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Effects of Biodiesel Fuels Use on Vehicle Emissions

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Abstract: Many countries are using and considering the increased use of biodiesel blended fuels to slow their growth of fossil fuel use for transportation purposes. Before the use of these fuels increase, it is critical that we understand the effect of using biodiesel blends on vehicle emissions, so that we better understand what air quality impacts to expect. Many previous reviews of biodiesel effects on emissions have combined all of the emissions data available to find a single value for the effects of a biodiesel blend on pollutant emissions. This includes combining emissions data from both light-duty (LD) and heavy-duty (HD) diesel vehicles and engines, combining vehicle data from chassis dynamometer and on-road emissions testing, and combining data using different oil feedstocks for producing biodiesel fuels.

In this review, the effects of switching from petroleum diesel fuel to biodiesel blended fuels on relative vehicle emissions for LD and HD vehicles are determined separately. We will not include engine emissions data in this analysis. For HD vehicles, we will also separate results for on-road emissions testing from chassis dynamometer testing. For HD vehicles, hydrocarbon (HC) emissions were significantly lower for B20 and B100 fuels from dynamometer and for B20 fuels from on-road emissions testing. For LD vehicles, there was no significant effect on HC emissions for B5, B10, B20, B30, B50 or B100 fuels. Nitrogen oxides (NO_x) emissions for HD dynamometer data was significantly higher for both B20 and B100, but no significant difference was found for the HD on-road emissions data. The NO_x emissions for the LD vehicles were significantly higher for B10, B20, B30, B50 and B100 blends. For carbon monoxide (CO) emissions there was no significant effect for B20 and a significant decrease for B100 based on HD dynamometer data, and a significant decrease for B20 based on HD on-road emissions data. LD dynamometer data found a significant decrease in CO emissions only for B20 blends. No significant effect was found for carbon dioxide (CO_2) emissions for HD vehicles using B20 fuels based on dynamometer or on-road emissions data. For LD vehicles a significant decrease in CO_2 emissions was found only for the B10 blend. Particulate matter (PM) emissions were significantly lower for B20 fuel in HD vehicles for both types of emissions tests. PM emissions decreased significantly for LD vehicles for B10, B20, B30 and B50 blends only. The HD dynamometer data showed a significant decrease in fuel economy for the B20 blend, but no significant effect was observed for either the HD on-road or LD dynamometer data. When the effects of a biodiesel blend on vehicle emissions in different categories were not significantly different, the results were combined to assess the effect of biodiesel use on the broader class of vehicles.

Keywords: Renewable fuels, Biodiesel, Vehicle emissions, Regulated air pollutants, Hazardous air pollutants.

1. Introduction

Many countries are evaluating a variety of alternative fuels for use in motor vehicles in an attempt to reduce greenhousegas emissions and to improve the energy security of the country. Biodiesel and other biofuels are substitute fuels capable ofreplacingfossil fuels on a large scale in the transportation sector. Althoughbiodiesel currently accounts for a small portion of the total dieselfuel used, increasing its use requires that we understand the impact that biodiesel could have on vehicle emissions, and ultimately on air quality. The focus of this review is on exhaust emissions from heavy-duty (HD) diesel vehicles that have a gross vehicle weight rating of more than 8500 lb in the USA or over3500 kg in Europe, and on light-duty (LD) diesel vehicle emissions.

The production of first-generation biofuels - such as sugarcane ethanol in Brazil, corn ethanol in USA, rapeseed biodiesel in Germany, and palm oil biodiesel in Malaysia - is well understood. The global demand for liquid biofuels more than tripled between 2000 and 2007. Driven by supportive policy actions of national governments, biofuels now account for over 1.5% of global transport fuels, around 34 Mtoe (metric ton of oil equivalent) in 2007 [1]. Vehicle fuel use data for the USA in 2008 suggested that ethanol use in gasoline blends was about 4.8% of the total gasoline used as transportation fuels, and that biodiesel use in diesel blends was about 0.8% of the total diesel used as transportation fuels [2-3]. Use of biofuels in some European countries is much higher, up to 10.9% in Germany and 5.6% in Sweden[4].

Vehicle emissions are affected by the fuel that is used. There have been several reviews of the effects of biodiesel fuel use on emissions, but many of these have used engine emissions tests in addition to/or instead of vehicle emissions tests [5-8]. Emission measurement methods typically include engine and chassis dynamometer tests, tunnel studies, and more recently, remote sensing and portable (or on-board) emissions monitoring systems. Engine dynamometer studies are quite useful for research purposes, but because these systems test only the engine, they are missing many factors that may affect the real-world emissions of vehicles. Chassis dynamometer studies test the entire vehicle and can use realistic driving cycles which producemore representative emissions results. Chassis dynamometer testing is more complicated and expensive than engine testing, so less of this data is available. Remote sensing and on-board emissions measurements have also been used to assess the effects of using different fuels on vehicle emissions. Remote sensing uses spectroscopic measurements of a vehicle that passes through the light beam to measure the concentrations of emitted pollutants. These measurements provide only a snapshot of the emissions at a particular location and thus cannot characterize an entire operating cycle for a vehicle. On-board emissions measurement systems offer the advantage of being able to capture real-world emissions during an entire operating cycle for the vehicle. In this review, we will focus on vehicle emissions data that is more representative of real-world operating conditions, from chassis dynamometer and on-board emissions measurement systems.

Previous studies have found that vehicle emissions can be quite variable. Data have been analyzed from a number of vehicle emissions tests, including chassis dynamometer, no-load idle tests, and on-road tests [9]. These data showed that the low emitting vehicles generally exhibit low emissions variability. On the other hand, it was found that some high emitters show high variability no matter what testing procedure was used. This finding is surprising, since it was expected that longer tests would show more consistent measurements from one test to another. It is apparent that the vehicle, not the test, is the dominant source of the large observed test-to-test emissions variability [9]. It has been found that the emissions of some vehicles are not consistent: different emissions occur from one test to another, even when test conditions are carefully controlled[10]. There are many emissions control components that can malfunction or fail. Different component malfunctions result in very different emissions. While some emissions control failures, such as a completely degraded catalyst, can lead to high emissions during all vehicle operation, other failures can be intermittent. Intermittent control system malfunctions can cause large changes in emissions from test to test, even when all factors are held constant. This results in a large uncertainty in the average emissions from such a vehicle [10].

Historically, in both the USA and Europe, HD diesel engines have been regulated for smoke opacity, nitrogen oxides (NO_x), particulate matter (PM), carbon monoxide (CO), and hydrocarbons (HC). Current standards also specify emission limits for non-methane hydrocarbons (NMHC). The U.S. Environmental Protection Agency (EPA), in its national emissions inventory [11], estimates that diesel vehicles emitted only 4% of total on-road HC and only 3% of on-road CO in1998. However, diesel vehicles were responsible for 60% of on-road emissions of $PM_{10}$and 34% of on-road NO_x. During this same year, diesel fuel use in vehicles was about 21% of the total vehicle fuel use [12]. Diesel vehicles are a less important contributor to CO and HC emissions, but a more important contributor to NO_x and PM_{10} emissions than would be expected based on the quantities of vehicle fuels consumed. By 2005 in Europe, about 60% of the fuel used for vehicles was diesel fuel. Diesel vehicles can be a very significant contributor to on-road vehicle emissions.

