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Gaseous and particle emissions from construction engines are an important fraction of the total emissions inventory and are gaining increasing regulatory attention. Quantification of $NO_x$ and PM is necessary to inventory the contribution of construction equipment to atmospheric loadings, particularly in urban non-attainment or maintenance areas. Data on emissions from construction equipment under in-use operating conditions is still very limited, however. Although a number of programs have begun to study this area, there is an increasing need to better characterize construction emissions and potential strategies to reduce these emissions. This includes strategies such as diesel particle filters (DPFs) and other after-treatment systems and renewable fuels that can potentially provide reductions in regulated emissions and in $CO_2$ and other important greenhouse gases.

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**Contract 65A0283**

**Final Report**

# Evaluation of the In-Field Emissions Impacts of Biodiesel fuels in Construction Equipment and Applications Under Actual In-use Conditions

**March 2010**

**Prepared for:**

**California Department of Transportation (Caltrans)**
**Division of Research and Innovation**

**and**

**I/O Environmental**

**Principal Investigators:** Thomas D. Durbin, J. Wayne Miller
**Co-Authors:** William A. Welch, Robert L. Russell

*College of Engineering-Center for Environmental Research and Technology*
*University of California*
*Riverside, CA 92521*
*(951) 781-5791*
*(951) 781-5790 fax*

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# Executive Summary

Gaseous and particle emissions from construction engines are an important fraction of the total emissions inventory and are gaining increasing regulatory attention. Quantification of $NO_x$ and PM is necessary to inventory the contribution of construction equipment to atmospheric loadings, particularly in urban non-attainment or maintenance areas. Data on emissions from construction equipment under in-use operating conditions is still very limited, however. Although a number of programs have begun to study this area, there is an increasing need to better characterize construction emissions and potential strategies to reduce these emissions. This includes strategies such as diesel particle filters (DPFs) and other aftertreatment systems and renewable fuels that can potentially provide reductions in regulated emissions and in $CO_2$ and other important greenhouse gases.

The goal of this research program was to carry out initial construction equipment emissions testing from two front-end loaders using standard diesel fuel and a 20% blend of biodiesel fuel (B20). The program consisted of two sets of in-use emissions tests: 1) in-use emissions tests of a standard front-end loader using diesel and B20; and 2) in-use emissions tests of an identical model front-end loader equipped with a Huss particulate filter using diesel and B20. The emissions measurements were made on a second-by-second basis using a portable emissions measurement system (PEMS) to develop relationships between $NO_x$ and PM and other emissions and fuel use.

Emissions measurements were made at two environmental remediation sites at Camp Pendleton, CA. Emission factors were determined in terms of g/kW-hr for two specific in-use activities: a lift/lower cycle and a transit cycle.

A summary of the major findings are as follows:

- There were no statistical differences in emissions from the loaders between standard diesel fuel and biodiesel fuel.

- The front-end loader equipped with the Huss filter appeared to have a lower PM emission factor on the lift/lower cycle than the standard loader, but but no reductions were seen for the transient cycle. For both cycles, the loader equipped with the Huss filter appeared to have higher $NO_x$ emission factors. This was not conclusive, however, as the average loads were different for the different sites, as discussed above. CO emissions showed reductions for the lift/lower cycles for the DPF-equipped loader, but no differences were found between the DPF-equipped loader and the stock loader for the transient cycle.

- For the two in-use activities studied, engine loads were at the low end of the power curve. At these low loads, it was more difficult to obtain consistent load and intercomparisons between the different fuels and aftertreatment.

Some difficulties were encountered in measuring the in-use emissions from this equipment; mainly related to abrupt movements that periodically dislodged sample probes or disconnected

signal cables. In addition, a conclusive comparison of emissions between the two loaders cannot be made due to differences in engine loads for the same activities.

# 1.0 Introduction

Gaseous and particle emissions from construction engines are an important fraction of the total emissions inventory and are gaining increasing regulatory attention. Quantification of $NO_x$ and PM is necessary to inventory the contribution of construction equipment to atmospheric loadings, particularly in urban non-attainment or maintenance areas. Data on emissions from construction equipment under in-use operating conditions is still very limited, however. Although a number of programs have begun to study this area, there is an increasing need to better characterize construction emissions and potential strategies to reduce these emissions. This includes strategies such as diesel particle filters (DPFs) and other aftertreatment systems and renewable fuels that can potentially provide reductions in regulated emissions and in $CO_2$ and other important greenhouse gases.

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Emissions measurements were made at two environmental remediation sites at Camp Pendleton, CA. Emission factors were determined in terms of g/kW-hr for two specific in-use activities: a lift/lower cycle and a transit cycle.

# 2.0 Experimental Procedures

## 2.1 Emissions Measurement Systems

The systems used in the project included a raw gas emissions analyzer, a dilution probe and analyzer for real-time PM measurement, and an integrated gravimetric raw gas PM sampler.

