Final Report

Evaluation of the Effects of Biodiesel Fuel on Emissions from Heavy-Duty Non-Road Vehicles

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Executive Summary

Construction applications could provide an important niche for biodiesel. Construction applications often require large quantities of fuel at remote sites where fueling infrastructure for some other alternative fuels, such as natural gas, is nearly impossible. The present project was a pilot study to evaluate the potential effectiveness of biodiesel in reducing emissions from off-road vehicles. For this program, opacity measurements were conducted on 4 off-road vehicles operated on a California in-use diesel fuel, and a blend of 20% biodiesel (B20) and 30% biodiesel (B30) with this fuel. This study was conducted at the Colton landfill site in Colton, CA. An additional aspect of this program was to evaluate available technologies for measuring emissions from construction off-road vehicles.

The results of the opacity tests are presented in Table ES-1. Overall, the results show that biodiesel blends are effective in reducing opacity from off-road vehicles. In particular, all vehicles showed reductions in opacity for B20 and B30. The differences between the different fuel blends were statistically significant for 3 of the 4 vehicles, with the opacity generally decreasing with increasing use of biodiesel. These results are consistent with previous opacity tests conducted on heavy-duty diesel trucks from the city of San Bernardino fleet. It is important to note that changes in the particulate composition could contribute, in part, to the observed reductions in opacity, however. Biodiesel blends have shown a tendency to have higher fractions of soluble or organic carbon in the particulate matter than standard diesel; this could contribute to the observed reductions in opacity.

Measurements of emissions from off-road vehicles can be obtained using both portable emissions systems and emissions trailers. The Environmental Protection Agency's (EPA's) ROVER system and the Clean Air Technologies International Inc. (CATI) OEM 2100 are two portable systems which could be used in this application. The CATI OEM 2100 uses a five gas analyzer in conjunction with exhaust flows obtained from engine parameters to determine emissions of THC, NO_x, CO, and CO_2. This flow measurement system would limit the use of this device to engines equipped with electronic control units; this would generally include engines in the model years 1994 to present. CATI is currently developing sensor array technologies for measuring vehicles older than 1994. EPA ROVER also uses a five gas analyzer but in conjunction with exhaust flows obtained from differential pressure measurements to determine emissions of THC, NO_x, CO, and CO_2. Particulate measurement capability is currently being added to both the ROVER and the OEM 2100.

Table ES-1. Test Results for Opacity Measurements for RFD and Biodiesel Blends

		Average	St Dev.	Median	High	Low	Statistics
Bulldozer	RFD	69.9	3.5	69.2	76.8	66.1	1,2,3
	B20	65.8	3.4	66.4	69.5	60.0	
	B30	58.1	4.9	56.1	66.6	53.1	
Compactor	RFD	37.0	5.4	39.5	41.9	24.4	0
	B20	33.5	4.8	35.8	38.0	23.4	
	B30	33.6	4.4	32.8	40.2	27.8	
Motor Grader	RFD	16.7	1.4	16.5	19.2	14.6	1*,2, 3
	B20	14.5	2.0	15.1	17.4	11.8	
	B30	11.3	1.4	11.6	13.7	8.7	
	Return to RFD	15.9	1.5	15.8	18.2	13.8	
Scraper	RFD	64.4	4.3	63.1	70.5	58.7	1,2,3
	B20	58.0	1.7	57.7	61.1	55.6	
	B30	53.4	2.0	54.0	56.2	49.6	
	Return to RFD	65.5	3.3	64.4	70.8	62.0	

0 = No statistically significant differences between any fuel pairs
1 = Statistically significant difference between RFD and 20% biodiesel
2 = Statistically significant difference between RFD and 30% biodiesel
3 = Statistically significant difference between 20% and 30% biodiesel
* = Difference statistically significant for first RFD run but not the replicate

Other ideas which could be incorporated into the design of a portable emissions systems include utilizing other flow meters such as a turbine meter, ultrasonic transit flow meter, or vortex flow meter or utilizing other dilution systems such as the one designed by Desert Research Institute or a porous stainless steel tube micro-dilution tunnel currently being marketed by Sierra Instruments Inc.

Several emissions trailers are also available which could be utilized to make off-road emissions measurements. These include trailers used by the EPA, and West Virginia University, as well as a trailer currently being constructed by the University of California at Riverside's Bourns College of Engineering-Center for Environmental Research and Technology (CE-CERT). These trailers could follow a piece of construction equipment as it moves from one location to another or monitor emissions in a stationary location while a piece of construction equipment performs a specific task such as lifting dirt.