Biodiesel is a renewable fuel consisting of mono-alkyl esters of long-chain fatty acids produced from plant oils, animal fats, or recycled cooking oils. In the USA, biodiesel intended for use in blends of up to 20% by volume must meet the most recent version of the ASTM International Standard for Biodiesel, ASTM D6751. In Europe, the applicable standard is EN14214, which applies to biodiesel intended for use in a blend or as a neat fuel. Today, B20 (20% biodiesel, 80% petroleum diesel) is one of the most commonly used form of biodiesel in the USA because it provides a good balance between material compatibility, cold-weather operability, performance, emission benefits, and costs [2]. The B20 blend can be used in most diesel engines with no modifications.

There have been several extensive reviews of the effects of biodiesel blended fuels on emissions of pollutants. One of theearlier of these reviews was conducted by the U.S. Environmental Protection Agency [13]. This report analyzed impacts of biodiesel blends in HD highway diesel engines. Using B20 blends of soy-based biodiesel, the HC emissions changed by -21.1%, the NO_x emissions changed by +2.0%, the CO emissions changed by -11.0%, and the PM emissions changed by -10.1%. This report showed that the emissions with soy-based biodiesel blend differed from those of rapeseed and animal-based biodiesel.

Yanowitz and McCormick [7] reviewed the effects of biodiesel blended fuels on the emissions of North American HD diesel engines. This analysis included the results of the earlier EPA study [13] augmented by a number of more recent studies. This study concluded that B20 biodiesel blends led to a change in HC emissions of -16%, a change in NO_x emissions of +2%, a change in CO emissions of -15%, and a change in PM emissions of -14%.

Another recent review by Hoekman et al. [8] analyzed vehicle and engine emissions data, and segregated this data into biodiesel blended fuel effects on HD and LD diesel. The effects of B20 and B100 blends on the emissions from HD diesel were -21.2% and -40.4% for HC emissions, -0.6 and +3.0% for NO_x emissions, -18.7% and -23.2% for CO emissions, and -24.1% and-42.2% for PM emissions. The effects of B20 and B100 blends on the emissions from LD diesel were -17.4% and -22.5% for HC emissions, +10.8 and +15.3% for NO_x emissions, -10.4% and -12.2% for CO emissions, and -13.9% and -32.1% for PM emissions. The study showed large differences between the emissions results for LD compared to HD diesel. The NO_x emissions increased much more for LD diesel than for HD diesel, and the decreases observed for HC, CO and PM emissions were much smaller for LD diesel than HD diesel.

In the current study, only vehicle emissions data will be used and the data will be segregated into that for HD and LD vehicles for analysis. To the extent feasible, the data will be further segregated to assess differences in results between dynamometer and on-road testing using portable emissions monitoring systems for HD vehicles. For LD vehicles, there are larger quantities of dynamometer data available and very little on-road testing data, hence only dynamometer data will be analyzed for LD vehicles. The LD emissions data will be used to assess differences in results of smaller engine diesel vehicles (<3L displacement) more commonly manufactured and used in Europe and Asia compared to larger engine diesel vehicles more commonly manufactured in North America. The effects of different biodiesel fuel feedstocks on the vehicle emissions will also be explored. When significant differences in the emissions cannot be detected, the data sets will be combined to assess the effects of biodiesel fuel use on a broader class of vehicle emissions. Often significant differences cannot be properly assessed due to the lack of adequate quantities of data in the various categories.

2. Analysis Approach

In this paper, the impact of biodiesel fuel use will be assessed by looking at the relative value of a property, such as pollutant emissions from biodiesel fuel use to that from petroleum diesel fuel use for a particular vehicle. This reduces some of the variability in analyzing vehicle emissions data, since vehicles that emit larger or smaller quantities of a pollutant when using diesel fuel are expected to also emit larger or smaller quantities of that pollutant when using a biodiesel blended fuel. If the use of biodiesel fuels does not affect the property being studied the relative value for that property will be 1. For example, a value of 1.12 indicates that the property changed by +12% with biodiesel fuel use and a value of 0.89 would indicate a changeof-11% with biodiesel fuel use. The relative values (numbers greater than or less than 1) will be used in the graphical representation of the effects; otherwise % changes will be presented.

In determining which of the available diesel/biodiesel vehicle emissions data would be included in these analyses, the goal was to include as much data as was available. Some data for emissions of a specific pollutant were excluded from analysis because this data was found to be an outlier. No more than one or two emissions measurements for any pollutant were excluded from further analysis in the LD or HD diesel vehicle emissions categories. One fairly extensive data set for LD diesel emissions was excluded from the analysis, because several months elapsed between the time the vehicles were tested with conventional diesel fuel and the tests with biodiesel blends. This data set was excluded from the analysis, because it added more variability and bias to the results.

In this analysis, at least 20 valid measurements were required to assess statistical significance. This minimum number of measurements was used in an attempt to assure the representativeness of the data. These relative emissions and fuel economy data were tested for normality using the Lilliefors test. These data were found not to be significantly different from a normal distribution. This allows the use of conventional statistical techniques in these analyses.

3. Heavy-Duty Diesel Vehicle Emissions

HD diesel vehicle emissions have been measured using chassis dynamometers, as well as on-road using portable emissions monitoring systems (PEMS). An extensive quantity of data exists for biodiesel blended fuels using both of these systems. Much of the data for HD diesel vehicle emissions is from studies conducted in North America. Many of the chassis dynamometer studies are for emissions from transit and school buses, and from long-haul HD diesel tractors. The PEMS emissionsstudies included many more construction related vehicles (dump trucks, cement mixers, graders, etc.). Neither data set included many urban diesel delivery vehicles.

3.1 Heavy-Duty Diesel Chassis Dynamometer Studies

The data used to assess the effect of biodiesel fuels use on HD vehicles from dynamometer studies comes from 19 different studies using 42 vehicles and includes 124 different pairs of tests. Several tests were conducted on the same vehicles, involving changes in the base fuel, the biodiesel blended with the base fuel, and the driving conditions. Seventy of these paired tests involved the use of a wide range of different dynamic driving cycles, while the remainder of the tests was steady-state tests conducted at different constant speed and load conditions.