### 2.1.1. Measuring Criteria Gaseous Emissions

The concentrations of gases in the raw exhaust were measured with a Horiba PG-250 portable multi-gas analyzer. The PG-250 can simultaneously measure up to five separate gas components using the measurement methods recommended by the EPA. The signal output of the instrument was interfaced directly with a data acquisition computer through an RS-232C interface to record measured values continuously. Other major features include a built-in sample conditioning system with sample pump, filters, and a thermoelectric cooler. The performance of the PG-250 was tested and verified under the U.S. EPA ETV program.

**Figure 1 - In-Field Illustration of Continuous Gas Analyzer and Computer for Data Logging**

Details of the gases and the ranges for the Horiba instrument are shown in Table 1.

For quality control, UCR carried out analyzer checks with calibration gases both before and after each test to check for drift. Because the instrument measures the concentration of five gases, the calibration gases were blended as super-blends of several gases made to within 1% specifications by Praxair (Los Angeles, CA). Analyzer drift was determined to be within manufacturer specifications of ± 1% full scale (F.S.) per day for all species, except for $SO_2$. The $SO_2$ channel was not calibrated for this testing since it was not an important part of the testing protocol. Other specifications of the instruments and detectors are provided in Table 2.

**Table 1 - Gas Analyzer Methods and Concentration Ranges**

| Component | Detector | Ranges |
|---|---|---|
| Nitrogen Oxides (NOx) | Heated Chemiluminescence Detector (HCLD) | 0-25, 50, 100, 250, 500, 1000, & 2500 ppmv |
| Carbon Monoxide (CO) | Non dispersive Infrared Absorption (NDIR) | 0-200, 500, 1000, 2000, & 5000 ppmv |
| Carbon Dioxide ($CO_2$) | Non dispersive Infrared Absorption (NDIR) | 0-5, 10, & 20 vol% |
| Sulfur Dioxide ($SO_2$) | Non dispersive Infrared Absorption (NDIR) | 0-200, 500, 1000, & 3000 ppmv |
| Oxygen | Zirconium oxide sensor | 0-5, 10, & 25 vol% |

**Table 2 - Quality Specifications for the Horiba PG-250**

| | |
|---|---|
| **Repeatability** | ±0.5% F.S. ($NO_x$: ≤100ppm range CO: ≤1000ppm range)<br>±1.0% F.S. |
| **Linearity** | ±2.0% F.S. |
| **Drift** | ±1.0% F.S./day($SO_2$: ±2.0%F.S./day) |

### 2.1.2. Measuring Continuous PM Emissions

The approach involved the use of a partial flow dilution system with an eductor. Raw exhaust gas was transferred from the exhaust pipe to the dilution tunnel through the sampling probe and the transfer tube due to the negative pressure created by the eductor. The transfer tube was insulated to prevent condensation of exhaust components at any point in the sampling and analytical systems. The flow rate for the dilution tunnel is determined by compared the measured pressure drop and comparing this against a previous measured calibration curve of flow rate vs. pressure drop.

The gas flow rate through the transfer tube depends on the momentum exchange at the eductor zone and is therefore affected by the absolute temperature of the gas at the exit of the transfer tube. Consequently, the exhaust split for a given tunnel flow rate is not constant, and the dilution ratio at low load is slightly lower than at high load. The dilute stream was then sampled using a DustTrak nephalometer, an instrument that measures particle concentrations using a light-scattering technique.

### 2.1.3. Integrated PM Emissions Measurements

A second PM sampling system was employed for the lift/lower testing cycles. A Simplified Field Test Method (SFTM) was developed to measure particulate matter (PM) emissions from compression ignition (CI) engine applications. The SFTM was intended as a screening tool to identify high-emitting engines or those with faulty emission control equipment.

The basic components of the SFTM sampling system included: 1) a small, short metal probe placed in the raw exhaust stream at a single sampling point, 2) an insulated filter holder, 3) a PTFE filter, 4) a moisture removal device, 5) a critical flow orifice (CFO), and 6) a sample pump. The key elements of the prototype design used in this research are shown in Figure 2.

