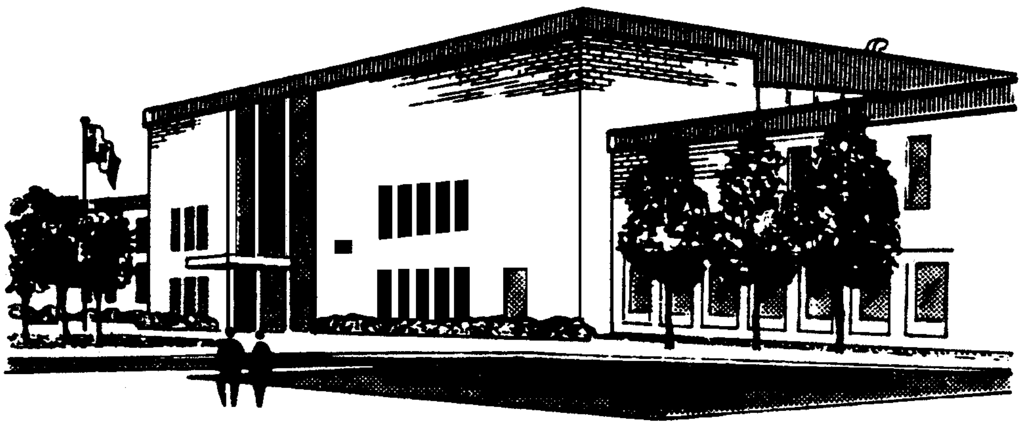
City of Houston Diesel Field Demonstration Project – Phase II



ERMD REPORT # 02-28
November, 2003
Prepared by: Jill Hendren
ENVIRONMENTAL TECHNOLOGY CENTRE
EMISSIONS RESEARCH AND MEASUREMENT DIVISION

Environment Canada Environnement Canada

Canada

NOTICE

Any comments concerning its content should be directed to:

Environment Canada

Environmental Technology Advancement Directorate

Environmental Technology Centre

Ottawa Ontario K1A 0H3

Executive Summary

The City of Houston, as part of its commitment to the SIP (State Implementation Plan), initiated a testing program in order to evaluate the ability of various emission control technologies to reduce NOx and TPM from a variety of vehicle types operating on diesel fuel. This project focused on two types of emission control technologies for on and/or off-road diesel vehicles: Englehard's exhaust gas recirculation (EGR) and DPX particulate filter system, and Extengine's selective catalytic reduction (SCR) system.

Testing was undertaken by staff from the Emissions Research and Measurement Division (ERMD) of Environment Canada who traveled to Houston, along with a mobile sampling unit and analyzer bench, in order to collect and analyze exhaust emission samples from the test vehicles operating, in the field, under real world conditions. The project was based at Ellington Field (EFD) airport, with the exception of the testing of one vehicle that took place from the Barbours Cut Cruise Terminal at the Port of Houston. Testing was completed over an 8 month time frame. This project formed phase II of the City of Houston Diesel Field Demonstration Project, ERMD report # 01-36 dated March 2002.

Testing of the various vehicles showed a wide range of emission reductions. Englehard's EGR/DPX system showed a 27% to 68% reduction in NO_x emissions, a 56% to 95% reduction in CO emissions, a 26% to 32% reduction in THC, and a 56% to 76% reduction in TPM. During testing with Extengine's SCR, THC showed reductions of up to 72%, while CO showed reductions of 51% to 89%, TPM was reduced up to 56%, and NOx showed up to 67% reductions. Neither system appeared to have a negative effect on vehicle emissions. Quite often there is a trade off between NOx and TPM emissions, and this can pose a problem when dealing with equipment implementation decisions.

Table of Contents

1.0 Introduction 1

2.0 Vehicles 2

3.0 Test Fuels 3

4.0 Sampling System 3

4.1 Dynamic Dilution On/Off-road Emission Sampling (DOES2) System 3
4.2 Analyzers 5
4.3 Data Acquisition 6

5.0 Vehicle Instrumentation 6

5.1 Engine Speed 7
5.2 Exhaust Temperature 7
5.3 Air Intake 7

6.0 Sampling Set up 8

6.1 Mounting of DOES2 and Generator 9
6.2 Heated Line and Exhaust Probe 10

7.0 Test Cycles 10

7.1 Dump truck Cycle (from the Ellington Field Location) 10
7.2 Gradall G3WD Test Cycle 11
7.3 Gradall XL5200 Test Cycle 13
7.4 Dump Truck Test Cycle (from the Barbours Cut Cruise Terminal) 14
7.5 Vacuum Pump Test Cycle 16
7.6 Automated Side loader Test Trace 17
7.7 Test Repeatability 19