The relative emissions of HC, NO_x, CO, carbon dioxide (CO_2), PM and fuel economy from chassis dynamometer test of HD vehicles using various biodiesel blended fuels have been analyzed [14-32]. Some data is available for different percentages of biodiesel, but most of the data are for 20% blends of biodiesel with petroleum diesel (B20) and neat biodiesel (B100) fuels. For the relative emissions and fuel economy, there is considerable scatter in the ratio both above and below 1. Table 1 shows an assessment of the significance of the biodiesel blended fuel effect on the HD vehicle emissions from chassis dynamometer studies. Since a total of 20 valid measurements are required in order to assess the significance of the effect of biodiesel blended fuels on a measurement, only HC, NO_x and CO had sufficient data for the assessment of both B20 and B100 biodiesel, while sufficient data was available for B20 blends to also assess the significance of the effects on CO_2, PM and fuel economy. For these HD vehicles, the use of biodiesel led to asignificant decrease for hydrocarbon emissions for B20 and for B100, no significant effect for CO emissions for B20 and a significant decrease for B100, and a significant increase in NO_x emissions for both B20 and B100. The use of B20 blended fuels also led to a decrease for CO_2 emissions that was not significant, for PM emissions and for fuel economy there was a significant decrease. There was an insufficient quantity of emissions test data for other biodiesel blends to characterize the variability in the emissions data, and to allow one to reliably assess the significance of other biodiesel blends on the emissions of HD vehicles tested using chassis dynamometers.

3.2 Heavy-Duty Diesel On-Road Vehicle Emissions Studies

The data used to assess the effect of biodiesel fuels use on HD vehicles from on-road vehicle emissions studies comes from 14 different studies using 50 vehicles and includes 94 different pairs of tests. Several tests were conducted on the samevehicles, involving changes in the base fuel, the biodiesel blended with the base fuel, the load on the vehicle and the driving conditions. Almost all of the relative emissions from on-road HD vehicle emissions studies of HC, NO_x, CO, CO_2, PM and fuel economy effects are for B20 biodiesel blended fuels [24, 33-45]. As was seen with the dynamometer data, there is considerable scatter in the ratio both above and below the ratio of 1.

Table 1. Effects (±95% confidence interval) and significance of biodiesel blends on the vehicle emissions and fuel economy for chassis dynamometer data with heavy-duty vehicles. A minimum of 20 measurements of a particular blend were required to assess the significance of the effect.

Emission	Biodiesel Blend	Effect ± 95% C.I.	Number of Measurements	Significant Effect[a]
HC	B20	-5.7 ± 4.4%	101	Lower
HC	B100	-23.0 ± 9.2%	54	Lower
NO_x	B20	+3.5 ± 2.3%	105	Higher
NO_x	B100	+9.0 ± 2.8%	57	Higher
CO	B20	-4.1 ± 6.4%	93	NS
CO	B100	-24.0 ± 7.2%	46	Lower
CO_2	B20	-0.4 ± 1.0%	52	NS
PM	B20	-13.3 ± 5.1%	67	Lower
Fuel Economy	B20	-2.6 ± 1.2%	46	Lower

[a] NS – not significant

Table 2 shows an assessment of the significance of the biodiesel blended fuel effect on the HD vehicle emissions based on on-road emissions studies. Since we are requiring a total of 20 valid measurements in order to assess the significance of the effect of biodiesel blended fuels on a measurement, only the significance of B20 blends can be assessed. For these HD vehicles, the use of B20 blends led to a significant decrease for hydrocarbon emissions and CO emissions, and a decrease in NO_x emissions that was not significant. The use of B20 blended fuels also led to no significant effect for CO_2 emissions and fuel economy, and a significant decrease for PM emissions.

Table 2. Effects (±95% confidence interval) and significance of biodiesel blends on the vehicle emissions and fuel economy for on-road vehicle tests with heavy-duty vehicles. A minimum of 20 measurements of a particular blend were required to assess the significance of the effect.

Emission	Biodiesel Blend	Effect ± 95% C.I.	Number of Measurements	Significant Effect[a]
HC	B20	-21.7 ± 4.4%	89	Lower
NO_x	B20	-3.3 ± 3.4%	92	NS
CO	B20	-6.6 ± 5.4%	90	Lower
CO_2	B20	+3.0 ± 3.6%	83	NS
PM	B20	-15.2 ± 6.0%	70	Lower
Fuel Economy	B20	+6.3 ± 8.1%	35	NS

[a] NS – not significant

One of the major complications of the on-road PEMS testing for evaluating different fuels is the much poorer matching of the operating conditions of the vehicles with these different fuels. This was especially apparent with some of the testing of non-road construction equipment reported by Frey, et al. [46]. From this work, it was found that vehicle emissions were strongly correlated with the operating load on the equipment. This is difficult to control under real-world conditions, especially for non-road construction equipment. Results for this type of equipment were not included in the data analyzed for this assessment. All of the test data reported in this work is for on-road vehicles and was for matched duty cycles (equipment activity), but engine load can be quite variable, and is expected to increase the variability in the results.

3.3 Differences between Chassis Dynamometer and On-Road Heavy-Duty Vehicle Emissions Data

A two-sample t-test was used to determine if the results of the chassis dynamometer and on-road HD vehicle emissions data were significantly different. It was found that there was no significant difference in the results of the two emissions test methods for the CO, CO_2 and PM data using B20 blends. However, the results were significantly different for the HC, NO_x and fuel economy data between the two data sets. For the HC data, B20 blends led to a significant decrease in HC emissionsin both cases, but only about -5.7% for the dynamometer studies and -21.7% for the on-road studies. The decrease from the on-road studies with B20 were similar to the effects of B100 seen with the dynamometer data. For the NO_x data, B20 blends led to a significant increase in NO_x emissions of about +3.5% for the dynamometer studies, while it led to a -3.3% change (not significant) in NO_x emissions in the on-road studies. The data continues to support an increase in NO_x emissions with biodiesel blends in HD diesel vehicles. In the case of the fuel economy data, B20 blends led to significantly lower fuel economy of about -2.6% from the dynamometer studies, but led to a +5.7% change (not significant) in fuel economy for the on-road studies. The data continues to support a decrease in fuel economy with B20 biodiesel blends in HD vehicles.

Since there was no significant difference in the results of the dynamometer and on-road emissions studies using B20 blends for the HD vehicle emissions of CO, CO_2 and PM, these data sets were combined and the significance of the effects on this larger, pooled data set were assessed. For the CO emissions data with B20, a -4.1% change (not significant) was found from the dynamometer studies and a significant -6.6% change was found from the on-road studies. With the combined data set, a significant change of -5.3±4.1% was found for CO using B20 blends. For the CO_2 emissions data with B20, a -0.4% change (not significant) was found from the dynamometer studies and a +3.0% change (not significant) was found from the on-road studies. With the combined data set, a +1.6±2.2% change (not significant) was found for CO_2 using B20 blends. These data support the conclusion that the use of B20 biodiesel fuels has no significant effects on the emissions of CO_2. For the PM emissions data with B20, a significant -13.8% change was found from the dynamometer studies and a significant -15.2% change was found from the on-road studies. With the combined data set, a significant change of -14.5±3.9% was found for PM using B20 blends.