Regardless of which measurement technique is utilized, it is suggested that fuel-based emission factors be developed in conjunction with the emissions tests results. In this approach, emissions factors would be based on mass of pollutant emitted per unit mass of fuel burned. These emissions factors could be compared from test to test to determine the variability of the emissions factors and how this variability compares with differences between fuels. The emissions factors could also be used in conjunction with fuel use records to provide a rough estimate of the off-road emissions inventory.

1.0 Introduction

Biodiesel has gained considerable attention in recent years as the need to develop alternatives to traditional diesel fuel increases. Biodiesel offers several important advantages in that it can be produced domestically and from renewable sources. It can also be substituted for traditional diesel with little or no engine modification. Effective in November of 1998, biodiesel was approved by Congress as an alternative fuel to meet the alternative fuel vehicle purchase requirements of the Energy Policy Act (EPACT) of 1992. This legislation has helped to increase the use of biodiesel as it is a cost competitive option compared with other alternative fuels such as natural gas in many applications. One area for which biodiesel is well suited is in construction applications. In particular, construction applications often require large quantities of fuel at remote sites where installing the fueling infrastructure for some other alternative fuels is nearly impossible.

The goal of the present project is to conduct an initial evaluation of the effectiveness of biodiesel in reducing opacity from off-road construction vehicles. This project is part of a larger program for the University of California at Riverside's Bourns College of Engineering-Center for Environmental Research and Technology (CE-CERT) in the area of biodiesel fuels. This program includes studies to evaluate emissions for light-heavy duty vehicles and opacity from heavier-duty vehicles. For this program, opacity measurements were conducted on 4 off-road vehicles operated on a California in-use diesel fuel, and blends of 20% and 30% biodiesel with this fuel. An evaluation of available technology for measuring emissions from construction vehicles was also conducted as part of this program.

2.0 Experimental Procedures

For this program, exhaust opacity measurements were conducted on 4 heavy-duty off-road construction vehicles operated on California Reformulated Diesel (RFD) and blends of 80% RFD/ 20% biodiesel (B20) and 70% RFD/ 30% biodiesel (B30). The four test vehicles were all located at the Colton landfill site in Colton, CA. This site is owned by the County of San Bernardino Waste Systems Division and operated by Norcal/San Bernardino, Inc. The vehicle matrix included a relatively wide range of vehicle types, as shown in Table 1.

Table 1. Vehicle Descriptions for Test Fleet

Vehicle Type	Model	Hours of Operation	Engine	Fuel, Air System
Bulldozer	D8L	4512	Caterpillar 3406	DI,TB
Compactor	826C	3488	Caterpillar 3406	DI,TB
Motor Grader	140G	814	Caterpillar 3306	DI,TB
Scraper	623B	2014	Caterpillar 3406	DI, TB

DI = direct injection, TB = turbocharged

Each vehicle was tested on RFD, B20, and B30 during the testing period, which lasted from December 1999 to early January 2000. The RFD was the standard diesel fuel used at the Colton landfill. It should be noted that the specifications for diesel fuel for off-road construction vehicles and on-highway diesel vehicles are the same in California. The biodiesel fuel was a SoyGold biodiesel fuel produced by Ag Processors, Inc., and supplied by Radtke & Tomberlin Distribution, Inc. The biodiesel fuel was splash blended in the fuel tank to form the biodiesel blends. Each vehicle was preconditioned for at least one day prior to testing on the B20 and B30 blends.

Testing on each fuel/vehicle combination was conducted over a 3 to 4 day period using the Snap and Idle Test procedure. A Wager (Mdl 6500) smoke meter was used for all testing. This meter is compliant with the SAE J1667 standard for Snap and Idle testing in California. For each day of testing, three Snap and Idle tests were conducted per fuel/vehicle combination in accordance with the SAE J1667 protocol. Testing was conducted with the vehicles warmed up to their operational temperature. In accordance with the SAE J1667, each vehicle was subjected to three “clean out” engine accelerations to the maximum governed engine RPM for approximately 3 seconds followed by a return to idle. Tests were then conducted by placing the sensor head across the exhaust stream, accelerating the engine to the maximum governed engine RPM for approximately 3 seconds and returning it to idle. This procedure was repeated for two additional Snap and Idle sequences. Criteria for acceptance for most tests was a span deviation of less than 5%. For some test sequences, and in particular for the scraper, span deviations of less that 5% could not be obtained on a regular basis. All tests with span deviations greater than 5% were checked to insure that they exhibited trends consistent with tests conducted on previous days and within the same day. Where possible, testing was conducted on consecutive working days, except in cases where vehicle maintenance or repairs were required.