8.0 Test Procedures 21

8.1 System Verification and Repeatability 22

9.0 Results and Discussions 23

9.1 Engelhard EGR System with a DPX Particulate Filter 24
9.2 Extengine SCR System 28
9.2.1 Ammonia Slip 36

10.0 Conclusions 37

Acknowledgements 37

List of Tables

Table 1. City of Houston Test Fleet Specifications 2
Table 2: Test Fuel Properties...3
Table 3. Operating Parameter Averages for Each Set of Tests for Dump TXDot 20-5737-E 21
Table 4. Automated Side Loader # 30319 Emissions Rates (g/min)..........................25
Table 5. Percent Difference in Emissions (g/min) Between the Baseline and Retrofit Average Results (From Table 4) 25
Table 6. Vacuum Pump #30491 Emissions Rates (g/min)...25
Table 7. Percent Difference in Emissions (g/min) Between the Baseline and Retrofit Average Results (From Table 6) 26
Table 8. Vacuum Pump #30490 Emissions Rates (g/min) Durability with Engelhard EGR/DPX...27
Table 9. Percent Difference in Emissions (g/min) Between the Baseline and the Retrofit Average Results (From Table 8)..28
Table 10. Gradall #23505 Emissions Rates (g/min) 30
Table 11. Percent Difference in Emissions (g/min) Between the Baseline and Retrofit Average Results (From Table 10)..30
Table 12. Gradall #26795 Emissions Rates (g/min) 31
Table 13. Percent Difference in Emissions (g/min) Between the Baseline and Retrofit Average Results (From Table 12)..31
Table 14. Gradall #30665 Emissions Rates (g/min) 32
Table 15. Percent Difference in Emissions (g/min) Between the Baseline and Retrofit Average Results (From Table 14)..32
Table 16. Dump Truck # 31520 Emissions Rates (g/min) 33
Table 17. Percent Difference in Emissions (g/min) Between the Baseline and Retrofit Average Results (From Table 16)..33
Table 18. Dump Truck # TXDot 20-5737-E Emissions Rates (g/min) 34
Table 19. Percent Difference in Emissions (g/min) Between the Baseline and Retrofit Average Results (From Table 18)..34
Table 20. Gradall #20025 Emissions Rates (g/min) 35
Table 21. Gradall #19546 Emissions Rates (g/min) 36
Table 22. Gradall #26609 Emissions Rates (g/min) 36

List of Figures

Figure 1. Schematic Flow Diagram of the DOES2 4
Figure 2. Analyzers and Gas Cylinders in the Barbours Cut Cruise Terminal at the Port of Houston 6
Figure 3. LFE Mounted to Engine Air intake on a Gradall Model G3WD................8
Figure 4. Exhaust Probe, Temperature Thermocouple, and Heated line 8
Figure 5. DOES2 and On Board Computer Fastened to Vacuum Pump..................9
Figure 6. DOES2 and On Board Computer Fastened to Gradall XL5100.................9
Figure 7. Typical Dump Truck (Ellington Field) Engine Air Intake Profile 11
Figure 8. Typical Dump Truck (Ellington Field) Exhaust Engine Profile 11
Figure 9. Typical Gradall G3WD Engine Air Intake Profile 12
Figure 10. Typical Gradall G3WD Exhaust Temperature Profile............................12
Figure 11. Typical Gradall G3WD Engine Speed Profile 13
Figure 12. Typical Gradall XL5200 Engine Air Intake Profile.................................13
Figure 13. Typical Gradall XL5200 Exhaust Temperature Profile 14
Figure 14. Typical Gradall XL5200 Engine Speed Profile..14
Figure 15. Typical Dump Truck (Barbours Cut Cruise Terminal) Air Intake Profile 15
Figure 16. Typical Dump Truck (Barbours Cut Cruise Terminal) Exhaust Temperature Profile...15
Figure 17. Typical Dump Truck (Barbours Cut Cruise Terminal) Engine Speed Profile 16
Figure 18. Typical Vacuum Pump Engine Air Intake Profile 16
Figure 19. Typical Vacuum Pump Exhaust Temperature Profile 17
Figure20. Typical Vacuum Pump Engine Speed Profile..17
Figure 22. Typical Automated Side loader Exhaust Temperature Profile...............18
Figure 23. Typical Automated Side loader Engine Speed Profile 19
Figure 24. Engine Speed Over Four Baseline and Four Retrofit Tests (Dump Truck # 31520) 20
Figure 25. Engine Air Intake Baseline vs. Retrofit (Dump Truck TXDoT 20-5737-E) 20
Figure 26. DOES2 System Verification Diagnostic Chart 22
Figure 27. Percent Reductions From Baseline: Retrofit vs. Durability...................28

1.0 Introduction

The state of the natural environment is fast becoming one of the most prominent issues facing governments and industry today. They find themselves under increasing pressure to curb the rise of, and even decrease vehicle emissions. One large area of focus is mobile source emissions. Vehicles operated on diesel fuel contribute significantly to ambient air pollutants. These emissions include Oxides of Nitrogen (NOx), Carbon Monoxide (CO), Carbon Dioxide (CO_2), unburned hydrocarbons (THC), and particulate matter, which was declared toxic by the California Air Resource Board.[1] These emissions are of concern for a number of reasons including, detrimental effects to human health,[2] and to the environment, where they contribute to ground level ozone, acid rain, and global warming.

The City of Houston, as part of its commitment to the SIP (State Implementation Plan), wanted to evaluate the ability of various emission control technologies to reduce NOx and TPM from a variety of vehicle types operating on diesel fuel, in the field under real world conditions. The SIP is the state of Texas' way of complying with the Federal Clean Air Act. In the State of Texas there are currently four urban areas that do not meet the federal ozone standards, one of which is the Houston-Galveston area[3]. This area is referred to as a severe-17 (ozone design value between 0.190 and 0.280 ppm)[4] non-attainment area (does not meet National Ambient Air Quality Standards established by the EPA), and has until 2007 to meet the federal one-hour standard of 0.12ppm.

Ozone is formed primarily through chemical reactions in the atmosphere between sunlight, and NOx and Volatile Organic Carbons (VOCs). This fact is important to this project as mobile sources account for 53% of NOx emissions; of this 53%, 12% is attributed to non-road mobile sources (construction, agricultural, and industrial equipment). [5,6] This project focused on two types of emission control technologies for on and/or off-road diesel vehicles: Englehard's exhaust gas recirculation (EGR) and DPX particulate filter system, and Extengine's selective catalytic reduction (SCR) system.