4. Light-Duty Diesel Vehicle Emissions

LD diesel vehicle emissions have been measured almost exclusively by use of chassis dynamometers. PEMS have not been used extensively in the study of LD diesel vehicle emissions. The available data consists of a number of studies conducted in North America, Europe, Asia and Australia. The studies conducted in North America tend to be dominated by studies of vehicles with larger engines, including pickup trucks, while those elsewhere in the world include a larger fraction of cars, passenger and delivery vans equipped with smaller engines. This data set also includes biodiesel fuels that are made from different biooilfeedstocks (soy, rapeseed, canola, palm, coconut, used cooking oils, animal fats, etc.). The emissions test data for LD vehicles contains many more tests with varying biodiesel percentages, not just B20 and B100.

4.1 Light-Duty Diesel Chassis Dynamometer Studies

The data used to assess the effect of biodiesel fuels use on LD vehicles from dynamometer studies comes from 47 different studies and includes 259 different paired tests. Several of these paired tests used several different biodiesel percentages, with all other fuel, vehicle and test conditions remaining unchanged. There is a large quantity of data available for the relative emissions of HC, NO_x, CO, CO_2, PM and fuel economy effects of using various biodiesel blended fuels for LD vehicles [16, 28, 30, 47-90]. For the regulated pollutant emissions, there are more than 20 sets of test results available for the B5, B10, B20, B30, B50 and B100 biodiesel blends. This allows the evaluation of statistical significance of the effects of these blends on vehicle emissions.

Table 3 shows an assessment of the significance of the biodiesel blended fuel effect on the LD vehicle emissions based on chassis dynamometer emissions studies. For the hydrocarbon emissions the effects of the biodiesel blends varied with both increases and decreases in hydrocarbon emissions, but none of the observed effects are statistically significant. For NO_x emissions the effects of the biodiesel blends resulted in an increase for B5 that was not statistically significant, and a statistically significant increase for all of the other blend levels (B10, B20, B30, B50 and B100). The effect of the biodiesel blends on CO emissions led to a decrease for B5, and increases for B10, B30, B50 and B100that were not statistically significant. For the B20 blend, the CO emissions had a statistically significant decrease. For the CO_2 emissions the effects of the biodiesel blends were a decrease for B5 and B20, and increases for B30, B50, and B100 that were not statistically significant. The B10 blend shows a small statistically significant decrease in CO_2 emissions. The effect of the biodiesel blends on PM emissions show decreases for B5 and B100 that are not statistically significant. Significant decreases in PM emissions were found for the B10, B20, B30

Table 3. Effects (±95% confidence interval) and significance of biodiesel blends on the vehicle emissions and fuel economy for chassis dynamometer data with light-duty vehicles. A minimum of 20 measurements of a particular blend were required to assess the significance of the effect.

Emission	Biodiesel Blend	Effect ± 95% C.I.	Number of Measurements	Significant Effect[a]
HC	B5	-1.6 ± 4.5%	28	NS
HC	B10	+4.2 ± 5.2%	68	NS
HC	B20	-4.1 ± 5.5%	103	NS
HC	B30	-0.3 ± 5.4%	47	NS
HC	B50	+0.9 ± 10.3%	52	NS
HC	B100	-5.8 ± 14.8%	68	NS
NO_x	B5	+1.1 ± 2.7%	30	NS
NO_x	B10	+5.1 ± 2.3%	82	Higher
NO_x	B20	+5.8 ± 2.2%	122	Higher
NO_x	B30	+7.2 ± 2.7%	61	Higher
NO_x	B50	+7.3 ± 3.5%	64	Higher
NO_x	B100	+6.5 ± 3.5%	86	Higher
CO	B5	-0.7 ± 2.9%	28	NS
CO	B10	+2.7 ± 5.9%	41	NS
CO	B20	-5.5 ± 3.5%	103	Lower
CO	B30	+4.8 ± 6.0%	44	NS
CO	B50	+4.7 ± 10.8%	49	NS
CO	B100	+12.9 ± 14.3%	68	NS
CO_2	B5	-2.0 ± 2.3%	21	NS
CO_2	B10	-1.1 ± 0.9%	70	Lower
CO_2	B20	-0.4 ± 1.2%	70	NS
CO_2	B30	+1.1 ± 1.4%	35	NS
CO_2	B50	+1.2 ± 1.3%	49	NS
CO_2	B100	+0.8 ± 1.4%	42	NS
PM	B5	-1.0 ± 5.0%	25	NS
PM	B10	-14.8 ± 3.5%	68	Lower
PM	B20	-5.8 ± 4.9%	109	Lower
PM	B30	-16.0 ± 3.6%	49	Lower
PM	B50	-9.1 ± 8.6%	57	Lower
PM	B100	-7.0 ± 14.8%	67	NS
Fuel Economy	B5	-0.4 ± 1.2%	22	NS
Fuel Economy	B10	-0.3 ± 1.0%	42	NS
Fuel Economy	B20	-1.0 ± 1.8%	48	NS
Fuel Economy	B30	-1.3 ± 2.0%	27	NS
Fuel Economy	B50	-1.9 ± 2.5%	37	NS

[a]NS – not significant

and B50 blends, and they are relatively large effects in the range of 6-16% decrease. For the fuel economy results, the B5, B10,B20, B30 and B50 blends had a sufficient quantity of data (morethan 20 values) to assess the significance of the effects. The fuel economy was found to decrease (or fuel consumption increased) for all of these blends, but none of the fuel economy effects were statistically significant.

Table 4 shows an assessment of the significance of the biodiesel blended fuel effect on the LD vehicle emissions for some hazardous air pollutants, based on the chassis dynamometer emissions studies [16, 49-55, 60-61, 63-65, 67, 69, 72, 75, 87, 91-94]. Only a few biodiesel blends had a sufficient quantity of data (more than 20 values) to assess the significance of the effects on emissions of formaldehyde, acetaldehyde or total polycyclic aromatic hydrocarbons (PAH). Smaller quantities of data were available for benzene, 1,3-butadiene, elemental and organic carbon emissions, so the effects of the use of biodiesel blends on emissions of these pollutants will not be discussed. The effects of the biodiesel blends on formaldehyde emissions resulted in statistically significant increases for B10, B20 and B30 blends in the range of 25-35%. The effects on acetaldehyde emissions also suggested increases for B10 and B20 blends of 40-70%, but these were not statistically significant. A statisticallysignificant change of +23.1±7.2% for B30 was found. There was considerable variation in the formaldehyde and even greater variability in the acetaldehyde emissions, but the increases observed for formaldehyde emissions from B10, B20 and B30 blends and for acetaldehyde emissions for B30 were statistically significant. The effects of the biodiesel blends on the emissions of total PAH were mixed. For the B10 the total PAH emissions decreased significantly, but for B30 the total PAH emissions increased significantly, and no significant effect was observed for the B20 and B100 blends. These opposite and significant effects for PAH emissions for different biodiesel blends are likely to be due to a lack of sufficient representative data to adequately describe the effects.

