6 Urban Bus Operation

The life cycles for biodiesel and petroleum diesel come together at the end-use stage in an urban bus. Thus, the combustion modeling for both fuels is described here in one section. This section includes two main subsections:

- ***6.1 Biodiesel Fuel Combustion:*** This section provides a review of published data on the use of biodiesel in blends and in neat form. It includes information on general fuel properties, fuel economy, and emissions for petroleum diesel and blends of petroleum diesel and biodiesel.
- ***6.2 Petroleum Diesel:*** This section includes basic data on fuel economy and emissions for low-sulfur petroleum diesel.

6.1 Biodiesel Fuel Combustion

The LCI modeling of biodiesel combustion in an urban bus is based on of the amount of biodiesel required to supply the functional unit of this study (1 bhp-h), and the emissions from the tailpipe of the bus. The amount of biodiesel required is dependent on the fuel economy of the bus engine, and the emissions are dependent on many factors, including the type of engine. The following sections outline how biodiesel combustion is modeled.

6.1.1 Comparison of Fuel Properties of Petroleum Diesel and Biodiesel

An implicit assumption in our modeling of biodiesel use is that biodiesel and its blends with petroleum diesel can be used directly in diesel engines with no impact on engine performance and engine life. This point is sufficiently critical that we felt it was worthwhile to review the literature on this question. What the literature shows is that, overall, biodiesel is compatible with current engines, with certain caveats. The most important of these are:

- Biodiesel exhibits cold weather problems
- Some types of biodiesel have exhibited storage instability that could lead to engine problems
- Diesel additives may not provide the same benefits when used with biodiesel.
- This literature review also shows that biodiesel has some significant advantages over petroleum, such as:
- Zero aromatic content (currently being regulated more stringently by EPA and the California Air Resources Board)
- Higher cetane numbers
- Zero sulfur content
- Low flash point.

Specific fuel characteristics and differences are not always captured in the LCI model. Some discussion is offered in the following sections to provide useful information to the reader.

NBB has been developing a fuel standard for biodiesel. The U.S. diesel engine manufacturers deem this standard as absolutely necessary for any manufacturer to extend warranty coverage to biodiesel-fueled engines. The NBB task force on biodiesel took the various European biodiesel standards as starting points.

Chemical and physical fuel properties are important. Table 108 summarizes reported fuel data for #2 diesel and a variety of biodiesels from a selection of biodiesel studies. The #2 diesel fuel analyses are provided to show the variation in fuel properties used in engine testing. The predominant ester studied is soy methyl ester, but other oils and alcohol combinations have been documented and continue to be studied. Table 107 provides a brief glossary for the items listed in Table 108. Many of these parameters are discussed in more detail in the subsequent section.

Table 107: Glossary of Terms for Fuel Properties

Iodine #	Standard natural oil assay to measure the degree of unsaturation (or the number of double bonds present) in vegetable oils and fats.
Cetane Number	Measure of fuel ignition characteristics. Like the octane number used for gasoline, the higher the value, the better the fuel performance. EPA also uses this parameter as a measure of aromatic content in fuel.
SPG	Specific gravity (density of the oil normalized to that of water).
Flash	Flash point. The temperature at which the vapor/air mixture above the fuel ignites.
IBP	Initial boiling point. The first data point measured on a standard ASTM distillation curve. This is the temperature at which the first vapor appears when heating the fuel.
T10, T50 and T90	Interim points on the standard ASTM distillation curve for diesel fuel. They correspond to the temperatures at which 10%, 50%, and 90% of the fuel vaporizes.
EP	End point. The final temperature measured in an ASTM distillation curve at which point all of the fuel has vaporized.
Cloud	Cloud point. The temperature at which the first wax crystals appear. Standardized ASTM test protocol is used to determine this temperature.
Pour	Pour point. The temperature at which the fuel is no longer pumpable. Standardized ASTM protocols are used to determine this temperature.
CFPP	Cold filter plugging point. An alternative to the cloud and pour point tests to assay cold flow properties of fuels.
HHV	Energy content of the fuel designated as the “higher heating value.” This measure ignores energy lost to vaporization of water formed during combustion.
LHV	Energy content of the fuel designated as the “lower heating value.” This measure accounts for energy used to vaporize water formed during combustion.
Carbon %	Amount of carbon in the fuel.
Gum Number	Measure of the tendency of a fuel to form gums via oxidation.