Staff from the Emissions Research and Measurement Division (ERMD) of Environment Canada traveled to Houston, along with a mobile sampling unit and analyzer bench, in order to collect and analyze exhaust emission samples from the test vehicles operating

---

[1] California Environmental protection Agency. Air Resources Board. "ARB Identifies Diesel ParticulateEmissions as a Toxic Air Contaminant." Release 98-51. August 1998.

[2] US Environmental Protection Agency. Office of Mobile Sources. Regulatory Announcement "New Emission Standards from Heavy Duty Diesel Engines Used in Trucks and Buses." EPA 420-F-97-016. 1997

[3] *Texas Natural Resource Conservation Commission*. URL:.Http://www.tnrcc.state.tx.us/air/monops/ozonefacts.html#extent. [Sept.2003].

[4] Clean Air Act 1990 Amendment. Title 1. Part D, Subpart 2. 181(a) 2.

[5] US Environmental Protection Agency. National Air Pollutants Emission Trends, 1990-1998. EPA-454/R-00-002. March, 2002.

[6] US Environmental Protection Agency. Office of Mobile Sources. "Reducing Non-road Diesel Emissions– Low Emissions Program Summary." EPA 420-F-03-008. April 2003

under real world conditions. The project was based at Ellington Field (EFD) airport, with the exception of the testing of one vehicle that took place at the Barbours Cut Cruise Terminal at the Port of Houston. Testing was completed over an 8-month time frame.

2.0 Vehicles

The test fleet consisted of a variety of on and off-road diesel vehicles. Details on the test vehicles are provided in Table 1.

Table 1. City of Houston Test Fleet Specifications

UNIT #	YEAR	EQUIPMENT TYPE	USE	ENGINE MANUFACTURER	ENGINE MODEL	TECHNOLOGY
19546*	1992	Gradall G3WD Excavator	Off-road	CUMMINS	6BTA 5.9 173HP	EXTENGINE SCR
20025	1992	Gradall G3WD Excavator	Off-road	CUMMINS	6BTA 5.9 173HP	EXTENGINE SCR
23505	1994	Gradall XL5100 Excavator	Off-road	CUMMINS	6CTA 8.3T 240HP	EXTENGINE SCR
26609*	1996	Gradall G3WD Excavator	Off-road	CUMMINS	6BTA 5.9 173HP	EXTENGINE SCR
26795	1997	Gradall XL5200 Excavator	Off-road	CUMMINS	6BTA 5.9 162HP	EXTENGINE SCR
30298*	1999	Automated Side loader WX64	On-road	VOLVO	VE 275 HP	ENGELHARD EGR
30319	1999	Automated Side loader WX64	On-road	VOLVO	VE 275 HP	ENGELHARD EGR
30490	2000	Vacuum Pump WG674	On-road	CUMMINS	ISM 365HP	ENGELHARD EGR
30491	2000	Vacuum Pump WG674	On-road	CUMMINS	ISM 365HP	ENGELHARD EGR
30665	2000	Gradall G3WD	Off-road	CUMMINS	6BTA 5.9 173HP	EXTENGINE SCR
31520 (replaced 31521)	2000	Volvo VHD64B Dump Truck	On-road	VOLVO	VED12B-345	EXTENGINE SCR
TXDoT 20-5737-E	1993	International 2574 6X4 Dump Truck	On-road	CAT	3176	EXTENGINE SCR

* Indicates vehicle testing was not completed.

3.0 Test Fuels

All of the test vehicles, with the exception of vacuum pump # 30490, and Automated Side Loader # 30298, were tested while running on regular #2 diesel fuel. This fuel was supplied by the City of Houston from their fleet stock. Vacuum pump #30490 and Automated Side Loader # 30298 were tested running on TexLed fuel. These two vehicles were originally tested with BP Amoco fuel (30ppm sulfur content) during Phase I of this study. Average fuel properties for the regular #2 diesel and TexLed fuels can be found in Table 2. One problem frequently encountered with the use of diesel with a high sulfur content, is the potential poisoning or clogging of catalysts over time, thus restricting the ability of emission control technologies to reduces emissions. This problem will be eased however, due to the implementation of new sulfur content limits in highway diesel fuel (<15ppm sulfur content). This regulation takes effect June 1, 2006[7]. The EPA is also proposing to reduce sulfur levels in non-road diesel fuel to 500ppm by 2007, and down to 15 ppm by 2010[8].

Table 2: Test Fuel Properties

Fuel Property	Regular #2 Diesel	TexLed
API Gravity	32-37	40.2
Sulfur % Weight	<0.05	<0.0015
Ash % Weight	<0.001	0.0014
Water % by Distillation	<0.05	<0.05
Cetane Index	46.0	53.5
Net CalorificValue (mg/kg)	139,568	?

4.0 Sampling System

The sampling set-up consisted of the Dynamic Dilution On/Off-road Emissions Sampling System (DOES2) system, and the following analyzers: a total hydrocarbon (THC) flame ionization detector (FID), an oxides of nitrogen (NOx) chemiluminescence analyzer, a non-dispersive infrared carbon monoxide analyzer (CO), and a non-dispersive infrared carbon dioxide (CO_2) analyzer.

4.1 Dynamic Dilution On/Off-road Emission Sampling (DOES2) System

The primary function of the DOES2 is to collect a known quantity of raw exhaust (partial flow) from the exhaust system of an engine and mix this with a known quantity of

[7] Federal Register. Rules and Regulations. Vol. 66, No.12. January 18, 2001.
[8] US Environmental Protection Agency. Office of Mobile Sources. "Reducing Non-road Diesel Emissions– Low Emissions Program Summary." EPA 420-F-03-008. April 2003

ambient dilution air. Diluting the raw exhaust with ambient air, while maintaining a constant temperature and flow velocity, conditions the sample and minimizes condensation, a major obstacle to particulate matter collection in the field.