3.0 Opacity Test Results

A summary of the test results including the average, standard deviation, median, high and low values for each of the vehicle/fuel combinations is provided in Table 2. This summary excludes a small subset of outlier tests for the bulldozer which exhibited trends significantly different than either the interday or the combined test sequence averages. More complete testing results are presented in Appendix A. Overall, the results show that biodiesel blends are effective in reducing opacity from off-road vehicles. All of the vehicles showed reductions in opacity for B20 and B30, with opacity generally decreasing with higher percentages of biodiesel. Statistical analyses were conducted to evaluate the significance of these reductions. For this test, a one-way analysis of variance (ANOVA) test was conducted in conjunction with Fischer's protected least significant difference means separation test with a significance level of 5%. These analyses showed that the differences between each of fuel blends were statistically significant for 3 of the 4 vehicles.

Table 2. Test Results for Opacity Measurements for RFD and Biodiesel Blends

		Average	St Dev.	Median	High	Low	Statistics
Bulldozer	RFD	69.9	3.5	69.2	76.8	66.1	1,2,3
	B20	65.8	3.4	66.4	69.5	60.0	
	B30	58.1	4.9	56.1	66.6	53.1	
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	Return to RFD	15.9	1.5	15.8	18.2	13.8	
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	B20	58.0	1.7	57.7	61.1	55.6	
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	Return to RFD	65.5	3.3	64.4	70.8	62.0	

0 = No statistically significant differences between any fuel pairs
1 = Statistically significant difference between RFD and 20% biodiesel
2 = Statistically significant difference between RFD and 30% biodiesel
3 = Statistically significant difference between 20% and 30% biodiesel
* = Difference statistically significant for first RFD run but not the replicate
Data presented above are based on at least 9 tests per vehicle/fuel combination, except the bulldozer on RFD which is based on only 8 tests.

These results are consistent with previous opacity tests conducted on heavy-duty diesel trucks from the city of San Bernardino fleet (Durbin et al., 2000). In that previous study, 4 vehicles were tested with 2 of the vehicles being relatively high emitters and 2 of the vehicles being relatively low emitters. The 2 high emitters both showed reductions in opacity for the biodiesel blends, although considerable variability was observed throughout testing. A clear and statistically significant trend of reduction in opacity was observed in that study for 1 of the vehicles on both B20 and B30 compared with RFD, while the second vehicle showed statistically significant reductions for only B30. The 2 high emitting vehicles were also repaired during the course of testing, with both vehicles showing reductions in opacity on B30 compared with RFD. For the 2 lower emitting vehicles, given the overall low opacity values and the test and vehicle variability, no significant trends between RFD and the biodiesel blends were found. Some studies have also shown reductions in opacity for biodiesel blends compared with Federal diesel (Fosseen Manufacturing and Development, 1995).

It is important to note that changes in the particulate composition could contribute, in part, to the observed reductions in opacity. In particular, studies have shown that light extinction in diesel exhaust is primarily attributable to the elemental carbon portion of the particulate (Japar et al., 1984; Moosmuller et al., 2000). Several previous studies have shown biodiesel fuels can have higher fractions of organic carbon relative to elemental carbon in the particulate matter than those for standard diesel (Sharp, 1998; McDonald et al., 1995; Spataru and Romig, 1995). This change in chemical composition could cause a reduction in the observed opacity even in the absence of reductions in total particulate matter. Although changes in the particulate chemical composition probably account for only a portion of the observed opacity reductions, this effect could not be estimated since samples for chemical analysis were not collected.

4.0 Evaluation of Technologies to Measure Gaseous and Particulate Emissions from Off-Road Vehicles under In-Use Conditions

As the reduction of diesel exhaust emissions becomes a more critical component of air quality plans, the need to measure diesel exhaust emissions under in-use conditions has grown in importance. Much of the emphasis to date has been on the development of emissions measurement systems for on-highway diesel vehicles. For on-highway diesel heavy-duty vehicles, a number of approaches are available including permanent and mobile chassis dynamometers, emissions trailers designed to follow class 8 heavy-duty tractors under on-road conditions, and portable emissions systems. The application of these devices to measure emissions from off-road vehicles presents additional challenges, including the development of "work cycles" representative of the real-world conditions. In the following section, technologies which are applicable to measuring exhaust from off-road vehicles will be discussed as well as the challenges inherent in quantifying emissions from off-road vehicles.