Table 108: Summary of Properties of Diesel and Various Biodiesel Esters

Author	Ester	IODINE #	CETANE NUMBER	SPG	FLASH (°F)	IBP (°F)	T10 (°F)	T50 (°F)	T90 (°F)	EP (°F)	Cloud (°F)	Pour (°F)	CFPP (°F)	HHV (BTU/ LB)	LHV (BTU/ LB)	Carbon %	GUM NUMBER	Viscosity @40°C	Surface Tension
Ali, Hanna, Cuppett(1995)	DIESEL			0.8383	130	355	414	504	619	619	5	-18		19578		0.18		2.07	
Clark et al(1984)	DIESEL		48.2	0.8470	172.4				565		-2.2	-9.4		19446			6	2.39	
FEV(1994)	DIESEL		52	0.8296										18533				2.49	
Geyer,Jacobus,Lestz(1984)	DIESEL		48	0.8500	125.6										19214				
Graboski et al(1994)	DIESEL		46.2	0.8468		387	429	527	632	677									
McDonnald, et al(1995)	DIESEL		43.2	0.8591	215.6						-4				18499			3	
Peterson et al(1995)	DIESEL	8.6	49.2	0.8495	165.2						10.4	-9.4		19540	18456	0.16		2.98	
Marshall(March,1994)	DIESEL			0.8370	148		404	479	582		-12	-25			18400			2.1	
Reece and Peterson(1993)	DIESEL		47.8	0.8520	176						10	-20		19443				3.2	22.5
AVERAGE	DIESEL	**8.6**	**47.8**	**0.8455**	**162**	**371**	**416**	**503**	**599**	**648**	**1**	**-16**		**19308**	**18642**	**0.17**	**6**	**2.6**	**22.5**
Ali & Hanna(1994)	METHYLTALLOWATE			0.8745		411		613		620									
Ali, Hanna, Cuppett(1995)	METHYLTALLOWATE			0.8772	205	424	613	629	667	669	54	48		17186		1.83		4.11	
Sims (1985)	METHYLTALLOWATE			0.8750		220		621	640			42.8		17380		0.01			
AVERAGE	METHYLTALLOWATE			**0.8756**	**205**	**352**	**613**	**621**	**654**	**644**	**54**	**45**		**17283**		**0.92**		**4.11**	
Ali, Hanna, Cuppett(1995)	METHYLSOYATE			0.8870	260	509	625	635		639	37	19		17243		1.74		4.06	
Clark et al(1983)	METHYLSOYATE	135.1	46.2	0.8840	285.8				648		35.6	33.8		17122			16,400	4.08	
FEV(1994)	METHYLSOYATE		48	0.8831										17991				3.77	
Graboski et al(1994)	METHYLSOYATE		56.4																
McDonnald, et al(1995)	METHYLSOYATE		54.7	0.8855	345.2						23				15961			3.9	
Marshall(1994)	METHYLSOYATE			0.8810							28	25			15700				
Schmaucher (1994)	METHYLSOYATE		45.8	0.8844	355						30	20	24	17650				4.06	
Stotler(1995)	METHYLSOYATE	130.5	56.9	0.8880			610(7%)									0.14		4.23	34.9
FSD(July 1994)	METHYLSOYATE		51.4	0.8855							29	32		17176	16000			3.97	
AVERAGE	METHYLSOYATE	**133**	**51.34**	**0.8848**	**312**	**509**	**617**	**635**	**648**	**639**	**30**	**26**	**24**	**17437**	**15887**	**0.94**	**16400**	**4.01**	**34.9**
Geyer,Jacobus,Lestz(1984)	METHYLSUNFLOWER	125.5	49	0.8800	361.4							19.4			16580				
Geyer,Jacobus,Lestz(1984)	METHYLCOTTONSEED	105.7	51.2	0.8800	230							37.4			16735				
Reece and Peterson(1993)	METHYLRAPE		54.4	0.8738	183						28	15		17930		0.044		6	25.4
Clark et al(1983)	ETHYLSOYATE	123	48.2	0.8810	320				651		30.2	24.8		17208			19,200	4.41	
Peterson et al(1995)	ETHYLFRYATE	63.5	61	0.8716	255.2						48.2	46.4		17428	16004	0.06		5.78	
Sims (1985)	ETHYLTALLOWATE			0.8710		210		635	660			42.8		17940		0.007			
Sims (1985)	BUTYLTALLOWATE			0.8680		236		655	668			42.8		17733		0.051			

6.1.1.1 Cetane Number

The cetane *number* of the fuel, specified by ASTM D-613, is a measure of its ignition quality. The cetane number of biodiesel exceeds that of #2 diesel, which implies that biodiesel may provide cetane enhancement when used neat or in blends, and may provide emission benefits that have been correlated to cetane number. Higher cetane numbers (as high as 55 to 60) generally improve diesel emissions, but above that level little improvement is demonstrated.

The cetane *index* is a calculated property that correlates well with cetane number for natural petroleum stocks, and is defined by ASTM D-976. Cetane index is also a measure of fuel aromaticity[62]. It is not relevant to biodiesel.

The cetane number of biodiesel depends on the oil or fat feedstock. Fatty acids consist of long chains of carbon atoms attached to carbonyl groups. Fats and oils contain a distribution of carbon chains of varying lengths, typically ranging from 10 to 18 carbons (referred to as C10 to C18 chains). Some carbon chains contain 0, 1, 2, or more double bonds between the carbons, and have carbonyl groups in different locations. Cetane number increases with chain length, decreases with number and location of double bonds, and changes with various locations of the carbonyl group. As bonds or carbonyl move toward the center of the chain, the cetane number decreases. Cetane numbers increases from 47.9 to 75.6 when the number of carbons in the fatty acids in biodiesel increases (Freedman and Bagby 1990). When the number of carbons in the fatty acid chains exceeds C12, the cetane number exceeds 60. For soy methyl ester, reported cetane numbers range from 45.8 to 56.9. The variation is due to the distribution of carbon chain lengths in each fuel tested. The average of the available data presented in Table 108 is 51.3.

Generally, the cetane number for a blend of biodiesel and either #1 or #2 diesel fuel is a nearly linear function equal to the average of the cetane numbers for the fuels (Midwest Biofuels 1993; Graboski 1994). This implies that the neat cetane numbers for diesel and biodiesel can be used to estimate the cetane number over the entire range of mixtures of biodiesel with diesel fuel.

6.1.1.2 Flash Point

Flash point, as defined by ASTM D-93, is a measure of the temperature to which a fuel must be heated such that a mixture of the vapor and air above the fuel can be ignited. All #2 diesel fuels have high flash points (54°C, minimum; 71°C, typical). The flash point of neat biodiesel is typically greater than 93°C (Interchem Industries Inc. 1992). The U.S. Department of Transportation considers a material with a flash point of 93°C or higher to be nonhazardous. From the perspective of storage and fire hazard, biodiesel is much safer than diesel. In blends, the diesel flash point will prevail.

The Engine Manufacturers' Association (EMA 1995) expressed concern that the oxidative instability of some types of biodiesel may result in fuels that have unacceptably low flash points after storage. Some biodiesels have excellent storage histories; others have tended to oxidize rapidly. An ASTM test method on oxidative stability of biodiesel is under development to help researchers test biodiesel and determine its storage characteristics.

The number and location of the double bonds have been identified as possibly contributing to the instability of biodiesel fuels. Fatty acid chains can be saturated (adding hydrogen or alcohol) to reduce the number of double bonds, and it may be possible to remove the fatty acids with excessive double bonds if indeed, these characteristics are confirmed as sources of the problem. In addition, soy oil contains natural antioxidants, which can be added back to the fuel if removed during processing. And a number of

[62] EPA uses cetane number and cetane index as indirect measures for controlling the aromatic content of diesel fuel. The current minimum cetane number of 40 is intended to regulate the aromatic content in diesel fuel.

antioxidants have been identified that significantly reduce the amount of oxidation that occurs during storage. Research is continuing is this area.

6.1.1.3 Distillation

Biodiesel fuels have a narrow range of boiling points from 327°C to 346°C. Some B20 blends have met the ASTM T-90 distillation specification, using ASTM D-86. However, EMA (1995) and others have reported that intake valve deposit formation is a problem with soy methyl esters at light load, which may be related to the large percentage of olefinic content in the B20 mixtures. Excess glycerine and glycerides in the fuel have also been associated with deposits. Quality control on biodiesel fuel standards was not evident before 1997 and remains an industry problem today; off spec fuel may also contribute to some of the fuel problems identified in past studies.