To collect the raw exhaust, a probe is inserted into the exhaust pipe of the engine. The probe exit is connected to a dilution tunnel by a heated sample line which is maintained at a temperature of 375 ± 20 degrees Fahrenheit. There are two large vacuum pumps (main and dilution air supply) contained within the vacuum pump enclosure that are used for the DOES2. The main pump is connected to the exit of the dilution tunnel and it draws a continuous quantity of sample through the dilution tunnel. The dilution pump draws air through a pre-filter in order to remove any ambient particle material and then through a variable flow solenoid valve to control the flow rate of the dilution air. The air then goes through the dilution pump and into a plenum located in the DOES2, and eventually through the dilution air Laminar Flow Element (LFE) to measure the flow rate. The dilution air is introduced into the dilution tunnel at a point approximately 3 inches from the raw exhaust inlet. Both streams then pass through a mixing orifice and are thoroughly mixed as they travel approximately 10 tunnel diameters where they reach a sample probe. The volume of diluted exhaust sample is drawn using small vacuum pumps and is set and maintained by mass flow controllers. The diluted sample is collected at the end of the sample line in a Cali-5-Bond™ (5-layer) sampling bag, and is drawn through a particulate filter. This technique is used in order to determine average weighted emission rates over defined periods of operation. Figure 1 represents a schematic flow diagram of the raw sample once it enters the DOES2.

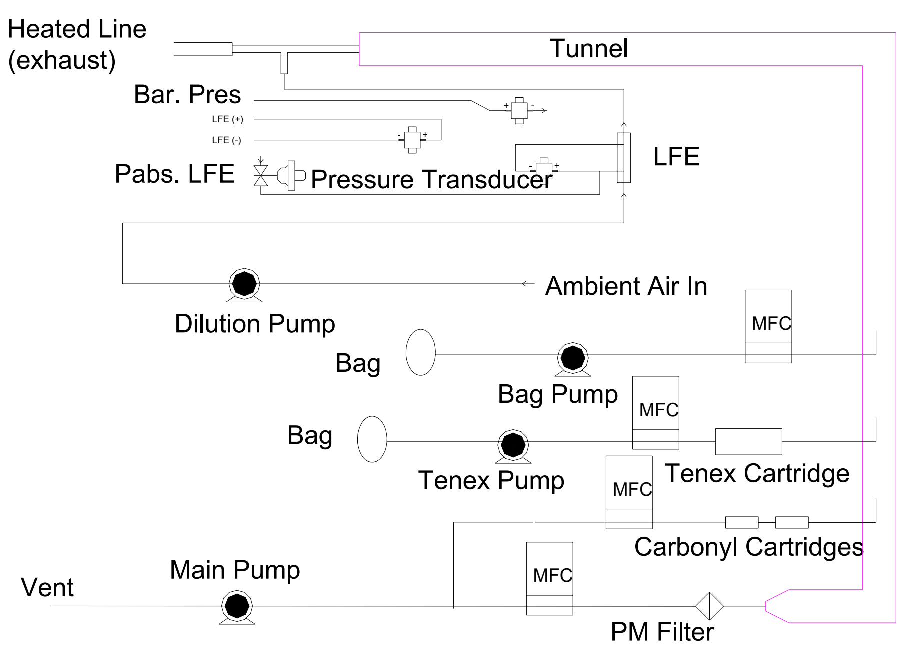


Figure 1. Schematic Flow Diagram of the DOES2

During operation, the engine functions under various speed and load conditions. As a result, the volume of exhaust varies, as does the concentration of the pollutants. In order to accurately measure the emissions under transient conditions, proportional sampling is employed. This is accomplished by varying the flow rate of the dilution air, inversely proportional with the volumetric engine inlet airflow. The instantaneous volume of dilution air is determined from the ratio of the engine inlet air mass at any given instant over the engine inlet air mass at idle. This ratio, multiplied by the exhaust sample flow at idle, is subtracted from the total mass flow rate through the tunnel (which is held constant).

$$Qdil\,(t_n) = Qtotal - \frac{[\text{engine inlet air}\,(t_n)]}{[\text{engine inlet air}\,(t_{idle})]} \times Qexhaust\,(t_{idle})$$

During testing, the engine air intake flow rates were measured using either a 400 or 1000 SCFM LFE connected to the engine air inlet. The airflow is determined on a per second time basis. Prior to commencing the actual test sequence the engine inlet air volume is measured with the engine at idle.

4.2 Analyzers

The emission analyzers and associated reference calibration gases were set up in a construction trailer located at Ellington Field during all but the final two days of testing. The equipment was then moved to the Port of Houston Authority Barbours Cut Cruise terminal for the testing of dump truck # 31520; see Figure 2. The temperature of both locations was maintained between 15 and 25°C.

The manually operated analysis bench, consisting of the following instruments, was used to analyze the gaseous emissions of the diluted samples:

1. Heated Flame ionization detector (HFID) for THC: the analyzer is fitted with a constant temperature oven housing the detector and sample-handling components. The detector, oven and sample-handling components must be suitable for temperatures of up to 395°F maintained by the detector. H_2/He fuel is necessary for the burner operation.
2. Non-dispersive infrared detectors (NDIR) for CO and CO_2: the maximum CO_2 interference measured from the minimum water ratio must be 1000:1 for CO analyzers and 100:1 for CO_2 analyzers, whereas the maximum CO_2 interference determined from the minimum CO_2 rejection ratio for CO analyzers shall be 5000:1.
3. Chemiluminescence (CL) for NOx: the NO_2 to NO converter efficiency must be at least 90% and the CO_2 quench interference less than 3%. Since the CL is not a high vacuum analyzer, the sample must be heated to a range of 140 to 446°F.

