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Emission Analysis of Heavy Duty Vehicles using Biodiesel Blends

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Abstract- **Biodiesel is a fuel-blending component produced from vegetable oils, animal fats, or waste grease by reaction with methanol or ethanol to produce methyl or ethyl esters. 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 emissions data from heavy-duty (HD) diesel vehicles and engines, combining vehicle data from chassis dynamometer and on-road emissions testing, and combining data using different oil feed stocks for producing biodiesel fuels. In this review, the effects of switching from petroleum diesel fuel to biodiesel blended fuels on relative vehicle emissions for 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. Nitrogen oxides (NOx) 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. 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.. No significant effect was found for carbon dioxide (CO2) emissions for HD vehicles using B20 fuels based on dynamometer or on-road emissions data. Particulate matter (PM) emissions were significantly lower for B20 fuel in HD vehicles for both types of emissions tests. The HD dynamometer data showed a significant decrease in fuel economy for the B20 blend.**

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.

IndexTerms - Renewable fuels, Biodiesel, Vehicle emissions, Regulated air pollutants, Hazardous air pollutants.

I. INTRODUCTION

The production of first-generation bio fuels - 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 bio fuels more than tripled between 2000 and 2007. Driven by supportive policy actions of national governments, bio fuels 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 bio fuels 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 produce more 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. 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 the earlier of these reviews was conducted by the U.S. Environmental Protection Agency [9]. 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 NOx 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 [9] 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 NOx 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 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 NOx emissions, -18.7% and -23.2% for CO emissions, and -24.1% and-42.2% for PM emissions. 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. The effects of different biodiesel fuel feed stocks 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.

II. 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.

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.

III. 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 emissions studies included many more construction related vehicles (dump trucks, cement mixers, graders, etc.). Neither data set included many urban diesel delivery vehicles.

Heavy-Duty Diesel Chassis Dynamometer Studies

The relative emissions of HC, NOx, CO, carbon dioxide (CO2), PM and fuel economy from chassis dynamometer test of HD vehicles using various biodiesel blended fuels have been analyzed [10]. 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, NOx 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 CO2, PM and fuel economy. For these HD vehicles, the use of biodiesel led to a significant 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 NOx emissions for both B20 and B100. The use of B20 blended fuels also led to a decrease for CO2 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.

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 same vehicles, 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, NOx, CO, CO2, PM and fuel economy effects are for B20 biodiesel blended fuels [11, 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 and significance of biodiesel blends

Emission	Biodiesel Blend	Effect ± 95% C.I	Number of Measurements
HC	B20	-5.7 ± 4.4%	101
HC	B100	-23.0 ± 9.2%	54
NOX	B20	+3.5 ± 2.3%	105
NOX	B100	+9.0 ± 2.8%	57
CO	B20	-4.1 ± 6.4%	93
CO	B100	-24.0 ± 7.2%	46
CO2	B20	-0.4 ± 1.0%	52
PM	B20	-13.3 ± 5.1%	67
Fuel Economy	B20	-2.6 ± 1.2%	46

Table 1 shows an assessment of the significance of the biodiesel blended fuel effect on the HD vehicle emissions based 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 NOx emissions that was not significant. The use of B20 blended fuels also led to no significant effect for CO2 emissions and fuel economy, and a significant decrease for PM emissions.

Table 2 Effects And Significance Of Biodiesel Blends On The Vehicle Emissions And Fuel Economy For On-Road Vehicle

Emission	Biodiesel Blend	Effect ± 95% C.I	Number of Measurements
HC	B20	-21.7 ± 4.4%	89
NOX	B20	-3.3 ± 3.4%	92
CO	B20	-6.6 ± 5.4%	90
CO2	B20	+3.0 ± 3.6%	83
PM	B20	-15.2 ± 6.0%	70
Fuel Economy	B20	+6.3 ± 8.1%	35

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. [12]. 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.

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, CO2 and PM data using B20 blends. However, the results were significantly different for the HC, NOx and fuel economy data between the two data sets. For the HC data, B20 blends led to a significant decrease in HC emissions in 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 NOx data, B20 blends led to a significant increase in NOx emissions of about +3.5% for the dynamometer studies, while it led to a -3.3% change (not significant) in NOx emissions in the on-road studies. The data continues to support an increase in NOx 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, CO2 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 CO2 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 CO2 using B20 blends. These data support the conclusion that the use of B20 biodiesel fuels has no significant effects on the emissions of CO2. 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.

IV. Trends in Vehicle Emissions with Increasing Biodiesel Percentage

The HD 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, NOx, CO, CO2, 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 NOx emissions was also statistically significant. The decrease in CO2 emissions 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.

Neither the decrease in HC emissions nor the intercept are statistically significant for this data. For the NOx 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 NOx 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 CO2 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 CO2 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.

The HD dynamometer data has sufficient data at two different biodiesel blends. If one looks at the NOx 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.

V. 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.

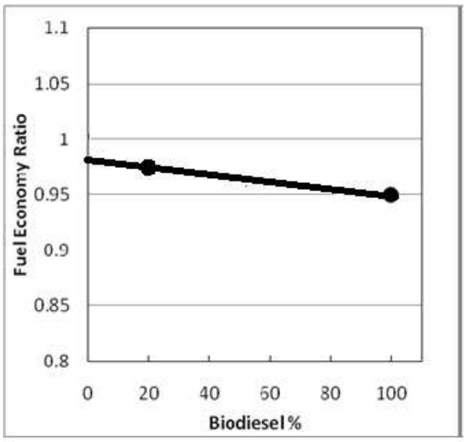

Figure 1: Best fit of relative emissions of fuel economy versus biodiesel fuel percentage

VI. CONCLUSION

Most reviews of the effects of biodiesel blended fuels use on emissions combine all of the available data engine and vehicle. 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 NOx emissions studies, a statistically significant increase in NOx 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 studies of B20 blended fuels for HC and NOx emissions and fuel economy to determine the effects of using these fuels in HD vehicles. But since the B20 data for CO, CO2 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.

The HD 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. The NOx emissions showed a significant increase with increasing biodiesel for the HD data. For the CO emissions from the HD data there was a significant decrease. For the CO2 emissions data, 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 biodiesel fuel use on emissions of hazardous air pollutants, such as benzene, 1,3-butadiene, etc. 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 feed stocks 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 feed stocks on vehicle emissions. Diesel fuels use varies considerably throughout the world, being most important as a fuel for HD vehicles in North America. 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 NOx 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 feed stocks on vehicle emissions, so that the impacts in specific regions of the world can be more properly evaluated.

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