6.1.1.4 Specific Gravity

Specific gravity is determined by ASTM D-287. Diesel #2 exhibits a specific gravity of 0.85. Biodiesel specific gravity is reported to vary between 0.86 and 0.90 depending on the feedstock used. The average gravity in Table 108 is 0.885 for soy methyl esters. The specific gravities of biodiesel and #2 diesel are very similar.

6.1.1.5 Energy Content

Generally, fuel consumption is proportional to the volumetric energy density of the fuel based on the lower or net heating value. Based on Table 108, #2 diesel contains about 131,295 Btu/gal while biodiesel contains approximately 117,093 Btu/gal. The ratio is 0.892. If biodiesel has no impact on engine efficiency, volumetric fuel economy would be approximately 10% lower for biodiesel compared to petroleum diesel. However, fuel efficiency and fuel economy of biodiesel tend to be only 2%-3% less than that of #2 diesel. The reasons behind this unexpected difference have not been established.

6.1.1.6 Flow Properties (Cold Temperature Sensitivity)

The key flow properties for Winter fuel specification are cloud and pour point. These are static tests that indicate first wax and non-flow temperatures for the fuel. Cloud point, as defined by ASTM D-2500, is a measure of the temperature at which the first wax crystals form, and is related to the warmest temperature at which these will form in the fuel. Wax crystals cause fuel filter plugging. Pour point is a measure of the fuel gelling temperature, at which point the fuel can no longer be pumped. The pour point, as defined by ASTM D-97, is always lower than the cloud point.

Additives called flow improvers do not generally affect the cloud point of conventional diesel fuel; however, they do reduce the size of the wax crystallites that form when the fuel cools. Additives tend to allow the fuel filters to operate at lower temperatures. Diesel #1 and kerosene are common pour point additives that reduce the fuel gelling temperature significantly when mixed with #2 diesel. Refiners and marketers vary fuel cloud and pour points to meet local climatic conditions, and ASTM provides recommended fuel characteristics by season and be degree of latitude.

The cloud point of soy methyl ester, used in this study, can be 30°C higher than that for diesel #2. The difference in pour points may be 10°C higher for soy methyl ester. The relevant structural properties of biodiesel that affect freezing point are degree of unsaturation, chain length, and degree of branching. Fully saturated fatty acid chains tend to become solids at relatively high temperatures (tallow, hydrogenated soy oil, palm oil). Rape and canola methyl esters have lower cloud and pour points than soy methyl ester (Peterson et al. 1997). Tallow methyl ester has a cloud point of 16°C and a pour point of 10°C. Producing biodiesel with ethanol instead of methanol tends to reduce the cloud and pour points by a few degrees. Rape ethyl esters have cloud points of 10°C and a pour point of 15°C. Isopropyl alcohol has been used to make a biodiesel with a pour point 90°C lower than methanol–based biodiesel; pour point temperature was reduced by 30°C (Foglia et al, 1997). Other solutions, such as customizing the fatty acid profiles of the fuel, remain possible but unexplored.

Traditionally, cloud and pour points of biodiesel blends have been modified by changing the amount of biodiesel in the blends. Biodiesel blends with #1 and #2 diesel #1 show that cloud and pour points increased as the amount of biodiesel increased. The effect was stronger with #1 diesel than with #2 diesel. Blends of more than 35% biodiesel demonstrate significant Winter problems in the Midwest, even when the base diesel as a 50-50 mix of #1 and #2 diesel fuels (AEP 1997).

In Europe, cold weather additives have been identified for use with rape methyl esters, but they are not effective with soy methyl esters.   Several studies have shown that a number of diesel flow improvers do not work for biodiesel blends (Midwest Biofuels 1993; Clark et al. 1984).

The biodiesel industry continues to fund research in this critical area. Currently, solutions are limited to recommending lower blends of biodiesel in the Winter compared to Summer, blending with #1 diesel or kerosene, and using heated storage tanks and in-line fuel heating systems in vehicles. There are at least two field demonstrations this Winter (1997-1998) using biodiesel blends of 20% to 35% in heavy-duty, on-road vehicles (Iowa and Idaho), but the precautions discussed earlier have been taken.

An approach being considered by the industry is marketing specific types of biodiesel to meet cold temperature by altering the types of alcohol and oil feedstocks used. By customizing seasonal fuel compositions, similar to diesel producers, more acceptance in cold weather could be established. Additives may still be necessary. A lot of research remains to be done in this area.

6.1.1.7 Viscosity and Surface Tension

The ASTM D-445 specification for viscosity at 40°C of 4 centistokes is generally met by biodiesel and biodiesel blends. However, the viscosity of biodiesel and its blends is higher than for #2 diesel. Soy methyl ester is reported to have a viscosity ranging from 3.8 to 4.1 centistokes at 40°C (Scholl and Sorenson 1993). Glycerine contamination will cause biodiesel viscosity to increase, among other problems. Estimates of the surface tension of biodiesel suggest that it may be two to three times as great as that for #2 diesel. These properties affect the fuel droplet size during injection. Biodiesel has both larger viscosity and surface tension, resulting in larger droplets, one of a number of contributing factors that have been identified as possible causes for higher NO_x emissions.

6.1.1.8 Oxidative Stability

Oxidative stability is a major industry issue for diesel and biodiesel fuels. Oxidative stability is measured by ASTM D2274. EMA (1995) reported that compared to #2 diesel, biodiesel fuels were far more prone to oxidation. The degree of saturation of the fatty acid chains tends to be correlated with its stability. Oxidation products formed in biodiesel will affect fuel life and contribute to deposit formation in tanks, fuel systems, and filters. Gum number is one of several possible measures of oxidative stability of a fuel, iodine value is another. Fuels with high iodine numbers may possess high gum numbers. Thermal and oxidative instability, and fuel oxidation during storage can lead to deposit formation and other potential engine problems. A recent draft report by Southwest Research Institute prepared for NREL evaluates this complex issue and recommends test methods and levels that correlate fuel oxidative characteristics with engine performance goals. No oxidative stability test method for biodiesel has been established by ASTM.