For each of the above analyzers, zero and span gases with the appropriate regulators were required at the test location for calibration. Every range used for each analyzer, required a span gas for this purpose.

Figure 2. Analyzers and Gas Cylinders in the Barbours Cut Cruise Terminal at the Port of Houston

4.3 Data Acquisition

A portable industrial grade computer controls the DOES2. The computer was connected to the DOES2 at the appropriate location with the supplied cables. The computer was used to read and record the signals from the various sensors, calculate the dilution air requirement, control the variable flow solenoid valve and calculate the emission rates for each of the regulated exhaust emissions. The computer was secured on each test vehicle and connected to the DOES2 by two 20-pin connectors and a 9-pin serial port connector. A line from the generator powered the computer.

The engine signals that were recorded include:

- Exhaust temperature: thermocouple located in the exhaust pipe
- Engine speed: Hall Effect sensor with magnet attached to flywheel

5.0 Vehicle Instrumentation

Each test vehicle was instrumented with various sensors in order to monitor the engine as it performed its duty cycle. The sensors included an engine speed sensor, an exhaust temperature probe, and an LFE for measuring air intake.

5.1 Engine Speed

The engine speed is normally measured using a rare earth magnet and a Hall effect sensor. The magnet is epoxied onto the crankshaft pulley and the Hall effect sensor is itself epoxied into a 4" long piece of stainless tubing. The pulse train from the sensor is fed into a frequency to voltage converter chip and the computer reads the corresponding voltage. Speed data, like exhaust temperature, is recorded primarily to verify the repeatability of the test cycle.

5.2 Exhaust Temperature

The exhaust temperature was measured using a K-type thermocouple installed in the exhaust manifold using an NPT to Swagelock™ fitting. The thermocouple was connected to the box using K-type extension wire connected to a high gain amplification board. The cold junction reference temperature was measured at the board.

5.3 Air Intake

The engine air intake was measured using either 400 or 1000 SCFM LFE, see Figure 3. The vehicle's air filter was removed and the LFE was placed over the intake pipe using rubber air intake boots and metal adapters. The LFE was secured to the vehicle, to prevent it from moving as the vehicle completed its duty cycle, by means of ratchet straps and bungee cords. To measure the air intake, the pressure drop across the flow element was recorded using a differential pressure transducer mounted in the DOES2. As well, the inlet air density to the element was determined by measuring the absolute pressure and the temperature. The absolute pressure was measured using the barometric pressure for the day. The inlet temperature to the LFE was measured using a thermometer and recorded at the beginning testing. The data from the LFE was converted to a flow rate by the computer, on a per second time basis.

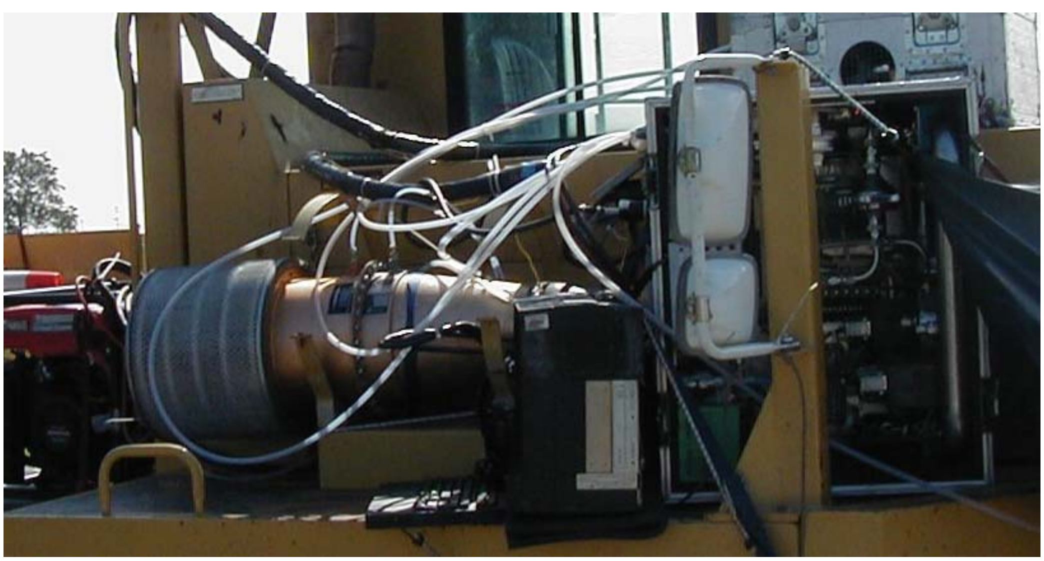


Figure 3. LFE Mounted to Engine Air intake on a Gradall Model G3WD

6.0 Sampling Set up

The set up involved mounting the DOES2 and the generator on the vehicle, installing the LFE, mounting the various sensors, installing the exhaust probe and heated line, running all the lines to the DOES2, and securing the computer on the vehicle. Figure 4. shows the exhaust probe, temperature thermocouple, and heated line, while Figures 5. and 6. show the DOES2 and on board computer mounted on two separate test vehicles.