Table 4. Effects (±95% confidence interval) and significance of biodiesel blends on the vehicle emissions of formaldehyde, acetaldehyde and total PAH for chassis dynamometer data with light-duty vehicles. A minimum of 20 measurements of a particular blend were required to assess the significance of the effect.

Emission	Biodiesel Blend	Effect ± 95% C.I.	Number of Measurements	Significant Effect[a]
Formaldehyde	B10	+28.9 ± 17.1%	47	Higher
Formaldehyde	B20	+27.5 ± 21.8%	36	Higher
Formaldehyde	B30	+34.9 ± 8.7%	35	Higher
Acetaldehyde	B10	+40.7 ± 76.1%	47	NS
Acetaldehyde	B20	+69.9 ± 126%	36	NS
Acetaldehyde	B30	+23.1 ± 7.2%	35	Higher
Total PAH	B10	-8.3 ± 6.4%	46	Lower
Total PAH	B20	-8.9 ± 9.8%	52	NS
Total PAH	B30	+21.2 ± 18.4%	44	Higher
Total PAH	B100	+33.4 ± 53.7	25	NS

[a] NS – not significant

4.2 Effect of Biodiesel Feedstock on Light-Duty Diesel Emissions

The LD vehicle test data had 20 or more sets of test data for some soy and rapeseed biodiesel blends, but smaller numbers of test results with the other biodiesel feedstocks. Table 5 summarizes the available results that allow one to explore the differences in the effects on emissions of the different biodiesel feedstocks. The hydrocarbon emissions from B20 blends of soybiodiesel showed a change in emissions of -4.3±10.2% that was not significant, while B20 rapeseed biodiesel resulted in a significant change of -10.6±7.9%. A two-sample t-test was used to assess the difference in the effectsof the pair of fuels, but the difference between the effects of B20 soy and B20 rapeseed on hydrocarbon emissions were not statistically significant. The effects of rapeseed biodiesel of hydrocarbon emissions for B10, B30, and B50 blends were not significant,but the B100 rapeseed blends resulted in a significant change of -20.9±19.3%. The NO_x emissions from B20 blends of soy and rapeseed biodiesel, the average effect was a significant change of +3.7±1.7% and a +3.2±4.8% change (not significant), respectively. There was no significant difference between the pair of B20 fuels for NO_x emissions. The effect of the B10 rapeseed blend on NO_x emissions was not significant, but theB30, B50 and B100 rapeseed blends resulted in significant increases. For the CO emissions from B20 blends of soy and rapeseed biodiesel, the average effect was a significant change of -6.4±5.6% and -9.6±6.5%, respectively. Again, there was no significant difference between the B20 fuels for CO emissions. The CO emissions for B30 rapeseed blends showed a significant increase, while the B50 and B100 rapeseed blends gave results that were not statistically significant. For PM emissions from B20 blends of soy and rapeseed biodiesel, the average effect was +3.5±10.7% and-0.8±9.5%, respectively. These results were not significant, and there was no significant difference between the pair of B20 fuels for PM emissions. Neither the B50 nor B100 rapeseed blends showed a significant effect on PM emissions. Sufficient data was not available for effects on CO_2 emissions or fuel economy to allow the effect of different feedstocks to be explored. A sufficient quantity of data for total PAH emissions were available for B20 soy biodiesel blends which resulted in a -22.2±13.2% significant change in emissions. These data suggest that there may be differences in the emissions effects between soy and rapeseed biodiesel with B20 blends, but the available data is insufficient to either identify significant differences or to validate that the results are significantly different. Insufficient data was available to explore the effects of other biodiesel feedstocks on vehicle emissions.

Table 5. Effects and significance of soy, rapeseed and palm biodiesel blends on the relative vehicle emissions for chassis dynamometer data with light-duty vehicles. A minimum of 20 measurements of a particular blend were required to assess the significance of the effect.

Emission	Biodiesel Blend	Effect ± 95% C.I.	Number of Measurements	Significant Effect[a]
HC	Rapeseed B10	+4.9 ± 5.0%	27	NS
HC	Soy B20	-4.3 ± 10.2%	39	NS
HC	Rapeseed B20	-10.6 ± 7.9%	28	Lower
HC	Rapeseed B30	+3.1 ± 5.7%	26	NS
HC	Rapeseed B50	+1.2 ± 15.7%	29	NS
HC	Rapeseed B100	-20.9 ± 19.3%	32	Lower
NO_x	Rapeseed B10	+0.9 ± 1.8%	27	NS
NO_x	Soy B20	+3.7 ± 1.7%	39	Higher
NO_x	Rapeseed B20	+3.2 ± 4.8%	28	NS
NO_x	Rapeseed B30	+4.5 ± 2.2%	26	Higher
NO_x	Rapeseed B50	+5.2 ± 4.3%	29	Higher
NO_x	Rapeseed B100	+5.7 ± 5.5%	33	Higher
CO	Soy B20	-6.4 ± 5.6%	39	Lower
CO	Rapeseed B20	-9.6 ± 6.5%	28	Lower
CO	Rapeseed B30	+11.6 ± 6.4%	23	Higher
CO	Rapeseed B50	+2.3 ± 16.6%	26	NS
CO	Rapeseed B100	-4.3 ± 19.3%	32	NS
PM	Soy B20	+3.5 ± 10.7%	35	NS
PM	Rapeseed B20	-0.8 ± 9.5%	21	NS
PM	Rapeseed B50	+6.4 ± 18.7%	20	NS
PM	Rapeseed B100	+4.5 ± 11.0%	26	NS
Total PAH	Soy B20	-22.2 ± 13.2%	21	Lower

[a] NS – not significant

4.3 Effect of Biodiesel Blends on Light-Duty Diesel Emissions with Larger and Smaller Engines

Segregating the LD vehicle emissions test data by engine sizereally segregates the data for several additional factors. The larger engine displacement vehicles were almost exclusively manufactured and tested in North America. This means that a larger fraction of these vehicles were tested with soy methyl ester fuels, than were the smaller engine displacement vehicles. Only B20 and B100 blends had a sufficient quantity of emissions test data in both engine sizes for comparison.