6.1.1.9 Sulfur, Aromatic, Ash, Sediments, Water, Methanol, Glycerine, and Glyceride Content

These contaminates, if they exist at all, are limited less than 2% in the biodiesel, in total. The ester content of a fuel-grade biodiesel generally exceeds 98%. Biodiesel is nonaromatic and does not contain sulfur. Sodium and potassium containing ash may be present because of contamination from catalysts used in transesterification. Phosphorous may be present from inferior oil refining (poor gum removal). Water and sediments may be by-products of long-term storage. Glycerine and methanol in the biodiesel may scavenge water. Glycerine, glycerides, and excess alcohol are major fuel contamination problems, and newly developed industry standards have taken aim at controlling these contaminants. Sediment may result from oxidation of esters and reactive glycerides in the fuel. Algae growth may also produce sediment.

6.1.1.10 Biodiesel Composition

Table 109 presents analytical data for soy methyl ester. These data, along with the energy density data presented in this section, are useful for estimating energy-based fuel economies for the various fuels and engine platforms investigated. The data of Graboski (1994) are important for quality checking the other sources because the oxygen weight percent reported was directly determined as opposed to determined by difference.

Table 109: Elemental Composition of Biodiesel and Petroleum Diesel

Source	WT%		
	Carbon	Hydrogen	Oxygen
FEV (1994)	78	11.5	10
Graboski (1994)	77.22	11.56	11.03
Schumacher (1994)	76.5	12.5	11
McDonald (1995)	77.55	11.56	10.88
Marshall (1994)	76.91	12.11	10.97
AVERAGE	77.24	11.85	10.78
STDEV	0.58	0.44	0.44
Low-sulfur #2 diesel	87	13	0

6.1.2 Biodiesel Fuel Economy

The fuel economy of the bus burning biodiesel is based on combustion data in a modern four-stroke diesel engine. Table 110 presents fuel economy data for the same four-stroke diesel engine used to calculate the fuel economy of the diesel fuel (Graboski 1997. The root mean square (RMS) error in fuel economy by each method is approximately 1.5%. The data clearly show the following:

- The energy efficiency determined by both methods (based on CO_2 and on fuel use) for each blend are the same within experimental error. Thus, the fuel composition and lower heating value data used to estimate fuel economy from CO_2 and fuel flow data are internally consistent.

- Within experimental error, the energy efficiency is independent of biodiesel content. The neat biodiesel actually shows a better fuel economy of around 3%. This is thought to be insignificant within the experimental error of the data.

Table 110: Economy Data for Biodiesel Fuels in a Modern Series 60 Engine

% Biodiesel by Volume in Diesel Fuel	Engine Efficiency (Btu/bhp-h)	
	Calculated from Measurements of CO_2 Emissions	Calculated from Fuel Consumption Data
0%	7176	7326
20%	7040	7192
35%	7080	7130
65%	7006	7133
100%	7038	7038
avg/stdv	7116	97(1.4%)

As discussed later in this section, biodiesel increases emissions of NO_x and decreases emissions of PM10 in urban bus engines. One approach often used to mitigate the NO_x increase associated with biodiesel is to change the timing of the engine. Retarding the timing of these engines tends to reduce NO_x emissions at the expense of increasing PM10. An oxidation catalyst can be added to the engine to bring PM10 emissions down again. Researchers have tested the effect of both the timing change and the catalyst on engine performance. Table 111 shows the effect that these two engine modifications can have on fuel economy for low-sulfur #2 diesel and for B20 blends. The data show that they have no measurable effect on fuel economy. The average amount of energy required to deliver 1 bhp-h of engine work increases by only 0.6% when both the timing change and the catalyst were applied in tests done on six different engines.

Table 111: Fuel Economy Data for a Series of Engines Operating with Catalysts and Timing Changes

FUEL	SETUP	DDEC 6V-92-TA 1991	MUI 6V-71N 1977	DDEC 6V-92TA 1988	MUI 6V-92 - 1981/1989	MECH-L-10 1987	MUI-6V-92TA 1987
DF-2	STOCK	8593	8374	8426	8735	7252	8911
B20	STOCK	8529	8439	8258	8759	7192	8837
B20	TIMING	8599	8375	8475	8874	7066	8873
B20	TIMING + CAT	8589	8835	8421	8835	7138	8819
	TIMING DEG	3	4	1	2	?	?
RATIO	TIME+CAT/ STOCK DF-2	0.9985	1.0551	0.9994	1.0115	0.9842	0.9897
AVG/S TDEV	1.0064	0.0256					

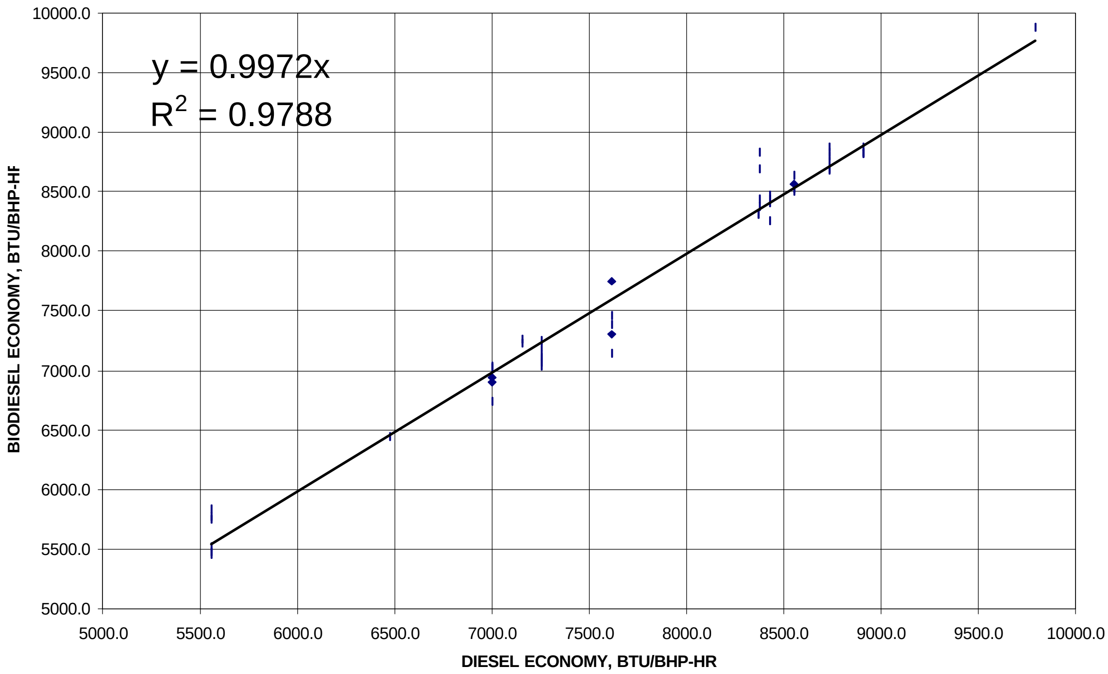

Figure 76: Energy Economy for Biodiesel-Fueled Engines

In addition to transient testing, energy fuel economy data are available for steady-state and multimode steady-state testing. Figure 76 presents energy economy data for biodiesel and biodiesel blends compared to #2 diesel for steady-state and transient testing and covering a broad range of engine models and vintages. Biodiesel blends vary from 10% to neat, and include methyl, ethyl, and butyl esters. As Figure 76 shows, the energy fuel economy is independent of the fuel mixture fed to the engine. Thus, the crude oil replacement benefits of biodiesel depend on the total quantity used but not the blend concentration.