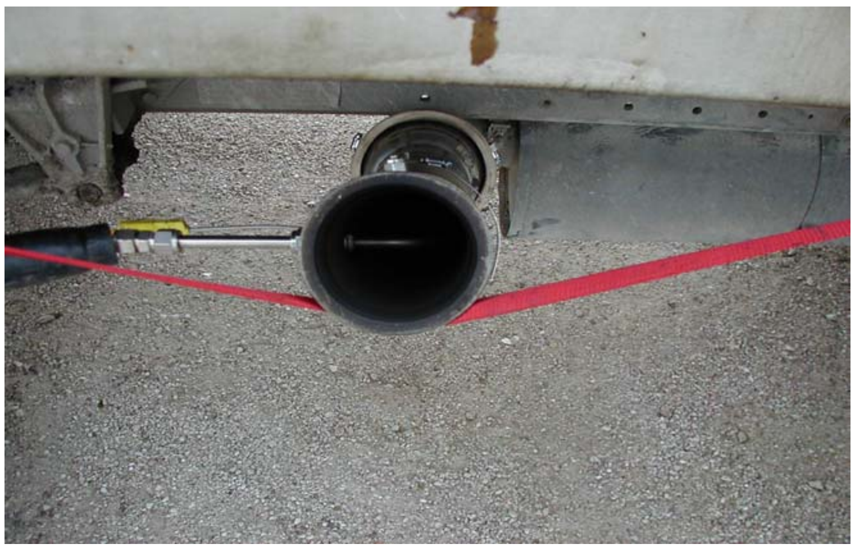


Figure 4. Exhaust Probe, Temperature Thermocouple, and Heated line

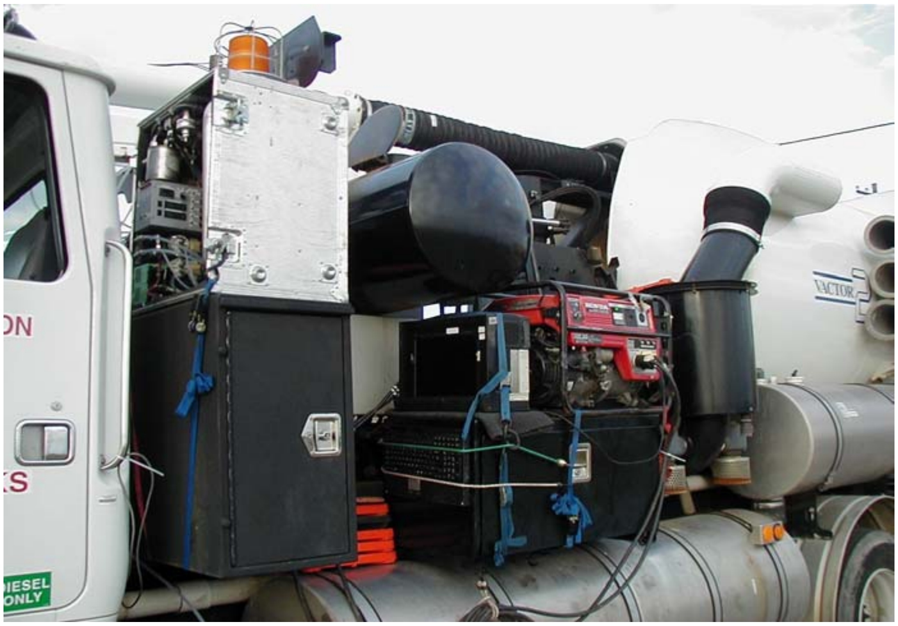


Figure 5. DOES2 and On Board Computer Fastened to Vacuum Pump

Figure 6. DOES2 and On Board Computer Fastened to Gradall XL5100

6.1 Mounting of DOES2 and Generator

The Generac generator, and the DOES2 were mounted at various locations on the test vehicle frames. Efforts were taken, where possible, to minimize the influence of the generator exhaust on the sample results. Possible contamination was dealt with by taking ambient air samples during a warm up run, which preceded the gathering of sample data.

6.2 Heated Line and Exhaust Probe

A 25' long length of heated line connected the exhaust probe to the DOES2. The line was fed out to the exhaust pipe from the DOES2 and fastened to the vehicle frame. The exhaust probe was a piece of $^3/_8$" stainless steel tubing which was bent in such a way as to fit at least 4" down inside the end of the exhaust pipe while being parallel to the flow and lying at the centre of the exhaust cross section. The probe was connected to the heated line with a Swagelock ™ fitting.

7.0 Test Cycles

Care was taken to choose routes that would simulate the normal operating conditions for each type of test vehicle. Another goal in the development of the test traces was to make them as repeatable as possible. The majority of testing took place at Ellington Field among the grid of side streets, where external traffic had, in general, a very minimal effect due to the low volume. Some obstacles encountered during testing included changes in drivers, which has been shown to potentially affect test repeatability, and the barricading of certain pre-determined routes due to security issues associated with the adjacent Armed Forces Base. Between each test cycle there was a 15 to 20 minute soak (dependant on where the test cycle finished and the consequent transit time back to the analysis location). Following the soak, the engine was brought back to operating temperature before the initiation of the next sample run.

7.1 Dump truck Cycle (from the Ellington Field Location)

This route began at the intersection of Galveston Highway #3 and FM 1959. The dump truck would proceed down FM 1959 to the ramp for the I-45 feeder road. Once on the I-45 feeder, the vehicle would exit at Scarsdale Blvd and continue back towards to Hwy #3. This loop would then be repeated for a total distance traveled of approximately 7.58 miles. During this drive cycle the vehicle would travel up to a maximum speed of 50 mph where traffic and speed limits allowed.