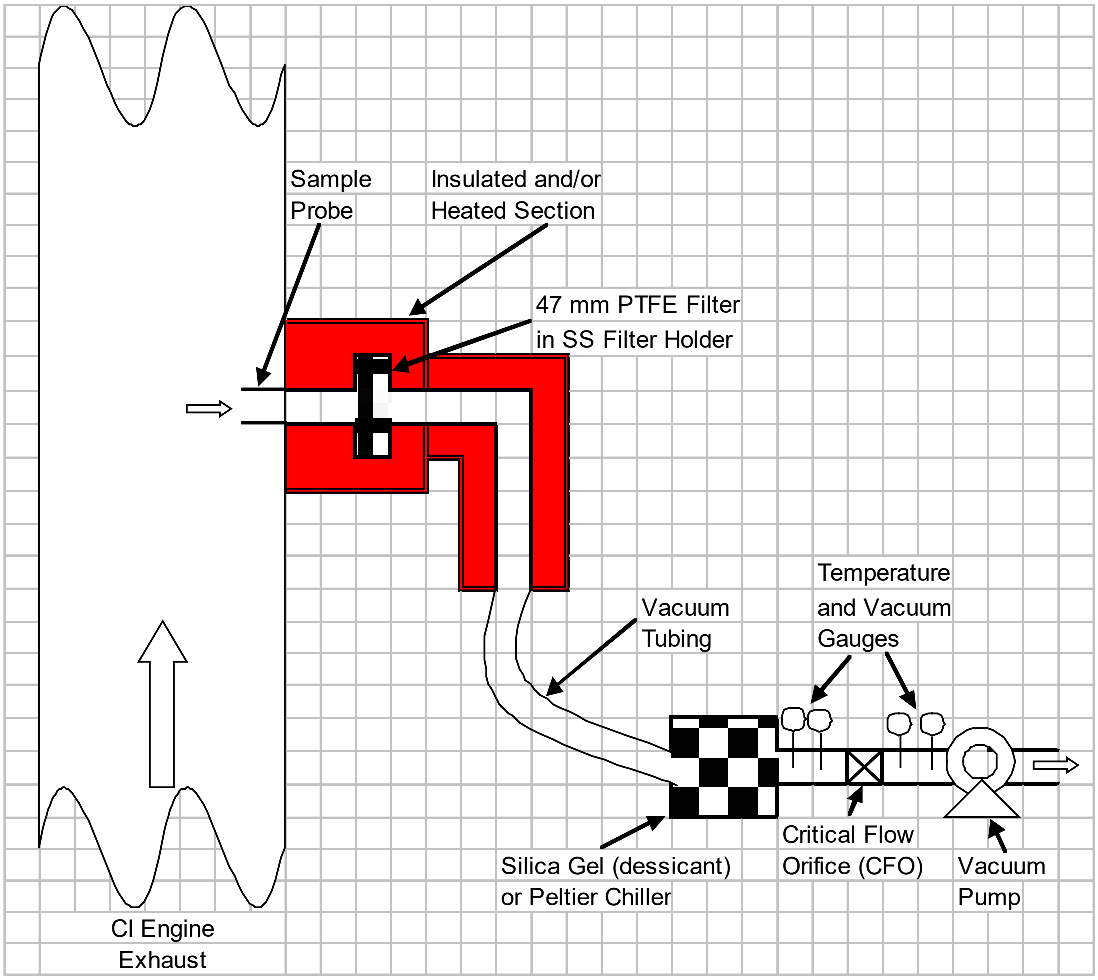



**Figure 2 - Design of the Simplified Field Test Method for Measuring PM**

PM samples were collected on a pre-weighed Teflo™ filter for the lift/lower cycles and were analyzed according to standard gravimetric procedures. Teflo™ filters used to acquire PM mass were weighed following the procedure of the Code of Federal Regulations (CFR) (40 CFR Part 86). Briefly, total PM was collected on Pall Gelman (Ann Arbor, MI) 47 mm Teflo™ filters and weighed using a Mettler (Toledo) microbalance. Before and after collection, the filters were conditioned for 24 hours in an environmentally controlled room (RH = 40%, $T$ = 25 °C) and weighed daily until two consecutive weight measurements were within 3 µg were obtained.

## 2.2. Test Set-up

The test setup included the emissions measurement systems, an engine control module interface, a power source, and data acquisition systems.

The emissions analyzer system on the construction equipment was powered by a small power generator that could provide sufficient power for the operation of the emissions units for an entire day. The emissions analyzers and data acquisition system were housed in an aluminum frame to provide protection from excessive vibration on the equipment and allow the analyzers to be effectively secured to the construction equipment. The frame was secured down to the equipment using straps and cross tied to ensure the analyzers were stable over the course of a test day. Figures 3 and 4 show the installations of the emissions analyzer on the front-end loader.

There were a number of problems encountered during the course of the test campaigns; mainly related to the dynamic forces of the in-use construction equipment on the sampling apparatus. The vibration and sudden movements associated with operating the equipment led to testing issues for a subset of the tests, including the dislodging of the sample probe from the exhaust stack, missing ECM data due to a disconnected signal cable, and a datalogger malfunction.

**Figure 3 - Installation of the Real-Time Emissions Measurement System on the Front-End Loader**


**Figure 4. Installation of the Generator and integrated PM Measurement System**

## 2.3. Testing

Arrangements were made with I/O Environmental and Camp Pendleton for in-field measurements of two front-end loaders. The loaders were being used for soil remediation projects at two different sites at Camp Pendleton. Both loaders were Caterpillar 966H models, manufactured in 2006. One loader was equipped with a Huss soot filter.