Several road tests support the conclusions from engine testing. Battelle (1995) reported on the B20 bus experiment carried out at Bi-State Development Agency in St. Louis, where five buses each were run on B20 and control diesel. Approximately 200,000 miles were accumulated with each fleet. The diesel buses were run 7 days per week; the biodiesel buses were operated 5 days per week. The measured fuel economy was 3.76 mpg for B20 and 4.01 mpg for control diesel, a 6% reduction. A 1% to 3% loss was expected based on fuel property estimates, and no explanation was provided for the discrepancy. The fuels were not interchanged for a given bus; the fleet size was so small that hardware differences may have a significant effect on mileage. Data on passenger loading, driver assignment, and routes were not provided.

ATE Management and Service Company, Inc. (1994) reported on a study conducted by Cincinnati Metro. Six buses were tested. Four were equipped with 1987 MUI and two with 1989 Electronic DDC two-stroke power plants. Before the test all engines were tuned up and received new injectors. B30 was used. Each bus was power baselined on a chassis dynamometer with #2 diesel. The buses were not assigned to fixed routes and experienced a variety of driving situations. Fuel mileage data were given for each bus. Mileage was on average 5% lower with B30. The expected loss in mileage based on energy use is 3.2%.

The agreement is excellent and the author indicated that the difference could be due to route bias for hill testing trials.

Daniel (1994) reported on the Link Transit 1 month 104,000-mile demonstration on B20 (soy). The base diesel was not defined. They saw no significant change in fuel economy for 1991 and 1993 6V-92TA DDEC II engines in Orion 1 Coaches. The expected change would have been a 2.2% loss in mileage.

Yost (1994) reported on a 6-month field test by Spokane Transit on #1 diesel blended with 30% soy methyl ester and 6 months on #1 diesel blended with 20% soy methyl ester. Eighteen bus coaches were used (six each 6V-71, 6V-92, and 6L-71; 1974 to 1992 vintage). The fuel mileage was 0.5 mpg better than with #1 diesel. The lower heating value of #1 diesel is approximately the same as for soy methyl ester. Thus, fuel economy may have been better for biodiesel blends. However, it is not known how fuel economy differences were actually computed and whether there was any control of properties on the #1 diesel employed.

Howes and Rideout (1995 a,b) investigated emissions and fuel economy for two urban buses using three bus chassis cycles for diesel; they examined B20 alone, then with timing changes and catalyst. Table 111 shows that the fuel economy in mpg. No data on fuel composition were given and it was not stated whether the B20 was produced with the diesel reference fuel. Three cycles of varying load were driven. Table 112 shows that there was no significant effect of B20 on mileage without or with a 1.5° timing change. This suggests a higher thermal efficiency for B20; the confidence limits on the data encompass the expected 2.2% loss in mileage. Addition of a catalyst caused a 6.2% and 8.3% loss in mileage for the 6V-92 and 8V-71, respectively. This probably points out the importance of backpressure on vehicle performance regardless of the fuel.

Table 112: Chassis Dynamometer-Based Fuel Economy Data

			mpg	
CYCLE		%Biodiesel	1988 6V-92TA	1981 DDC 8V-71
CBD	STOCK	0%	3.69	3.59
ARTERIAL	STOCK	0%	4.67	3.92
COMPOSITE	STOCK	0%	3.70	3.66
CBD	STOCK	20%	3.68	3.63
ARTERIAL	STOCK	20%	4.72	3.91
COMPOSITE	STOCK	20%	3.63	3.52
CBD	TIMING	20%	3.54	3.59
ARTERIAL	TIMING	20%	4.89	3.93
COMPOSITE	TIMING	20%	3.50	3.63
CBD	CAT	20%	3.35	3.18
ARTERIAL	CAT	20%	4.64	3.40
COMPOSITE	CAT	20%	3.34	3.21
CBD	TIMING+CAT	20%	3.26	3.30
ARTERIAL	TIMING+CAT	20%	4.56	3.84
COMPOSITE	TIMING+CAT	20%	3.33	3.43

Clark et al. (1984) studied diesel, soy methyl ester, and soy ethyl ester in a John Deere 4239TF direct-injected turbocharged diesel engine attached to an eddy current dynamometer. Fuel economy, torque, and horsepower were all directly related to volumetric heating value of the fuels.

Klopfenstein and Walker (1983) reported on an investigation of thermal efficiency of nine pure esters and eight whole oils using a Fairbanks Morse one-cylinder direct-injection engine rated at 5.25 bhp at 1800 rpm. Methyl esters made from lauric acid (C12), mystiric acid (C14), palmitic acid (C16), stearic acid, oleic acid (C18, one double bond), linoleic acid (C18, two double bonds), and linolenic acid (C18, three double bonds) were tested. Ethyl and butyl esters of oleic acid were examined. The heats of combustion were measured using a bomb calorimeter. Thermal efficiency was reported to increase with decreasing fatty acid chain length from 20% at C18 to 24.4% at C12. The ethyl ester also yielded a high thermal efficiency of 24.8%. The butyl ester gave a low efficiency of 20.3%. No explanation is given for the trend and no description of the possible error in measurement, repeatability, or repeated diesel testing for control purposes is given. The diesel fuel gave 21.7% efficiency. The cetane number for the diesel fuel was not reported.

Based on these data, neat biodiesel and biodiesel blends should exhibit a fuel economy proportional to the lower heating value of the blend. No improvement in energy efficiency is expected. Therefore, the fuel economy of the biodiesel bus is assumed to be the same as for a conventional diesel fueled bus — 7.5 MJ/bhp-h.