Table 6 summarizes the available results that allow us to explore the differences in emissions effects for different engine sizes and the other associated differences. The hydrocarbon emissions from both the larger engines (>3 L) and smaller engines (<3 L) with B20blends showed emissions decreases that were not significant. The hydrocarbon emissions for the larger engines showed a significant decrease for the B100 blend, but there was no significant effect for the smaller engines. A two-sample t-test was used to assess the statistical significance of the differences between the hydrocarbon emissions for the different engine sizes. The differences between these emissions results were not statistically significant. The NO_x emissions with B20 blends for both engine sizes showed significant increases, while for B100 the larger engine showed no significant effect and the smaller engine showed a significant increase. There was a statistically significant difference between the NO_x emissions for the smaller engine vehicles compared to the larger engine vehicles for both blends, with the relative increase in NO_x emissions for the smaller engine vehicles being greater. The CO emissions from B20 blends for the larger engine vehicles showed a significant decrease while the effect for the smaller engine was not significant. CO emissions with the B100 blend for the larger engine vehicles showed no significant effect and the smaller engine showed a significant increase. The difference in the CO emissions between the large and small engines for the B20 blend was not statistically significant, but the difference for the B100 blend was statistically significant, with the smaller engine having higher relative emissions. Sufficient data was available for CO_2 emissions from the large and small engines only for B20 blends. The CO_2 emissions changes for both engine sizes were not significant, nor were the difference between the results for the two engine sizes. PM emissions with the B20 blend in the larger engine showed no significant effect, while the smaller engine had a significant decrease in emissions. Again for B100, the PM emissions for the larger engine did not change significantly, while the emissions for the smaller engine vehicles decreased significantly. The difference between the results for the two engine sizes was not statistically significant for either the B20 or B100 blend.

5. Comparison of Heavy-Duty and Light-Duty Diesel Vehicle Emissions

The only comparison that can be made between HD and LD diesel vehicle emissions are for B20 blends, where sufficient data exists for the HD diesel dynamometer and on-road and LD dynamometer tests, and for HC, NO_x and CO emissions from B100 where sufficient data exists for HD and LD dynamometer tests. The results of these comparisons are shown in Table 7. For HC emissions, we have found that the emissions from HD vehicles in the on-road emissions studies are significantly lower than the HD dynamometer test results. The HD on-road emissions results are also significantly lower than the LD dynamometer results, and the HD and LD dynamometer results are not significantly different from each other. The HD and LD dynamometer results have been combined resulting in an overall HC emissions change of -4.9±3.5%for the B20 blend and of -13.4±9.2% for B100. Again for NO_x emissions, the HD on-road emissions results were significantly lower than the HD dynamometer results and were significantly lower than the LD dynamometer results. There was no significant difference between the HD and LD dynamometer results for NO_x. The HD and LD dynamometer results have been combined resulting in an overall NO_x emissions change of +4.7±1.6% for B20 and of +7.5±2.4% for B100. For CO emissions, the HD on-road emissions results were not significantly different than the HD dynamometer results, and the combined HD emissions results were not significantly different from the LD dynamometer results. The HD dynamometer and on-road emissions results and the LD dynamometer emissions results were combined for the B20 blend, resulting in an overall CO emissions change of -5.4±2.9%. The CO emissions from the B100 blend, the heavy-duty dynamometer results were significantly lower than the LD dynamometer results. For CO_2 emissions, the HD on-road emissions results were not significantly different than the HD dynamometer results, and the combined HD emissions results were not significantly different from the LD dynamometer results. The HD dynamometer and on-road emissions results and the LD dynamometer emissions results were combined for the B20 blend, resulting in an overall CO_2 emissions change of +0.9±1.5%. For PM emissions, the HD on-

Table 6. Effects and significance of biodiesel blends on the relative vehicle emissions for chassis dynamometer data with light-duty vehicles having larger (>3 L) and smaller (<3 L) engine displacements.Also presented is the significance of differences in emissions between the larger and smaller engines. A minimum of 20 measurements of a particular blend were required to assess the significance of the effect.

Emission	Engine Size	Biodiesel Blend	Effect ± 95% C.I.	Number of Measurements	Significant Effect[a]	Large – Small Engine Difference
HC	>3L	B20	-4.8 ± 8.4%	54	NS	Not Significant
HC	< 3L	B20	-2.0 ± 8.3%	42	NS	
HC	>3L	B100	-19.1 ± 18.6%	31	Lower	Not Significant
HC	< 3L	B100	+6.6 ± 22.9%	36	NS	
NO_x	>3L	B20	+3.9 ± 2.6%	61	Higher	<3 L Significantly Higher
NO_x	< 3L	B20	+8.7 ± 3.8%	54	Higher	
NO_x	>3L	B100	-1.3 ± 4.6%	37	NS	<3 L Significantly Higher
NO_x	< 3L	B100	+12.8 ± 4.7%	48	Higher	
CO	>3L	B20	-8.3 ± 5.1%	54	Lower	Not Significant
CO	< 3L	B20	-3.3 ± 5.3%	42	NS	
CO	>3L	B100	-11.4 ± 14.6%	31	NS	<3 L Significantly Higher
CO	< 3L	B100	+34.3 ± 22.3%	36	Higher	
CO_2	>3L	B20	-0.4 ± 1.4%	24	NS	Not Significant
CO_2	< 3L	B20	-0.4 ± 1.8%	46	NS	
PM	>3L	B20	-5.0 ± 8.6%	56	NS	Not Significant
PM	< 3L	B20	-7.5 ± 4.9%	49	Lower	
PM	>3L	B100	+10.9 ± 34.3	23	NS	Not Significant
PM	< 3L	B100	-16.5 ± 14.5%	43	Lower	

[a]NS – not significant

Table 7. Effects and significance of B20 biodiesel blends on the relative vehicle emissions for combinations of heavy-duty diesel vehicles based on chassis dynamometer and on-road emissions data,and for light-duty diesel vehicles based on chassis dynamometer data for sets of data that are not significantly different.

Emission	Biodiesel Blend	Tests	Effect ± 95% C.I.	Number of Measurements	Significant Effect[a]
HC	B20	HD & LD Dyno	-4.9 ± 3.5%	204	Lower
HC	B20	HD On-road	-21.7 ± 4.4%	89	Lower
HC	B100	HD & LD Dyno	-13.4 ± 9.2%	122	Lower
NO_x	B20	HD & LD Dyno	+4.7 ± 1.6%	227	Higher
NO_x	B20	HD On-road	-3.3 ± 3.4%	92	NS
NO_x	B100	HD & LD Dyno	+7.5 ± 2.4%	143	Higher
CO	B20	HD, LD Dyno& HD On-road	-5.4 ± 2.9%	286	Lower
CO_2	B20	HD, LD Dyno& HD On-road	+0.9 ± 1.5%	205	NS
PM	B20	HD Dyno& HD On-road	-14.5 ± 3.9%	137	Lower
PM	B20	LD Dyno	-5.8 ± 4.9%	109	Lower
Fuel Economy	B20	HD & LD Dyno	-1.8 ± 1.1%	94	Lower
Fuel Economy	B20	HD On-road& LD Dyno	+2.1 ± 3.6%	83	NS

[a]NS – not significant

road emissions results were not significantly different than the HD dynamometer results, but the combined HD emissions results were significantly lower than the LD dynamometer results. The HD dynamometer and on-road emissions results were combined for the B20 blend, resulting in an overall PM emissions change of -14.5±3.9%. The fuel economy of HD vehicles in the on-road studies is significantly higher than the HD dynamometer test results. The HD on-road fuel economy results are not significantly different from the LD dynamometer results, and the HD and LD dynamometer results are not significantly different from each other. The HD and LD dynamometer results have been combined for the B20 blend, resulting in an overall fuel economy change of -1.8±1.1%, and the HD on-road and LD dynamometer data have been combined with no statistically significant effect.