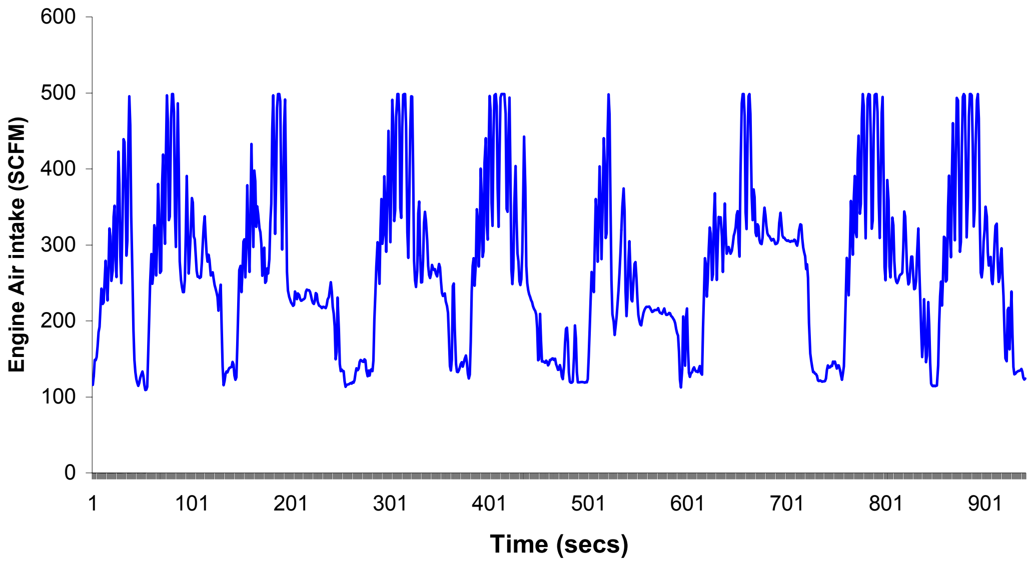


Figure 7. Typical Dump Truck (Ellington Field) Engine Air Intake Profile

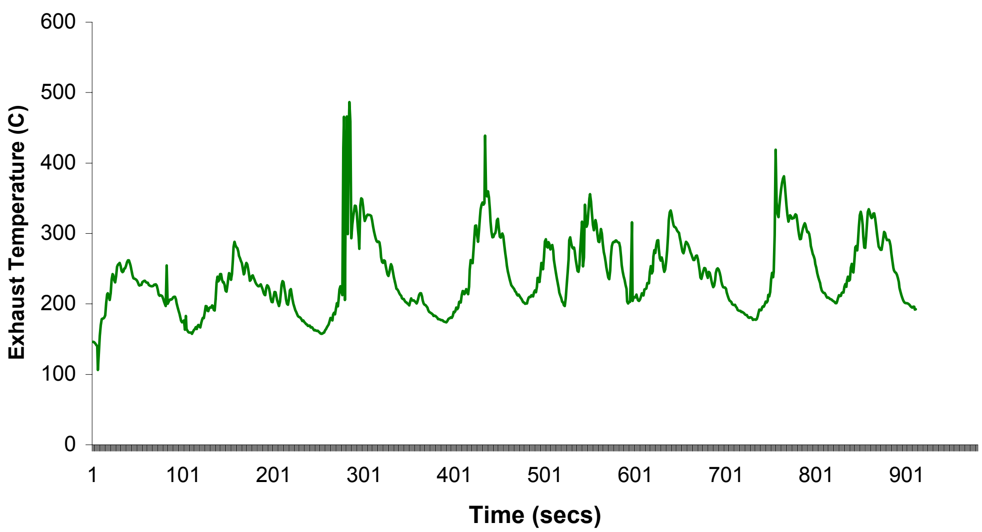


Figure 8. Typical Dump Truck (Ellington Field) Exhaust Engine Profile

7.2 Gradall G3WD Test Cycle

For this model of Gradall, a test cycle was developed that included on-road, as well as off-road, run segments. The driving portion of this test trace began at the intersection of Kirk and Scholl streets at Ellington Field. The vehicle then continued to follow a set route on the grid of streets at Ellington Field for a total time of approximately 7 minutes and 1.2 miles. At the end of the driving portion, the sampling system was paused and the vehicle proceeded to a designated dirt pile nearby. The Gradall would then proceed to 'dump and scoop' for ten minutes.