The lower heating value of biodiesel is used to determine the amount of fuel needed per functional unit. The lower heating value of biodiesel is assumed to be 36.95 MJ/kg. Therefore, 0.203 kg of biodiesel are required per brake horsepower hour of engine use.

6.1.3 Biodiesel Tailpipe Emissions

The regulated emissions data, NO_x, CO, NMHC, PM10, and SO_x, from engines fueled with biodiesel can be separated into data for older two-stroke engines embodied as various DDC-6V-71 and 92 engines and for modern four-stroke engines embodied as the DDC Series 50 and 60 engines. We focus our attention on these newer four-stroke engines to be consistent with the "current" timeframe of our study.

Figure 77 and Figure 78 show how biodiesel emissions of NO_x and PM10 change with blend level in four-stroke engines. Figure 79 and Figure 80 show the effect of biodiesel on CO and NMHC emissions in four-stroke engines. These results are from four independent studies (Sharp 1994; Ross 1994; Graboski, 1994; and Ortech, 1995). The emissions tests were done on at least three Series 60 engines, and three calibrations (1991, 1994, 1998). Data for a Cummins N-14 engine (Ortech 1995) are also included. Figure 77 shows that the newer four-stroke engines have emissions of NO_x that increase with the blend level of biodiesel. PM10, on the other hand, drops significantly with increasing blend levels of biodiesel (see Figure 78). Both CO and NMHC decrease as the blend level of biodiesel increases.

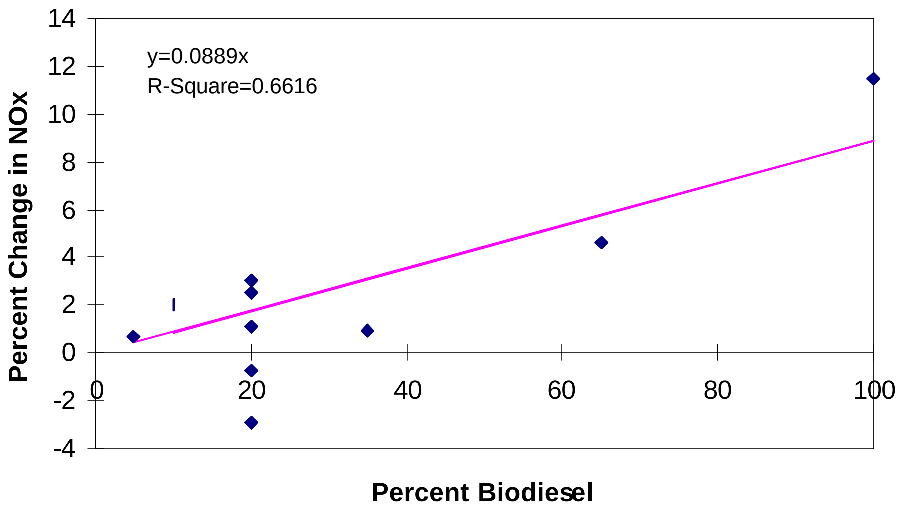

Figure 77: Effect of Biodiesel Blend Level on NO_x Emissions for Four-Stroke Diesel Engines

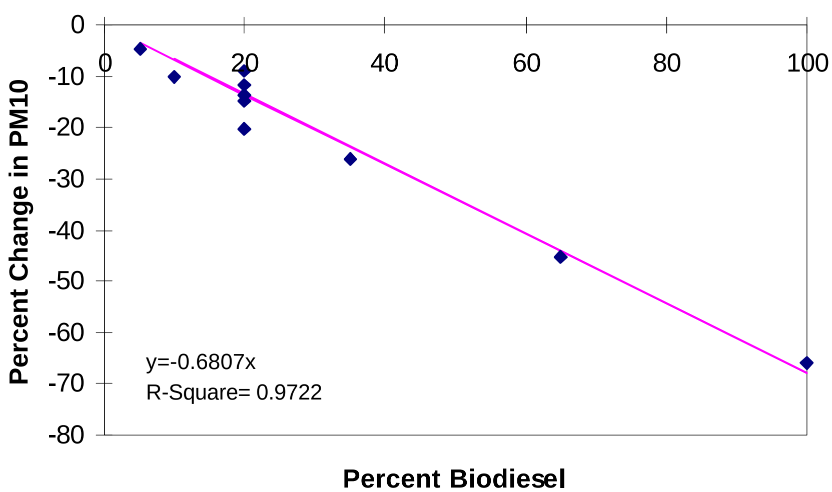

Figure 78: Effect of Biodiesel Blend Level on PM10 Emissions for Four-Stroke Engines

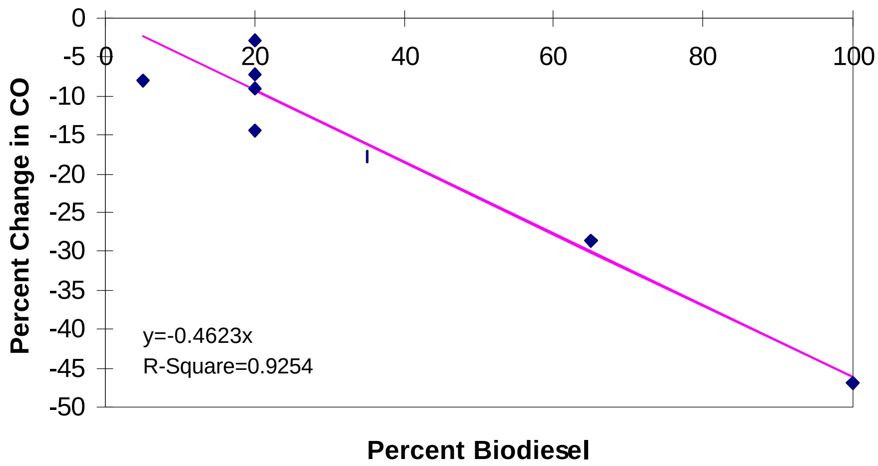

Figure 79: Effect of Biodiesel Blend Level on CO Emissions for Four-Stroke Engines

