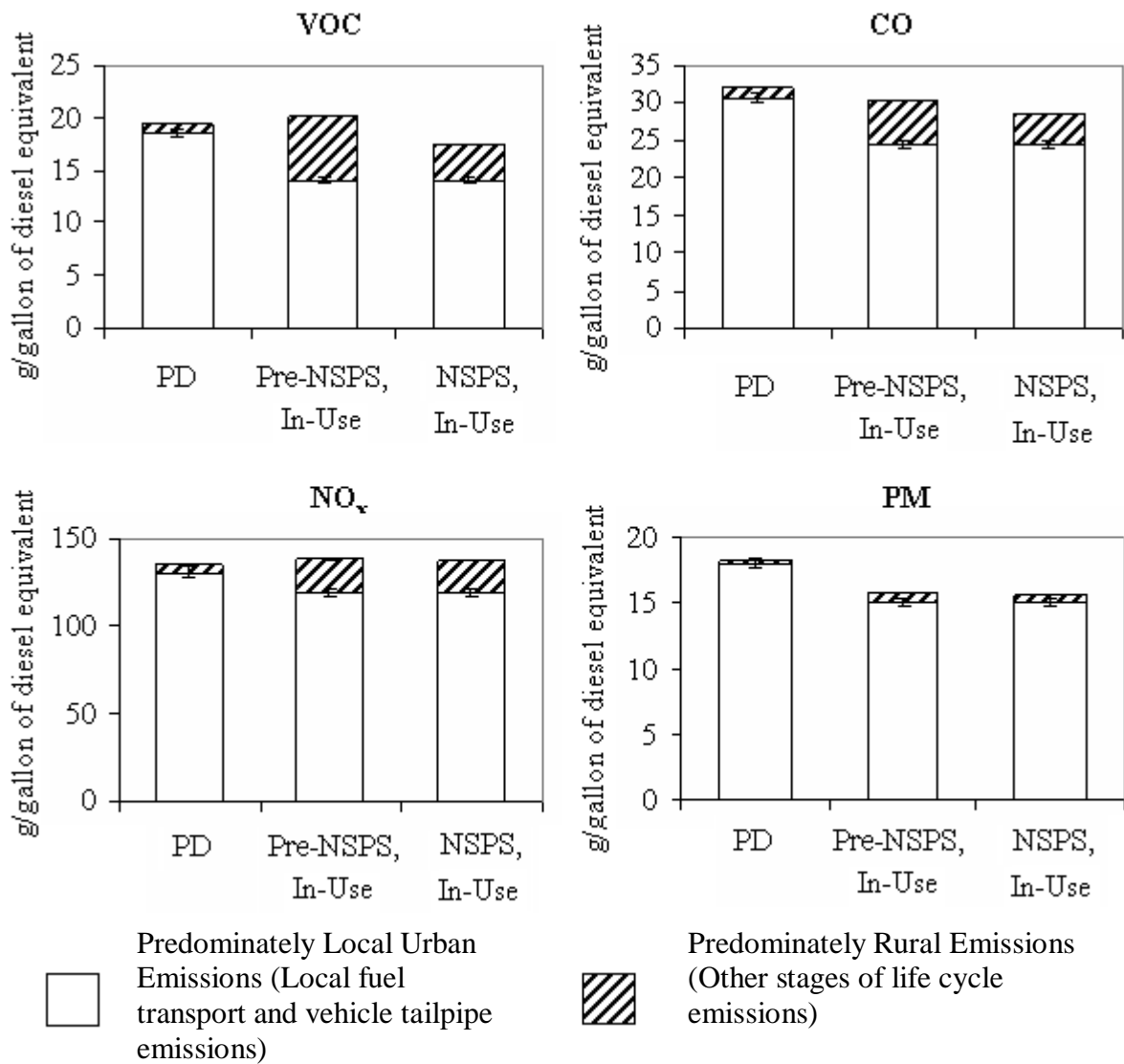


Figure 4. Comparison of Typical Local Urban and Total Emissions Based on Life Cycle Inventory Scenario 1, 2, and 5