Two test modes were developed to simulate the actual in-use activity of the front-end loader application. One involved lifting and lowering a full load of dirt in the front shovel. Each lift/lower repetition occurred at approximately 13 second intervals, but varied somewhat between different operators. The lift/lower cycles were repeated for 6 minutes continuously during sample collection. The second mode consisted of a transit cycle, simulating travel to and from the remediation site and the clean-up pile. This cycle was simulated by driving the loader approximately 50 yards, stopping, backing up, turning around, and driving back. This cycle was repeated for approximately 21 minutes, with the data parsed into three 7 minute segments.

For the lift/lower cycles, integrated PM samples and real-time gaseous and PM samples were acquired. For the transit cycles, only the real-time instruments were used.

For each loader, the cycles were tested first using CARB off-road (red dye) diesel fuel. A second set a tests was then performed using a 20% blend of biodiesel in CARB diesel (B20).

# 3.0 Results

The real-time results for typical runs are provided below in Figures 5 and 6. The data are presented on a concentration basis. The data for $CO_2$ are divided by 75 so that all pollutants can be shown on the same graph.

Figure 5 shows data collected with the measurement system for the standard front-end loader performing lift/lower cycles using CARB diesel. This data shows peaks during the lift portions of the cycle, followed by drop-offs during the lowering portions of the cycle.

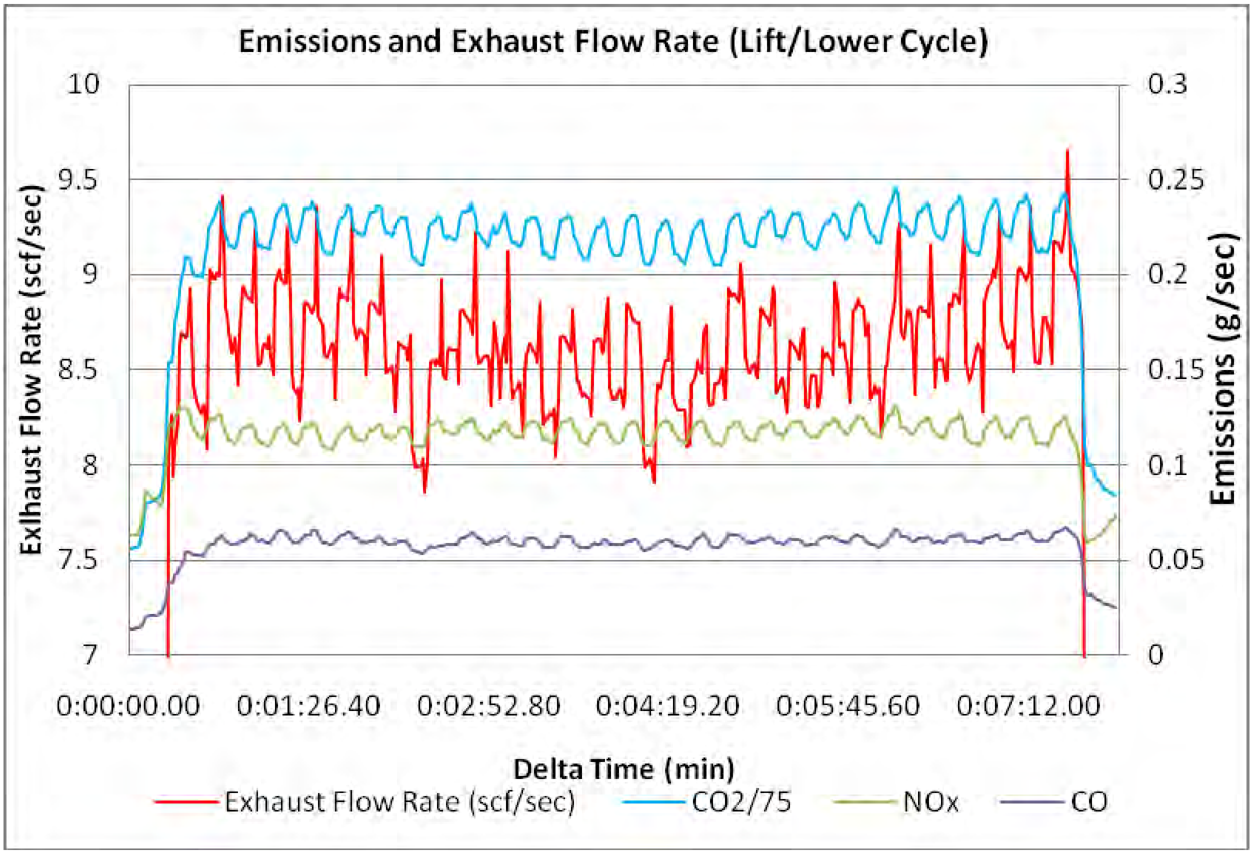



**Figure 5 – Real-Time Emissions Concentrations (Lift/Lower Cycle)**

Figure 6 shows a test run on the front end loader running a transit cycle on CARB diesel. The peaks and valleys correspond to the loader stopping, turning around, and resuming the transit in repetition. Note that the exhaust flow rate and emission concentrations are higher for the transit cycles than for the lift/lower cycles.