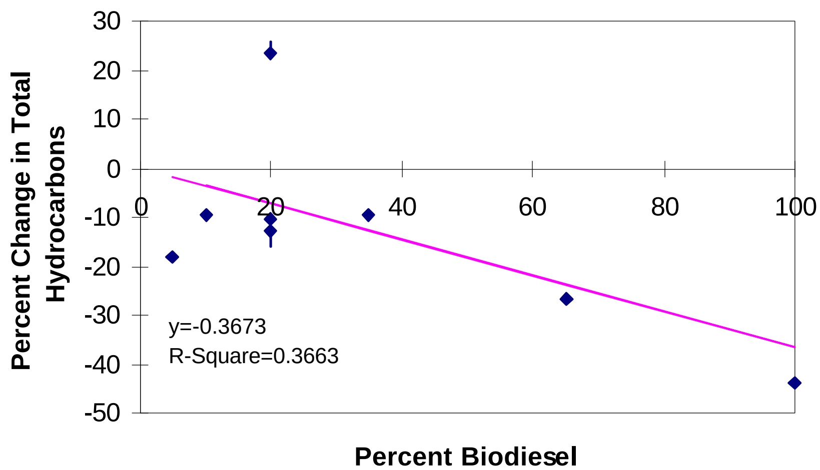

Figure 80: Effect of Biodiesel Blend Level on NMHC for Four-Stroke Engines

These figures suggest that the regulated emissions change nearly linearly with biodiesel content. If linearity is assumed, the specific emissions effect of biodiesel is independent of its concentration in #2 diesel fuel. This is an important result because it allows us to predict the tailpipe emissions for any blend of biodiesel and #2 diesel. The assumption of linearity is quite reasonable for CO and PM10 emissions, each of which exhibit correlations with R-squares of 0.9722 and 0.9254, respectively. This strong correlation supports the widely held view that oxygenates in diesel fuel lead to lower CO and PM emissions by improving the degree of complete combustion (Liotta 1993). The linear correlation between biodiesel blend level and NO_x is weaker (R-square=0.6616), though a visual inspection of the data supports the conclusion that high blend levels of biodiesel result in higher NO_x emissions in four-stroke engines. The issue is whether or not this trend is linear. The variability of the data makes more sophisticated interpretations of the trend meaningless. The rate of increase in NO_x with blend level may be lower at lower blend levels. Better data are needed to evaluate this possibility. For the purposes of this study, we assume a linear response across the full range of blend levels from 0% to 100% biodiesel. NMHC emissions show the weakest correlation with biodiesel blend level (R-square of 0.3663). This is due to the high degree of variability in data reported on the 20% blend level. Once again, for our purposes, we model emissions of HC from the engine as a linear function of biodiesel blend level.

The following formulas are used to represent the relationship between the oxygen content of the fuel and the emissions:

- NO_x → y = 0.0889x
- PM → y = -0.6807x
- CO → y = -0.4623x
- NMHC → y = -0.3673x Where:

  y = the percent change in the emissions relative to standard low-sulfur #2 diesel fuel

  x = the biodiesel blend level expressed as a volume percent in the fuel

The baseline emissions for which the percent of change (y) is applied are the same baseline emissions that are used for the diesel fuel combustion emissions (see section 6.2.2).

We assumed that there is no sulfur in the biodiesel. Therefore, there are no SO_x emissions from the combustion of neat biodiesel (B100). The level of SO_x emissions for biodiesel blends is assumed to decrease linearly with the level of biodiesel present in the fuel.

6.1.4 The Fate of Biomass Carbon Leaving the Tailpipe of the Bus

Table 113 indicates actual measurements of carbon in biodiesel. The average carbon content is 77.2%. Biodiesel combusted in the bus engine contains carbon that is derived from biomass and from fossil fuels. Methanol chemically coupled to the fatty acids from soybean oil contains fossil carbon. The fatty acid portion of the methyl ester contains only biomass-derived carbon. The distinction is important in identifying the amount of CO_2 derived from biomass. This portion of the CO_2 emissions does not contribute to total CO_2 in the atmosphere because of its recycle in the production of soybean oil. As discussed in the section describing biodiesel production, biodiesel contains 73.2% biomass carbon and 4% fossil-derived carbon. Thus, 73.2% of the total CO_2 emitted at the tailpipe is recycled in the agriculture step of the life cycle for biodiesel[63].

In an engine that completely combusts the carbon in the fuel, all the carbon would end up in CO_2. As discussed in section 6.1.3, the emissions from diesel engines include PM10, CO, and NMHC, as well as CO_2. The carbon is partitioned among all four components. The carbon partitioned in CO is estimated as the product of the total mass of CO times the percent carbon in each molecule. The percent carbon in CO is 42.9%[64]. The complex natures of the CH and PM make this calculation more difficult. We used data from Sharp (1996) to estimate the composition of these components[65].

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[63] This assumes that biomass carbon and fossil carbon partition equally among the carbon containing combustion products.

[64] %C in CO = MW_C/MW_{CO} = 12/(12+16) = 42.9%.

[65] Sharp, Christopher A. *Emissions and Lubricity Evaluation of Rapeseed Derived Biodiesel Fuels.* Report SwRI #7507. Southwest Research Institute, San Antonio, TX, December 1996.

Table 113: Analytical Data for Soy Methyl Ester

	wt%		
Study	C	H	O
FEV (1994)	78	11.5	10
GRABOSKI (1994)	77.22	11.56	11.03
SCHUMACHER (?)	76.5	12.5	11
MCDONALD (1995)	77.55	11.56	10.88
MARSHALL (1994)	76.91	12.11	10.97
AVERAGE	77.24	11.85	10.78
STDEV	0.58	0.44	0.44
DIESEL	87	13	0

PM contains two basic components: soot and the volatile organic fraction (VOF). Soot is essentially 100% carbon resulting from pyrolysis reactions during combustion. The amount of soot present in the particulates is strongly affected by the amount of biodiesel-derived oxygen in the fuel. Sharp (1996) includes data on the relative soot content of particulates for a range of biodiesel blends. The data from this study were used to develop a predictive correlation for soot content (see Figure 81). The parameters for the linear model developed using these data are shown in Table 114. The model predicts that 100% petroleum diesel emits PM containing 54% carbon as soot. B100 emits PM with only 30% carbon as soot, while blends contain soot at levels between the values for each neat fuel.

Table 114: Percent Soot as a Function of Percent Oxygen in Fuel

Parameter	Value
Slope	-2.437
Intercept	54.179
R-Square	0.933

Sharp reports that the VOF is dominated by long-chain alkanes and alkenes. We estimated the carbon content of these compounds to be 85%.[66] Sharp also reports speciated data for the HC from the tailpipe. The analytical results were quantitative for HC with a carbon number of 12 or lower. An evaluation of the distribution of C1 through C12 paraffins, olefins, and aldehydes reported in this study indicates an average carbon content of around 72%. The higher carbon number compounds were assumed to be 85% carbon.