6. Trends in Vehicle Emissions with Increasing Biodiesel Percentage

The HD and LD diesel dynamometer data includes sufficient measurements with different percentages of biodiesel fuel to explore the effect of the increase in biodiesel in the fuel blend. Figure 1 shows the results of linear fits to the relative emissions for HC, NO_x, CO, CO_2, and PM, and change in relative fuel economy for the biodiesel blends compared to diesel fuel with increasing biodiesel percentage in the blend. For HD diesel dynamometer data, the decrease in HC, CO and PM emissions are statistically significant. The increase in NO_x emissions was also statistically significant. The decrease in CO_2emissions is not statistically significant. Each of these emissions the intercept is not significantly different from 1.For the biodiesel effect on fuel economy, the decrease is significant, as is the intercept being less than 1. Although this expression does not describe the effect of increasing biodiesel in the blend on fuel economy well, the data clearly suggest that biodiesel blends lead to a decrease in fuel economy in HD diesel vehicles.

Figure 1 also shows linear fits to the relative emissions for increasing biodiesel percentages for the LD dynamometer data. Neither the decrease in HC emissions nor the intercept are statistically significant for this data. For the NO_x emissions data, the increase in emissions with increasing biodiesel is not significant, but the intercept is significantly greater than 1. This relationship does not describe the effect well, but clearly NO_x emissions increase with biodiesel fuel use. For the CO emissions data, the increase in emissions with increasing biodiesel is significant, while the intercept of the fit is not significantly different from 1. For CO_2 emissions, both the increase in emissions with increasing biodiesel and the intercept for the relationship being less than 1 are significant. Again this relationship does not describe the effect well, and there is no clear effect of biodiesel use on CO_2 emissions. For PM emissions, the increase in emissions with increasing biodiesel is not significant, but the intercept is significantly less than 1. Again this relationship does not describe the effect well, and it appears that biodiesel use reduces PM emissions. The effect of biodiesel use on fuel economy shows a decrease with increasing biodiesel that is significant, and an intercept that is not significantly different than 1. This data clearly suggests that fuel economy decreases with increasing percentages of biodiesel in fuel blends.

Sufficient LD dynamometer exists for significance tests at five or six different biodiesel blend compositions, while the HD dynamometer data only has sufficient data at two different biodiesel blends. Some of the LD dynamometer data suggests that a linear description of the effect of fuel composition on emissions may not be appropriate. If one looks at the NO_x and PM emissions results in Figure 1, one might conclude that at biodiesel compositions above about 10-20%, the effect is largely independent of increasing biodiesel in the blend. Clearly, additional emissions data is required to allow one to better describe the relationship between vehicle emissions and biodiesel blended fuel use.

7. Other Observations

Many of the effects of biodiesel fuel use on vehicle emissions have not been studied adequately to allow significant conclusions to be drawn. There is sufficient data to be able to begin assessing the effects of biodiesel fuel use on the emissions of formaldehyde, acetaldehyde and polycyclic aromatic hydrocarbons. Adequate data does not exist to allow one to assess the effects of biodiesel fuel use on the emissions of other hazardous air pollutants, such as benzene, 1,3-butadiene, etc. As seen in this work and that of McCormick [5], sufficient data is not available to reliably assess the effects of biodiesel fuel use on the emissions of hazardous air pollutants. Adequate data is available to allow one to begin to assess the effects of biodiesel fuel use on the emissions of particulate mass, but adequate data is not available to allow one to begin to understand other changes in the PM emissions, such as organic and elemental carbon emissions, particle number and the particle size distribution in emissions. Kumar, et al [95-96] have discussed the effects of biodiesel fuel use on the increase in number of particles emitted and on decreasing the mean diameter of the particles emitted. That work also discussed the potential health and environmental effects of more and smaller particles in the atmosphere.

When we discuss the effects of biodiesel fuel use on vehicle emissions, we are treating all biodiesel fuels as if they are equivalent, but they are not. Many different biodiesel