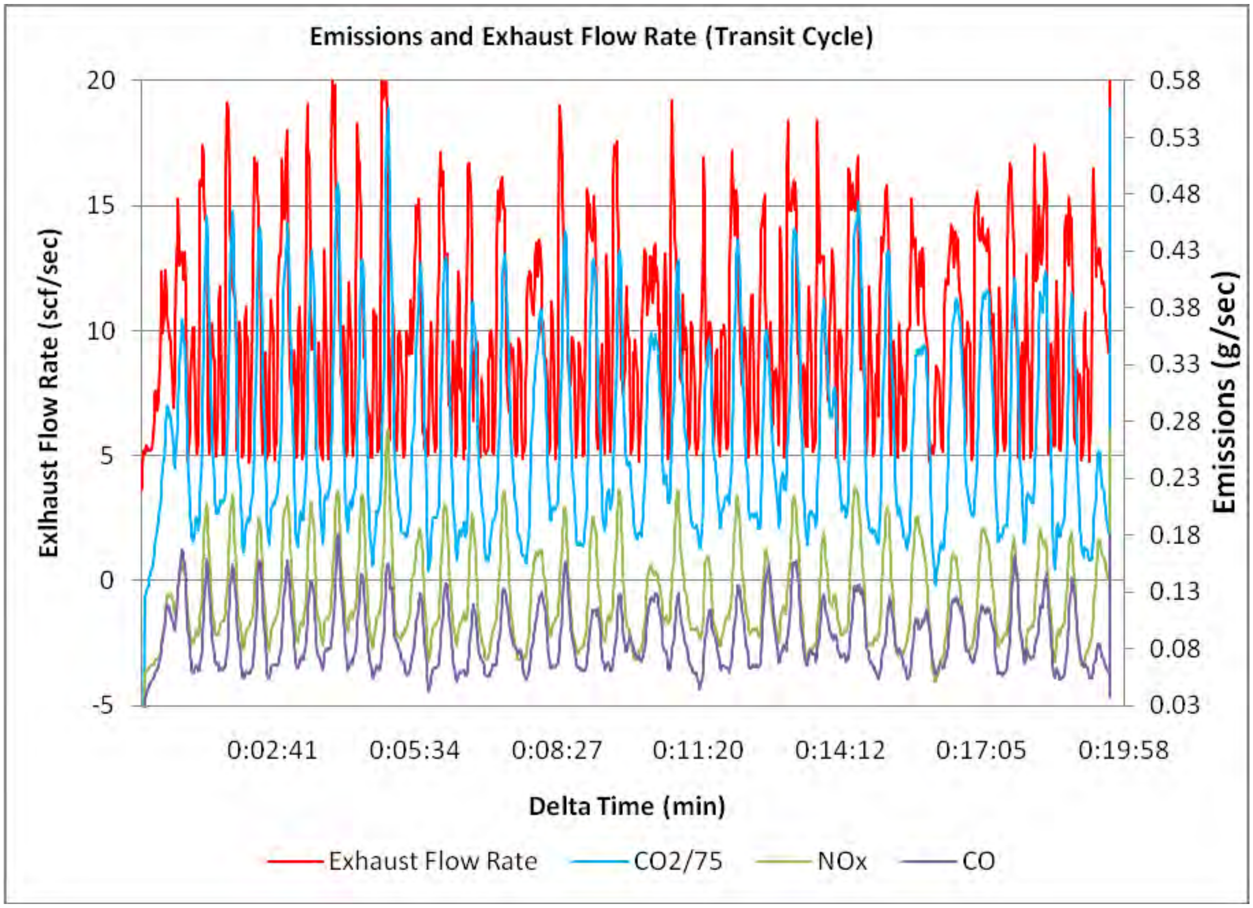



**Figure 6 – Real-Time Emissions Concentrations (Transit Cycle)**

Exhaust flow rate was determined from data collected from the engine control module (ECM). Specifically, flow rate was calculated from the engine displacement, engine speed, boost pressure, and intake manifold temperature. Average brake-specific emission factors were determined for each of the test cycles for both front-end loaders. Tables 3 and 4 contain the average emission factors for the standard loader and loader equipped with the PM filter, respectively. The PM emission factors for the transit cycles are based upon the correlation between the PM filter samples and the DustTrak nephalometer continuous PM measurements. Emissions data for the lift/lower cycle for the stock front-end loader running B20 was unavailable because the sample probe was dislodged from the exhaust stack. ECM data was missing for the transit cycle for the stock loader running on diesel because the signal cable disconnected at the beginning of the test. Finally, there was no emissions data collected for the transit cycle for the filter-equipped loader running on B20 due to a datalogger malfunction.