Using the emission correlations in Figure 78, Figure 79, and Figure 80, in conjunction with the carbon content estimates for each pollutant, we calculated the amount of carbon that is tied up in CO, PM, and

[66] Based on molecular weight, alkanes from C10 to C18 contain 85% carbon. Long chain alkenes with one double bond contain 86% carbon.

HC. The remainder of the carbon is assumed to be CO_2. The carbon balanced closed within 1.5%, which provides an estimate of robustness to this analysis.

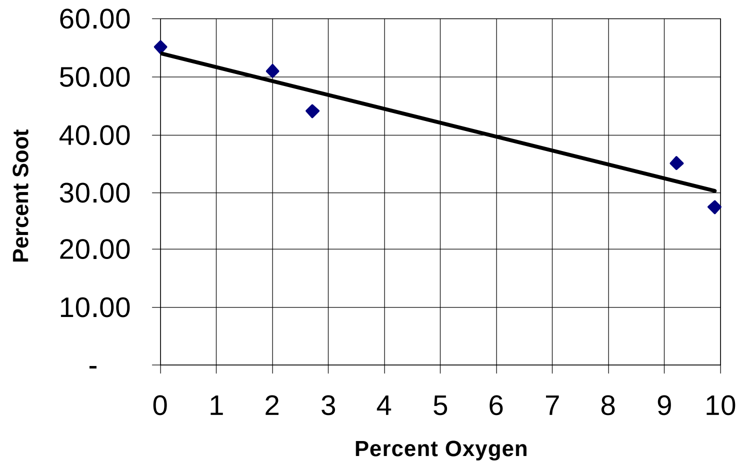

Figure 81: Correlation for Soot Content in PM as a Function of Oxygen Content

6.1.5 Biodiesel Combustion Results

Table 115 shows estimates from the LCI model for emissions from petroleum diesel and biodiesel blends based on the linear models described in section 6.1.4. The diesel fuel baseline emissions are outlined in Section 6.2.2, the biodiesel emissions are based on the formulas described earlier. The change in tailpipe emissions resulting from the biodiesel use is assumed to be linear. Therefore, emissions for other biodiesel blends can be extrapolated from the results shown in Table 115.

Table 115: Effect of Biodiesel on Tailpipe Emissions (g/bhp-h)

Emission	Diesel Fuel Baseline	20% Biodiesel Blend	100% Neat Biodiesel
Carbon Dioxide (fossil)	633.28	534.10	136.45
Carbon Dioxide (biomass)	0	108.7	543.34
Carbon Monoxide	1.2	1.089	0.6452
Hydrocarbons	0.1	0.09265	0.06327
Particulate Matter (PM10)	0.08	0.0691	0.02554
Sulfur Oxides (as SO_2)	0.17	0.14	0
Nitrogen Oxides (as NO_2)	4.8	4.885	5.227

6.2 Diesel Fuel Combustion

The LCI modeling of combustion of diesel fuel in an urban bus is composed of the amount of diesel fuel required to supply 1 bhp-h, and the emissions from the tailpipe of the bus. The amount of diesel fuel required depends on the fuel economy of the bus engine. The emissions depend on many factors, including the type of engine, but in this study we have assumed that they equal the EPA standards for diesel emissions from heavy duty vehicles. The following sections outline how this diesel combustion is modeled.

6.2.1 Diesel Fuel Economy

The fuel economy of the diesel bus is based on combustion in a modern four-stroke diesel engine. The fuel economy for petroleum diesel is based on data collected by Graboski (1997). Fuel economy was determined for a four-stroke diesel engine operating on a range of fuels including low- sulfur diesel and blends of biodiesel from 20% to 100%. A more specific discussion of the data analysis for fuel economy is presented in section 6.1.2. The work by Graboski demonstrates that fuel economy does not vary as a function of biodiesel blended in the fuel. We use an average of the data collected from this study as the fuel economy for the diesel engine independent of fuel choice. Fuel economy can vary from engine to engine. This approach allows us to compare relative performance of the two fuels using the same engine data for fuel economy. These were by fuel mass and by the emissions-based carbon balance for EPA transient testing. The fuel economy for our combustion model is 7,250 Btu/bhp-h, or 7.5 MJ/bhp-h.

The lower heating value of #2 low-sulfur diesel fuel is used to determine the amount of fuel needed per functional unit. The lower heating value of diesel fuel is assumed to be 43.5 MJ/kg. Therefore, 0.172 kg of diesel fuel are required per brake horsepower hour of engine use.

6.2.2 Tailpipe Emissions

Our early modeling of the emissions from diesel engines was based on EPA's 1994 standards for diesel engines. Based on feedback during the final review process, we switched from the 1994 standards to actual data for 1994 engines as certified by the engine manufacturers with EPA. It turns out that emissions from 1994 engines were, for some pollutants, much lower than what was allowed under the standards.

Table 116 compares certification data for the Series 50 and Series 60 engines to the 1994 standards. These engines actually have much lower emissions of NMHC and CO. They are almost identical in emission performance. The Series 50 engine data was used as the basis for comparing low-sulfur #2 diesel fuel and biodiesel blends. SO_x emissions are calculated by assuming all the sulfur in the diesel fuel is converted to SO_2. The sulfur content of #2 low-sulfur diesel fuel is assumed to be 0.05 % by weight.

6.3 Combustion End-use Results

The only environmental flows tracked in the end-use system of the TEAM™, model are the air emissions. Refer to Table 115 for a summary of the emissions for petroleum diesel, B20, and B100. All emissions are reported on the basis of 1 bhp-h.

Table 116: 1994 U.S. EPA Emission Standards for Diesel Engines versus Engine Certification Data[67] for Two Common Urban Bus Engines (g/bhp-h)

Pollutant	1994 EPA Emission Standards for Diesel Engines	1994 Engine Certification Data for Detroit Diesel Series 60 (11.1 liter) Engine	1994 Engine Certification Data for Detroit Diesel Series 50 (8.5 liter) Engine
NMHC	1.3	0.1	0.1
CO	15.5	1.2	1.1
NO_x	5.0	4.9	4.8
PM10	0.05	0.06	0.08

[67] U.S. Environmental Protection Agency. *1994 Summary Report: Diesel Heavy Duty Engines*. August 24, 1994. Downloaded from the EPA Office of Mobile Sources web site at www.epa.gov/omswww/gopher.