4.1 Portable Emissions Measurement Systems

The cheapest and most practical emissions measurement systems for off-road vehicles in the near term are portable systems. Such systems are generally designed to fit within the cab of a heavy-duty vehicle with probes sampling directly from the exhaust pipe to measure raw gaseous emissions in real time. Such systems typically utilize five gas analyzers to measure concentrations of gaseous pollutants including total hydrocarbons (THC), nitrogen oxides (NO_x), carbon monoxide (CO), and carbon dioxide (CO_2), as well as oxygen (O_2). Pollutant emission rates are then determined based on the measured concentrations and measured exhaust flows.

Two example portable systems include the EPA's ROVER system and the OEM 2100 developed by Clean Air Technologies International Inc. (CATI). The EPA's ROVER system is currently under evaluation by researchers at West Virginia University as a possible alternative for measuring in-use diesel emissions as part of the consent decree between EPA and the diesel engine manufacturers. Other studies of the ROVER instrument have shown favorable correlations for diesel emissions for NO_x and CO_2 with traditional laboratory measurements with poorer correlations for THC (Scarbro and Whitney, 2000). The CATI OEM 2100 unit is designed to measure emissions from either gasoline or diesel vehicles. This unit is currently being utilized in studies conducted at North Carolina State University, University of Pittsburgh, the City of

New York (NY), Syracuse NY, and the NY State Department of Conservation. This instrument is also currently under evaluation.

These units use different methods for measuring exhaust flows. The CATI OEM 2100 determines the flow rates using parameters obtained from the engine control unit. This limits the application of the instrument to vehicles with engines equipped with ECUs. For off-road vehicles, this includes engines in the approximate model year range from 1994 to present. CATI is currently developing sensor array technologies for measuring vehicles older than 1994. The system can readily be upgraded once this unit is available to allow for measurements from a broader range of vehicle types. The ROVER system utilizes differential pressure measurements to monitor exhaust flow rates and is not limited to newer model year vehicles (Breton, 2000).

Other technologies that could be used to measure exhaust flow rates include turbine meters, ultrasonic flowmeters, and vortex flowmeters. Turbine meters monitor the flow through a turbine and count the corresponding number of revolutions of the turbine. One of the problems with turbine meters is that the pick-up sensors that count the revolutions have a limited temperature range. This could potentially be overcome by mounting the sensors in locations where they are less exposed to high temperatures.

Ultrasonic transit flow meters use two diametrically opposed ultrasonic transducers to transmit sound pulses alternately upstream and downstream through the flow. Measurements of these sound waves can be used to determine the time differential as the sound is being carried downstream by the flow and delayed by the flow while transmitting upstream. This difference is directly proportional to the velocity of the fluid being measured. These meters generally have good accuracy, do not obstruct the flow, and have a wide flow rangeability (100 to 1 or more). The velocity measurement is independent of temperature and pressure, although it is a function of flow profile which can change as a function of Reynolds number (which can vary with temperature and pressure). These meters are relatively expensive (~$50,000-$100,000) and require temperature conditioning of the flow to protect the transducer.

Vortex meters detect vortices created in the flow stream, to produce an output pulse rate (the vortex frequency) proportional to the volumetric flow rate of the gas. The vortices are produced as the moving fluid passes a strut or rounded rod. These vortices are swept downstream at the fluid velocity. Since the vortices are carried downstream at the free stream velocity, the frequency at which they pass between the ultrasonic monitoring transducers is linearly related to the fluid velocity. Such instruments have been used by automotive researchers in Texas since late 1996 at exhaust gas temperatures up to 950ºF (Testing Technology International).

Particulates are also important to measure from off-road vehicles. Particulate measurement capacity is currently being added to the OEM 2100, with commercialization scheduled for the fall or winter of 2000. One concept for the particulate measurement system is based on a tapered element oscillating microbalance (TEOM) principle, being co-developed by two companies that specialize in this type of equipment. Researchers at EPA are also developing a system for measuring particulate emissions with ROVER, although this system has not been tested or implemented yet (Breton, 2000).