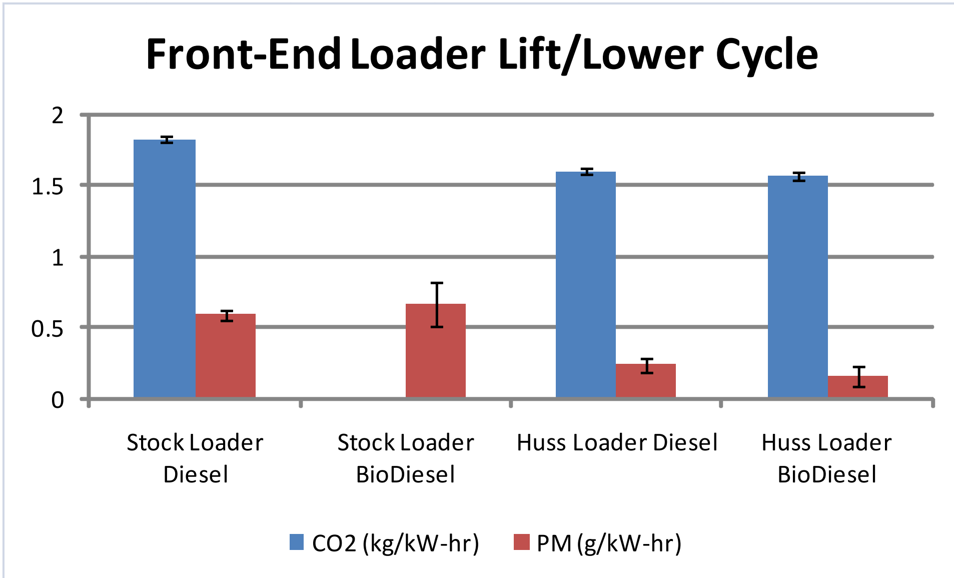
**Table 3 - Emission Factors for Standard Front-End Loader**

| | test # | Power (kW) | NOx (g/kW-hr) | CO (g/kW-hr) | CO2 (kg/kW-hr) | PM (g/kw-hr) |
|---|---|---|---|---|---|---|
| **lift/lower diesel** | 1 | 51.55 | 5.97 | 9.50 | 1.83 | 0.63 |
| | 2 | 51.47 | 5.91 | 9.54 | 1.83 | 0.57 |
| | 3 | 51.74 | 6.10 | 9.30 | 1.79 | 0.57 |
| | **AVG** | **51.59** | **5.99** | **9.45** | **1.82** | **0.59** |
| | **SD** | **0.139** | **0.10** | **0.13** | **0.02** | **0.033** |
| | test # | Power (kW) | | | | **PM (g/kw-hr)** |
| **lift/lower biodiesel** | 1 | 75.63 | | | | 0.81 |
| | 2 | 60.54 | | | | 0.67 |
| | 3 | 62.43 | | | | 0.51 |
| | **AVG** | **66.20** | | | | **0.67** |
| | **SD** | **8.221** | | | | **0.151** |
| | **test #** | **Power (kW)** | **NOx (g/kW-hr)** | **CO (g/kW-hr)** | **CO2 (kg/kW-hr)** | **PM (g/kw-hr)** |
| **transit biodiesel** | 1 | 86.53 | 6.17 | 6.02 | 1.36 | 0.161 |
| | 2 | 78.87 | 5.89 | 5.96 | 1.32 | 0.159 |
| | 3 | 74.13 | 6.03 | 5.88 | 1.34 | 0.162 |
| | **AVG** | **79.85** | **6.03** | **5.95** | **1.34** | **0.161** |
| | **SD** | **6.258** | **0.14** | **0.07** | **0.02** | **0.001** |

**Table 4 - Emission Factors for a Front-End Loader Equipped with a PM Filter**

| | test # | Power (kW) | NOx (g/kW-hr) | CO (g/kW-hr) | CO2 kg/kW-hr | PM (g/kW-hr) |
|---|---|---|---|---|---|---|
| **lift/lower diesel** | 1 | 33.22 | 12.28 | 5.67 | 1.62 | |
| | 2 | 38.11 | 11.12 | 5.66 | 1.58 | 0.28 |
| | 3 | 38.76 | 10.85 | 5.76 | 1.58 | 0.21 |
| | **AVG** | **36.70** | **11.70** | **5.67** | **1.60** | **0.24** |
| | **SD** | **3.029** | **0.82** | **0.01** | **0.02** | **0.05** |
| | **test #** | **Power (kW)** | **NOx (g/kW-hr)** | **CO (g/kW-hr)** | **CO2 kg/kW-hr** | **PM (g/kW-hr)** |
| **lift/lower biodiesel** | 1 | 39.84 | 10.91 | 5.61 | 1.57 | 0.25 |
| | 2 | 38.84 | 10.85 | 5.60 | 1.55 | 0.13 |
| | 3 | 36.65 | 11.32 | 5.81 | 1.61 | 0.10 |
| | **AVG** | **38.44** | **11.03** | **5.67** | **1.57** | **0.16** |
| | **SD** | **1.635** | **0.25** | **0.12** | **0.03** | **0.076** |
| | **test #** | **Power (kW)** | **NOx (g/kW-hr)** | **CO (g/kW-hr)** | **CO2 kg/kW-hr** | **PM (g/kW-hr)** |
| **transit diesel** | 1 | 60.72 | 7.65 | 5.21 | 1.18 | 0.188 |
| | 2 | 58.78 | 7.61 | 5.30 | 1.21 | 0.191 |
| | 3 | 56.96 | 7.84 | 5.84 | 1.30 | 0.196 |
| | **AVG** | **58.82** | **7.70** | **5.45** | **1.23** | **0.192** |
| | **SD** | **1.881** | **0.12** | **0.34** | **0.06** | **0.004** |