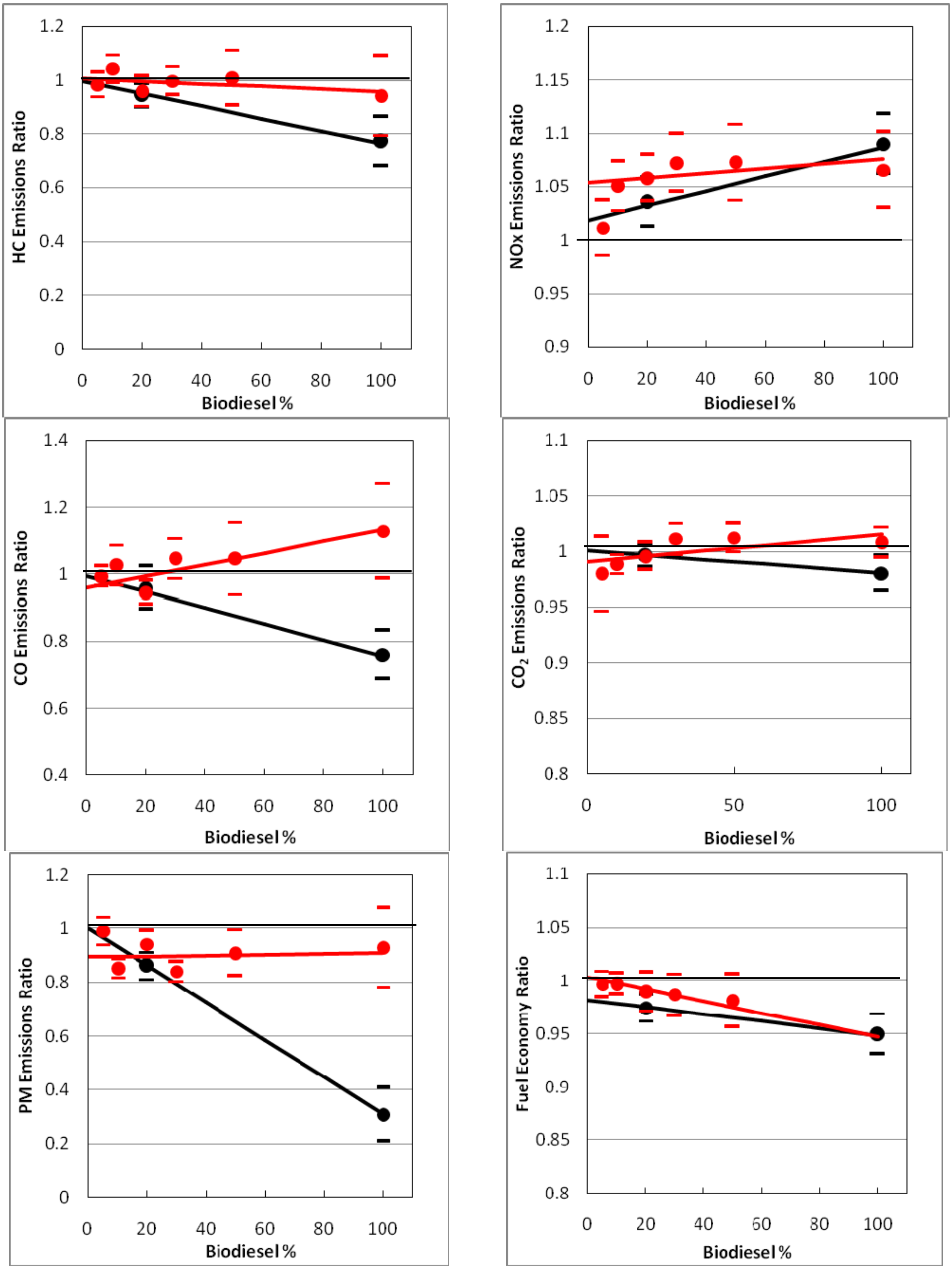

Figure 1. Best fit of relative emissions of hydrocarbons (a), nitrogen oxides (b), carbon monoxide (c), carbon dioxide (d), particulate matter (e), and vehicle fuel economy (f)versus biodiesel fuel percentage for heavy-duty (black line) and light-duty (red line) diesel vehicle dynamometer data.The mean effect (●) and 95% confidence intervals (□) for biodiesel blends for which sufficient data are indicated for the heavy-duty (black) and light-duty (red) diesel vehicle dynamometer data.

feedstocks are used in different parts of the world. Biodiesel commonly means soy methyl ester in the United States, rapeseed methyl ester in Europe, and palm methyl ester in the southern parts of Asia. Several previous studies [13, 97-98] have demonstrated different effects of various biodiesel fuels on engine emissions. In the current work, there is also an indication of such difference on vehicle emissions. But again, adequate data is not available to allow us to assess these effects for the range of first-generation biodiesel fuels that are currently in use.

8. Conclusions

Most reviews of the effects of biodiesel blended fuels use on emissions combine all of the available data engine and vehicle, LD and HD to assess the effects. As has been found in this work, this is not always a valid approach. In this work, we have only used vehicle emissions data, no engine data, and we have found some significant differences in subsets of this vehicle data.

It was found that some of the emissions for HD diesel vehicles tested using dynamometers and on-road techniques were significantly different. For B20 blends, the HC emissions for both test procedures led to significant decreases in these emissions, but also a significant difference between the dynamometer and the on-road emissions. In the cases of NO_x emissions studies, a statistically significant increase in NO_x emissions was found for B20 blends from the dynamometer data, while the on-road studies resulted in a decrease that was not significant. For fuel economy, the dynamometer data for B20 showed a significant decrease in fuel economy, while the on-road data gave an increase that was not significant. For each of these three pollutant and fuel economy effects for the two different sources of HD vehicle emissions data, the dynamometer data was significantly different from the on-road data. It is not valid to combine data from the dynamometer and on-road studiesof B20 blended fuels for HC and NO_x emissions and fuel economy to determine the effects of using these fuels in HD vehicles. But since the B20 data for CO, CO_2 and PM emissions derived from these two different test procedures are not significantly different; it is valid to combine these data sets to assess the overall effects of B20 on these emissions from HD vehicles.

In comparing the results of studies on LD and HD vehicles for B20 blends, we have found no significant differences in HC and NO_x emissions and fuel economy between the LD and HD dynamometer studies, and we have found no significant differences in emissions of CO and CO_2 between the LD dynamometer and the combined HD dynamometer and on-road test data. But the PM emissions for B20 fuels are significantly different between the LD dynamometer and the combined HD dynamometer and on-road test data. Table 7 summarizes the statistically significant results for B20 blended fuels, where the HD and LD data are combined when there is no significant difference between the subsets of the data.

Both the HD and LD dynamometer data have sufficient emissions data at different biodiesel compositions to permit an assessment of the effect of biodiesel blend level on the relative vehicle emissions. These data were analyzed using a linear fit. For the HD test data, the effect of increasing biodiesel led to a significant decrease in HC emissions, but there was no significant effect for the LD test data. The NO_x emissions showed a significant increase with increasing biodiesel for the HD data, but the linear coefficient was not significant for the LD data, although the relative NO_x emissions were significantly greater than 1 at all biodiesel levels above B5. For the CO emissions from the HD data there was a significant decrease, while for the LD data there was a significant increase with increasing biodiesel blend levels. For the CO_2 emissions data, there was no significant effect of the biodiesel blend level for the HD or LD data. The PM emissions for the HD data showed a significant decrease with increasing biodiesel blends, but the PM emissions were consistently slightly lower than 1 for the LD data. Both the HD and LD data showed a significant decrease in fuel economy with increasing biodiesel blends. The emissions data for HD and LD vehicles suggest that there are significant differences of the effects of biodiesel for some of these vehicle emissions.

The LD vehicle emissions data was segregated between larger (>3 L) and smaller (<3 L) engines. The larger engines were mostly manufactured and tested in North American, while the smaller engines were largely manufactured and tested in Europe and Asia. It was found that the relative NO_x emissions increase for the smaller displacement engines was significantly greater than that for the larger engines. For CO emissions, the B100 blend led to a CO decrease for the larger engines, but to a significantly different CO increase for the smaller engines. None of the other differences between emissions from larger and smaller engines were statistically significant.

Being able to partition data to allow one to explore subsets of vehicle emissions data requires large quantities of data. Many other factors need to be explored, but there is a shortage of adequate data to be representative of these other factors. Adequate data is not available to allow one to assess the effects of biodieselfuel use on emissions of hazardous air pollutants, such as benzene, 1,3-butadiene, etc. As seen in this work, there is sufficient data to begin exploring the effects on LD vehicle emissions of formaldehyde, acetaldehyde, and polycyclic aromatic hydrocarbons. We need much more data to begin assessing the effects of biodiesel fuel use on ultrafine particulate emissions, especially, particle number and particle size distributions in emissions. Different biodiesel feedstocks are more commonly used in different areas of the world, such as soy oil in North America, rapeseed oil in Europe and palm oil in southern parts of Asia. Additional vehicle emissions data is necessary to explore the effects of different biodiesel feedstocks on vehicle emissions.

Diesel fuels use varies considerably throughout the world, being most important as a fuel for HD vehicles in North America, and as a fuel for LD vehicles in much of Europe and Asia. It is important that planners and regulators recognize the differences in effects of biodiesel on vehicle emissions for different types of vehicles. These effects are particularly important for the emissions of NO_x and PM, where diesel vehicles are expected to be major contributors to the on-road emissions of these pollutants. The primary feedstock that is available for production of biodiesel varies greatly in different parts of the world. It is also critical that planners and regulators understand the effects of different biodiesel feedstocks on vehicle emissions, so that the impacts in specific regions of the world can be more properly evaluated.

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