An important factor in measuring particulate is the cooling of the sample to a temperature of 52ºC or less. For the EPA ROVER system, a dilution system is being incorporated for particulate measurements. For the OEM 2100, dilution and natural cooling options are both being investigated for particulate sampling. Other dilution systems for independent particulate measurements may also be available. CE-CERT in conjunction with the Desert Research Institute (DRI) is conducting a project with the California Air Resources Board (CARB) to measure particulate emissions from three off-road vehicles (Fitz, 2000). This project will utilize a dilution stack sampler developed by DRI based on the design utilized in earlier work by the California Institute of Technology (Hildemann et al., 1991). With this sampler, the emissions will be drawn from the stack through a heated stainless steel probe followed by a cyclone to remove particles greater than 2.5 µm aerodynamic diameter. The stack gases are transferred through a heated stainless steel probe followed by a copper line to the dilution tunnel. In the tunnel, exhaust is mixed with dilution air under turbulent flow conditions, to cool and dilute the exhaust to near-ambient conditions. Ambient air for dilution is filtered through a high efficiency particulate air (HEPA) filter (to remove particulate matter) and an activated carbon bed (to remove gas-phase organics). The dilution ratio can be set from 25 to 100-fold dilution. After passing through a tunnel length equal to ~10 tunnel diameters, a fraction of the diluted exhaust enters a large chamber, where additional residence time is provided before the samples are collected. The samples are drawn through a plenum to acquire samples for inorganic and organic speciation. The rest of the diluted exhaust passes through a high-volume sampler filter before being exhausted. This filter can also be analyzed for a PM_{10}-type sample, if a short residence time is not of concern.

Researchers at Caterpillar Inc. have developed a micro-dilution system for measuring particulates. This system draws exhaust directly from the stack, eliminating the need for long transfer tubes. The exhaust sample is passed through a porous stainless steel tube enclosed in a pressurized chamber. Dry, hydrocarbon-free air is metered into the chamber under pressure and permeates the porous stainless steel tube to mix with the exhaust sample. Sufficient air is mixed with the exhaust gases to provide a mixture with a maximum temperature of 52ºC which can be subsequently sampled. This diluter was designed to eliminate the problems associated with long transfer tubes between the exhaust stack and the dilution point, which can contribute to losses of particles due to thermophoresis, electrophoresis, and, to a lesser extent, inertia impact. This unit is licensed to flow-instrumentation specialists Sierra Instruments Inc. (Monterey, CA), which assisted in the development of the system.

4.2 Mobile Emissions Laboratory Trailers

Mobile emissions trailers could also be used to investigate emissions from off-road vehicles. These trailers could follow off-road vehicles over a course of realistic events and measure emissions. This could include following a piece of construction equipment as it moves from one location to another. Correspondingly, the trailer could be set up to monitor emissions in a stationary location with the piece of construction equipment performing a specified task such as lifting dirt.

CE-CERT is currently in the process of constructing an emissions trailer which would be suitable for this application (Norbeck et al., 2000). The CE-CERT diesel emissions trailer is designed to provide laboratory quality emissions measurements from heavy-duty trucks while on the road. This trailer (with a corresponding tractor) could also be used to monitor emissions from off-road vehicles as they perform stationary operations or as they move. The CE-CERT trailer will provide a full dilution system and is designed to produce laboratory quality results. The dilution system is designed around a Horiba Instruments Smooth Approach Orifice (SAO) dual venturi and bulkstream control system. The analytical system will provide for continuous gaseous measurements from the dilution tunnel or integrated bag samples. The analytical system will include all typical components of a standard emissions laboratory including a flame ionization detector (FID) for THCs, a chemiluminescence analyzer for NO_x, and a non-dispersive infrared detector for CO and CO_2. It is also planned to incorporate particulate measurement capability for analysis of particulate mass and composition as well as near-real-time measurement of particulate emissions. The trailer itself is a 53-foot Utility refrigerator which has inherently good longitudinal and torsional strength as well as low thermal and acoustic transmission properties. The unit is equipped with a 225 kW Caterpillar Prime Power generator to support the significant power requirements of the sampling and analyzer system and a 5-ton AC unit.

Other mobile emissions trailers which may also be used for this type of work could include trailers operated by the EPA's Office of Research and Development (Harris et al., 1996) and West Virginia University (Lyons et al. 1991). The EPA trailer collects a raw sample from the exhaust for analysis, i.e., no dilution. The continuous emissions monitoring system measures O_2, CO_2, CO, NO_x, and THC. Exhaust flow is calculated from velocity head and static pressure measurements, then used to calculate emissions in grams/hour. These emissions can be converted to grams/mile or grams/brakehorsepower-hour using the speed sensor and the real-time horsepower measurement system. This trailer has also been equipped to collect particulate measurements (Harris et al., 2000).