Graphical comparisons between the two loaders are presented in Figures 7 and 8. Figure 7 shows the emission factors for both loaders performing the lift/lower cycle. Figure 8 shows the emission factors for both loaders performing the transit cycle.



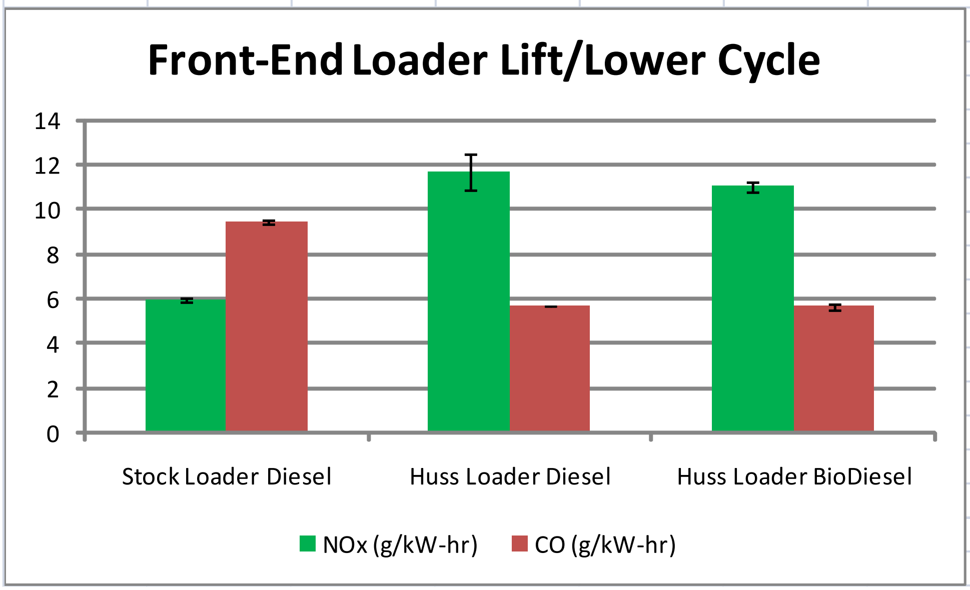




**Figure 7 – Front-End Loader Emission Factors for Lift/Lower Cycles**

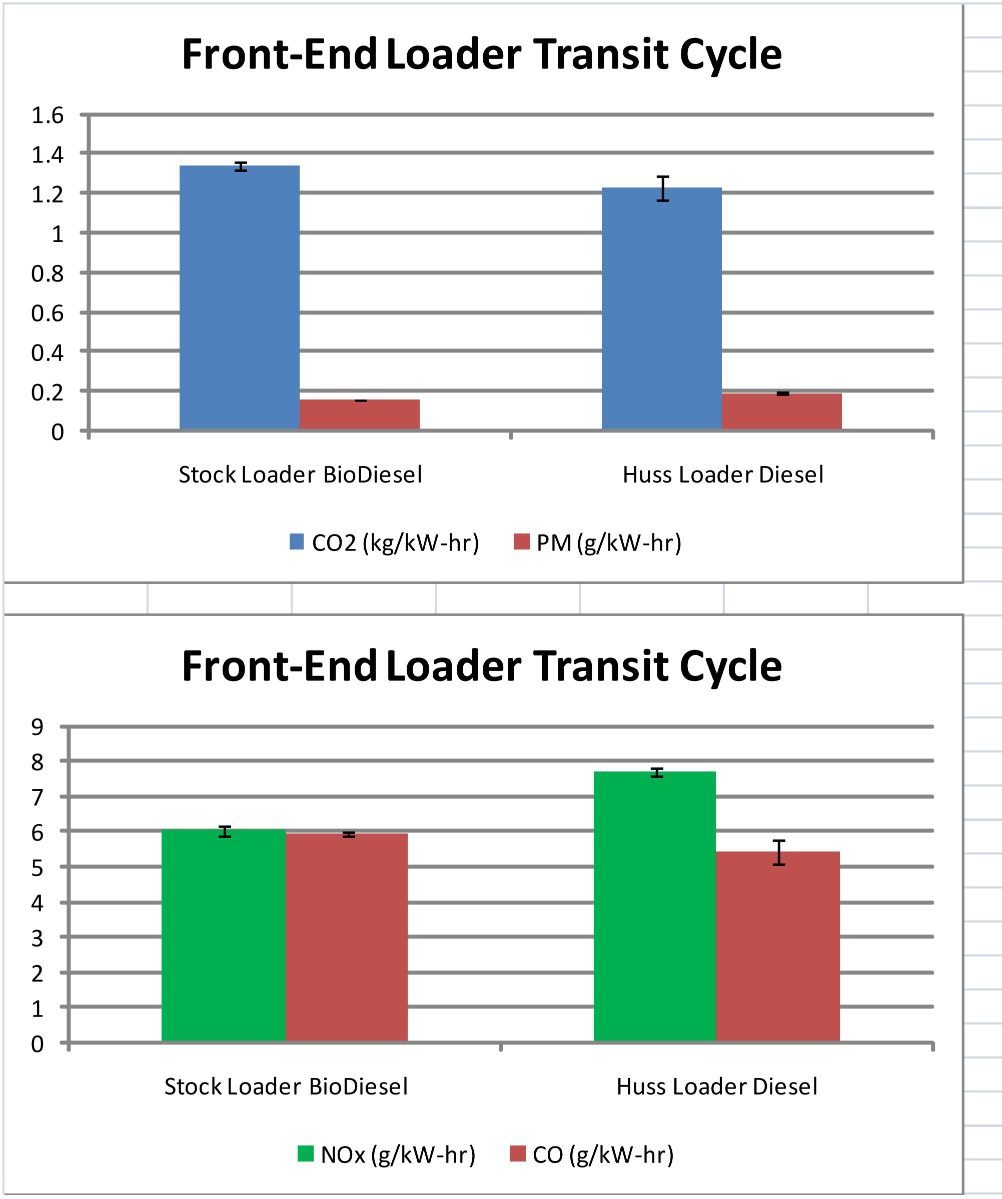



**Figure 8 – Front-End Loader Emission Factors for Transit Cycles**

# 4.0 Discussion

This research program focused on construction equipment emissions testing using baseline diesel fuel, a 20% blend of biodiesel, and a DPF. The two front-end loaders tested had identical power plants, with one of the engines equipped with a flow-through particulate matter filter. The emissions measurements were made on a second-by-second basis using a portable emissions measurement system (PEMS) to develop emission factors for two types of "in-use" cycles.

Key findings of the two test campaigns include:

- It is critical to provide as consistent and repeatable as possible driving patterns to evaluate the effects of aftertreatment or fuels. For the test cycles studied, the engines were operating at the very low end of the power curve (between 5% to 50% full load). At lower loads, emission factors increase and become less consistent. For example, power ratings for the stock lift and lower cycles ranged from 52 to 66 kW compared to 37-38 kW for the DPF equipped filter. Similarly, the power for the stock transient cycle averaged 80 kW compared to 59 kW for the DPF equipped filter. This made comparisons between the two loaders and the different emissions strategies more difficult.

- The DPF provided reductions in PM for the lift/lower cycle, but no reductions were seen for the transient cycle. There were no consistent differences in emissions between baseline diesel fuel and biodiesel for either of the loaders or test cycles. For the transient cycle, the emissions for the DPF-equipped loader running on biodiesel were actually slightly higher than those for the stock loader. This is probably due to the differences in operation and power/load levels between the two sites.

- For both the lift/lower and transient cycles, $NO_x$.emissions were higher for the the test with the DPF-equipped loader. This was not conclusive, however, as the average loads were different for the different sites, as discussed above.

- CO emissions showed reductions for the lift/lower cycles for the DPF-equipped loader, but no differences were found between the DPF-equipped loader and the stock loader for the transient cycle.

- $CO_2$ emissions showed some differences between the stock loader and the DPF-equipped loader for the lift/lower cycle. These differences are probably related to the differences in load conditions seen for the two pieces of equipment. Smaller differences in $CO_2$ emissions were seen between the two vehicles for the transient cycle.

The overall results did not show any conclusive differences between the standard front-end loader and the loader equipped with the DPF, with the exception of the PM reductions found for the lift/lower cycle. This result could be due in part to the difficulties in obtaining consistent power loads for the comparison tests. The results showed no difference in emission factors between the baseline diesel and B20 fuels.

There were a number of problems encountered during the course of the test campaigns; mainly related to the dynamic forces of the in-use construction equipment on the sampling apparatus. The vibration and sudden movements associated with operating the equipment led to testing issues for a subset of the tests, including the dislodging of the sample probe from the exhaust stack, missing ECM data due to a disconnected signal cable, and a datalogger malfunction.