The West Virginia University transportable emissions testing laboratory (Lyons et al., 1991) is typically used for chassis dynamometer emissions measurements for on-road trucks and buses. The unit consists of two separate trailers: one of which houses the chassis dynamometer while the other houses the emissions test equipment and the dilution tunnel. The emissions measuring system is equipped with the capability of measuring particulate matter, CO, CO_2, NO_x, HC, formaldehyde, methanol and methane. Although the chassis dynamometer portion of the test laboratory would not be required for the emissions measurements of off-road vehicles, it is presumed that the separate emissions trailer could be used to conduct the required measurements on the off-road vehicles.

4.3 Test Methodology

The difficulties in developing methodologies for testing off-road vehicles should not be underestimated. This is important given that operating conditions and loads typically experienced by these vehicles may be difficult to simulate. These difficulties will be particularly prevalent in scenarios where reproducibility is critical, such as relative comparisons between different fuel types.

In another CE-CERT program with the CARB, samples will be collected from three representative off-road diesel engines: one intermediate duty backhoe (40 hp), one intermediate duty tractor, and one heavy-duty vibratory roller (Fitz, 2000). The test sequence to be used in that study is one example of the types of tests that can be conducted. This test sequence will consist of a three-mode test. The first mode consists of a cold start and 5 minute steady state idle at 0% load. The second mode will consist of series of operational cycles consistent with the normal operation of the equipment. For the backhoe, the second mode will consist of excavating earth and piling it next to the excavation followed by replacing the soil into the excavation and tamping it down. The second mode for the vibratory roller will consist of continuous tamping of the fill made by the backhoe. In the second mode for the tractor, it will pull a weight along the ground that will approximate half throttle operation. The total duration of the second mode will be determined by the loading necessary to supply sufficient sample of particulate for analysis. For the last mode, engine load will be removed and the throttle position will be maintained at a hot stabilized idle for a cool-down period of 5 minutes. Particulate and gaseous samples will be collected during all modes of operation by inserting the inlet probe of the DRI dilution sampling system, discussed above, directly into the exhaust.

Given the inherent difficulties that may be encountered in creating reproducible off-road duty cycles, it is suggested that fuel based emissions factors be developed in conjunction with the emissions testing results. Dreher and Harley (1998) have previously investigated a fuel-based method for estimating diesel truck emissions inventories. In this approach, emissions factors are based on the mass of pollutant emitted per unit mass of fuel burned. Such factors could easily be developed for the test cycles described above with the pollutant measurements and corresponding CO_2 emissions. These emissions factors could be compared from test to test to determine the variability of the emissions factors and how this variability compares with differences between fuels. The emissions factors could also be used in conjunction with fuel use records to provide a rough estimate of the off-road emissions inventory.

5.0 Summary and Conclusions

The present project was a pilot study to evaluate the potential effectiveness of biodiesel in reducing particulate emissions from off-road vehicles. For this program, opacity measurements were conducted on 4 off-road vehicles operated on a California in-use diesel fuel, and a blend of 20% and 30% biodiesel with this fuel. An additional aspect of this program was to evaluate available technology for measuring emissions from construction vehicles. The major results of this study are:

- The biodiesel blends were effective in reducing opacity from off-road vehicles. In particular, all vehicles showed reductions in opacity for B20 and B30. The differences between the different fuel blends were statistically significant for 3 of the 4 vehicles, with the opacity decreasing with increasing use of biodiesel.

- These results are consistent with previous opacity tests conducted on heavy-duty diesel trucks from the city of San Bernardino fleet.

- Changes in the particulate composition could contribute, in part, to the observed reductions in opacity. Biodiesel blends tend to have higher fractions of soluble or organic carbon in the particulate matter than those for standard diesel, which could contribute to the observed opacity reductions.

- The measurements of emissions from off-road vehicles can be performed using both portable emissions measurement systems or emissions trailers.

- The EPA's ROVER system and the CATI OEM 2100 are two portable systems which could be used in this application. Both use five gas analyzers in conjunction with measurements of exhaust flow to determine emissions. Particulate emissions measurement capability is currently being incorporated into both systems.

- Other ideas that could be incorporated into the design of a portable emission systems include utilizing other flow meters such as a turbine meter, ultrasonic transit flow meter, or vortex flow meter or utilizing other dilution systems such as the one designed by DRI or the porous stainless steel tube micro-dilution tunnel currently being marketed by Sierra Instruments Inc.

- Emissions trailers such as those developed by CE-CERT, the U.S. EPA, and WVU could also potentially be utilized to make off-road emissions measurements.

- Regardless of which measurement technique is utilized, it is suggested that emission factors based on mass of pollutant emitted per unit mass of fuel burned be developed in conjunction with the emissions tests results.

6.0 Acknowledgments

The authors acknowledge the contribution and support of the staff of Norcal/San Bernardino who operate the Colton landfill site. We also acknowledge Radke & Tomberlin Distribution, Inc. and Ag Processors which donated the biodiesel fuel for this project.

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Appendix A – Complete Opacity Results

Bulldozer Opacity Results

Fuel		RFD			B20				B30	
Test Day	12/7/99	12/8/99	12/9/99	12/15/99	12/16/99	12/17/99	12/22/99	1/5/00	1/6/00	1/7/00
Hours	4512	NA	4536	4577	4584	4588	4589	4687	4696	4707
Test 1	67.6	72.1	66.4	47.2	66.9	63	71.3	54	65.4	64
	65.8	71.4	67.7	42.1	67.7	68.2	65	55.2	65.3	63.8
	64.8	74	68.4	44.6	71.7	68.1	67.1	57.5	69	63.6
ave test 1	66.1	72.5	67.5	44.6	68.8	66.4	67.8	55.6	66.6	63.8
Test 2	69.1	77.9	66.7	41.9	63	68.4	61.3	54.8	55.4	63.4
	71.7	75.5	67	42.1	64.6	68.9	59.8	56.5	51.7	56.5
	72.1	77.1	67.7	42.6	66.2	71.2	61.6	58.7	54.1	61.5
ave test 2	71.0	76.8	67.1	42.2	64.6	69.5	60.9	56.7	53.7	60.5
Test 3	66.3	70.6	48	41.5	64.8	65.7	58.9	54.7	51.8	60.8
	67.8	69.9	46.7	46.1	66.1	69.7	61.8	50.1	55	61.6
	69.8	71	43.7	45.2	67.4	68.2	59.4	54.4	56.4	66
ave test 3	68.0	70.5	46.1	44.3	66.1	67.9	60.0	53.1	54.4	62.8
Test 4									56.4	
									52.4	
									51.5	
ave test 4									53.4	
daily ave.	68.3	73.3	60.3	43.7	66.5	67.9	62.9	55.1	57.0	62.4
St. Dev	2.5	3.2	12.2	1.3	2.1	1.5	4.3	1.8	6.4	1.7
All Tests										
Ave	69.9				65.8			58.1		
St. Dev	3.5				3.4			4.9		
Median	69.2				66.4			56.1		
High	76.8				69.5			66.6		
Low	66.1				60.0			53.1		
	excludes final test on 12/9/00				excludes tests on 12/15/99					

Compactor Opacity Results

Fuel	RFD			B20			B30		
Test Day	12/7/99	12/8/99	12/9/99	12/15/99	12/16/99	12/17/99	12/21/99	12/22/99	1/4/00
Hours	3488	3490	3496	3537	3546	3556	3577	3586	3664
Test 1	33.1	40.1	39.0	33.1	33.9	25.4	39.2	35.1	31.9
	33.3	37.8	42.3	35.0	36.6	23.3	38.9	31.8	31.9
	34.9	40.5	40.1	33.5	37.0	21.6	42.6	32.2	31.7
ave test 1	33.8	39.5	40.5	33.9	35.8	23.4	40.2	33.0	31.8
Test 2	38.7	33.2	37.1	35.1	37.5	28.3	35.5	33.5	25.8
	40.3	34.1	38.5	36.5	35.7	32.0	38.2	32.5	29.7
	39.8	37.6	40.4	37.1	40.8	28.9	38.1	32.3	28.0
ave test 2	39.6	35.0	38.7	36.2	38.0	29.7	37.3	32.8	27.8
Test 3	22.8	36.3	39.3	36.3	34.8	28.6	38.2	31.7	25.2
	24.1	41.7	42.7	35.9	38.0	28.9	39.6	31.0	28.8
	26.3	40.4	43.7	37.5	38.9	33.2	40.0	31.9	31.9
ave test 3	24.4	39.5	41.9	36.6	37.2	30.2	39.3	31.5	28.6
daily ave.	32.6	38.0	40.3	35.6	37.0	27.8	38.9	32.4	29.4
St. Dev	7.7	2.6	1.6	1.5	1.1	3.8	1.5	0.8	2.1
All Tests									
Ave	37.0			33.5			33.6		
St. Dev	5.4			4.8			4.4		
Median	39.5			35.8			32.8		
High	41.9			38.0			40.2		
Low	24.4			23.4			27.8		

Motor Grader Opacity Results

Fuel	RFD			B20			B30			Return to RFD		
Test Day	12/7/99	12/8/99	12/9/99	12/15/99	12/16/99	12/17/99	12/21/99	12/22/99	12/23/99	1/3/00	1/4/00	1/7/00
Hours	814	817	820	840	843	845	853	856	859	876	880	896
Test 1	18.1	12.8	16.7	12.3	15.5	16	9.4	10.3	8.9	17.2	19.9	17.1
	19	16.2	14.8	13.8	15.1	19	13	12.1	8.8	15.9	17	15.6
	18.2	14.8	15.8	15.2	14.6	17.3	13.9	13.5	8.3	16.1	17.6	14.7
ave test 1	18.4	14.6	15.8	13.8	15.1	17.4	12.1	12.0	8.7	16.4	18.2	15.8
Test 2	17.1	16.2	18.9	11.9	12.3	17	10.4	13.6	12.3	16.8	19	16.1
	18.2	16.3	19	12.8	12.5	17.9	11.2	15	11	12.6	16.9	14.3
	16.2	16.2	19.6	13.9	10.6	12.9	10.4	12.6	12	13.7	16.5	14.7
ave test 2	17.2	16.2	19.2	12.9	11.8	15.9	10.7	13.7	11.8	14.4	17.5	15.0
Test 3	17.5	18.3	17.1	16	11.7	17.3	9.2	11.8	12.1	13.8	18.1	16.1
	14.3	16.9	16.2	16.4	12.1	14.9	12.1	11.5	10.4	13	17	14.1
	14.4	14.3	18.2	16.2	12.3	15.3	10.3	11.4	10.2	14.5	16.4	14.5
ave test 3	15.4	16.5	17.2	16.2	12.0	15.8	10.5	11.6	10.9	13.8	17.2	14.9
daily ave.	17.0	15.8	17.4	14.3	13.0	16.4	11.1	12.4	10.4	14.8	17.6	15.2
St. Dev	1.5	1.0	1.7	1.7	1.8	0.9	0.9	1.2	1.6	1.4	0.5	0.5
All tests												
Ave	16.7			14.5			11.3			15.9		
St. Dev	1.4			2.0			1.4			1.5		
Median	16.5			15.1			11.6			15.8		
High	19.2			17.4			13.7			18.2		
Low	14.6			11.8			8.7			13.8		

Scraper Opacity Results

Fuel	RFD			B20			B30			Return to RFD		
Test Day	12/7/99	12/8/99	12/9/99	12/15/99	12/16/99	12/17/99	12/21/99	12/22/99	12/23/99	1/3/00	1/6/00	1/7/00
Hours	2014	2018	2023	2042	2047	2051	2058	2062	2065	2106	2120	2127
Test 1	57.6	54.8	60.8	56.8	54.2	54.5	47.8	46.3	50.5	68.8	63.1	59.7
	61.6	60.9	63.8	60.5	56.5	57	51.1	47.9	56	68.8	64.4	62.7
	64.8	64.1	64.8	65.9	59.3	59.4	54.3	54.6	57.6	73.4	66.4	66.6
ave test 1	61.3	59.9	63.1	61.1	56.7	57.0	51.1	49.6	54.7	70.3	64.6	63.0
Test 2	64.4	52.6	66.8	59.1	55	54.4	50.4	48.9	50.8	65.9	62.6	59.1
	72.5	59.4	70.1	59.6	56.2	58.7	55.1	53	52.9	66.2	64.1	64.2
	74.5	64	73.6	62.2	63.5	60.9	56.7	56.9	57.5	71	66.5	66.9
ave test 2	70.5	58.7	70.2	60.3	58.2	58.0	54.1	52.9	53.7	67.7	64.4	63.4
Test 3	62.3	53.8	65.1	56.8	53.8	52.3	50.8	52	50.8	68.6	61.1	57.4
	66.2	62.4	65.9	52.9	56.8	57.7	53.9	57.6	53.4	70.1	62.9	61.1
	70.6	70.2	70.8	57.1	62.6	61.9	57.3	59.1	58.5	73.6	66	67.5
ave test 3	66.4	62.1	67.3	55.6	57.7	57.3	54.0	56.2	54.2	70.8	63.3	62.0
daily ave.	66.1	60.2	66.9	59.0	57.5	57.4	53.0	52.9	54.2	69.6	64.1	62.8
St. Dev	4.6	1.8	3.5	3.0	0.8	0.5	1.7	3.3	0.5	1.7	0.7	0.7
All Tests												
Ave	64.4			58.0			53.4			65.5		
St. Dev	4.3			1.7			2.0			3.3		
Median	63.1			57.7			54.0			64.4		
High	70.5			61.1			56.2			70.8		
Low	58.7			55.6			49.6			62.0		