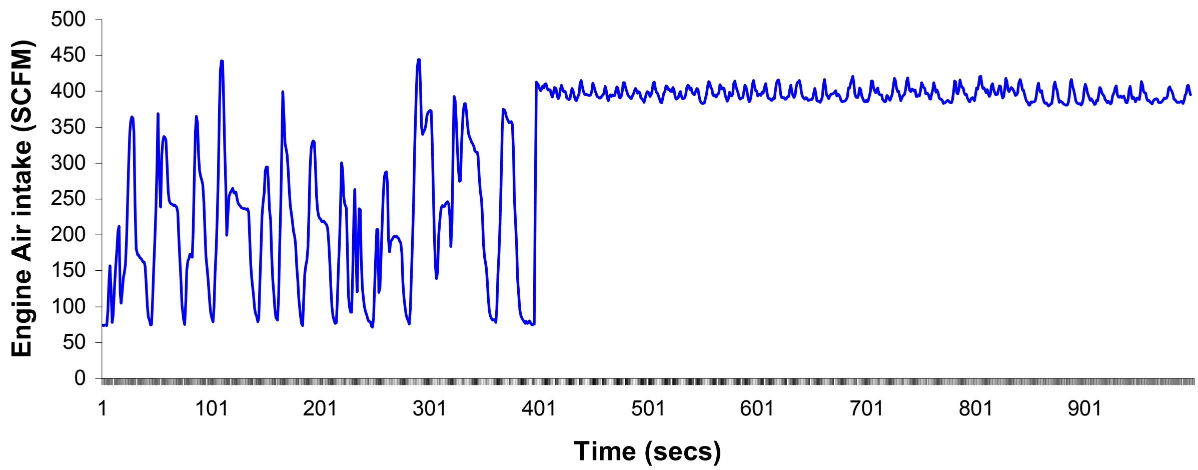


Figure 9. Typical Gradall G3WD Engine Air Intake Profile

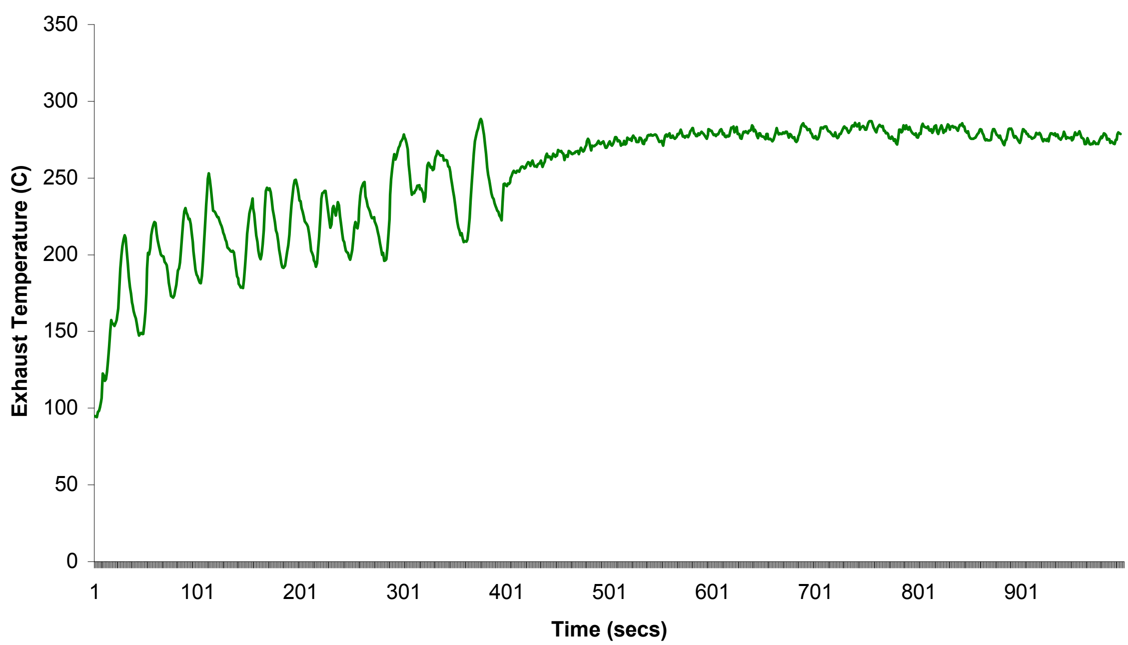


Figure 10. Typical Gradall G3WD Exhaust Temperature Profile

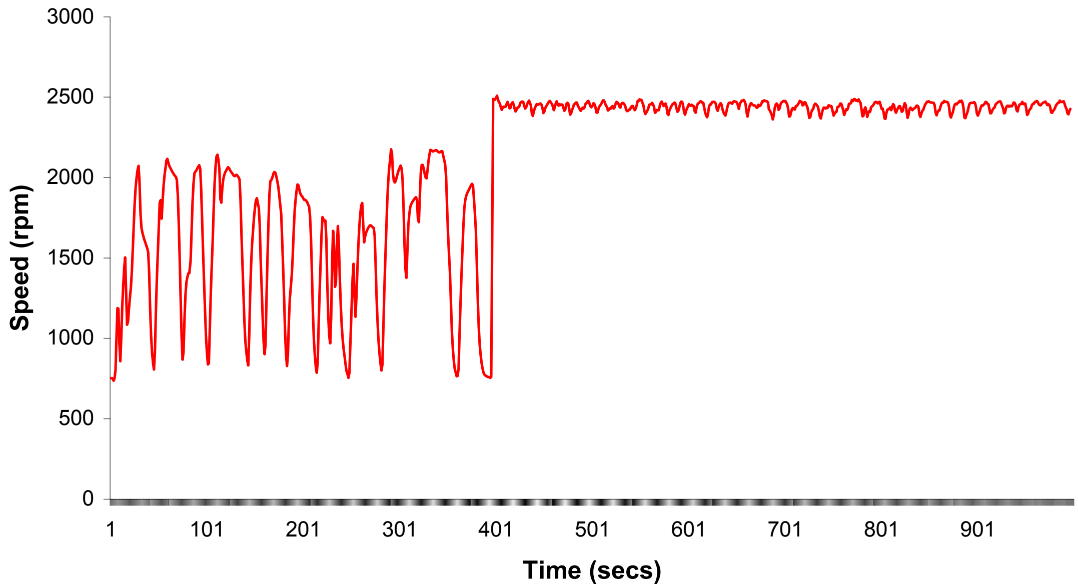


Figure 11. Typical Gradall G3WD Engine Speed Profile

7.3 Gradall XL5200 Test Cycle

The 12 minute test cycle began with one minute of idling, followed by ten minutes of high rpm (approx.2300) digging, and concluded with one minute back at low idle. Gradall XL5100 exhibited similar traits for each parameter (slightly higher exhaust temperatures). Note that these two models of Gradall are equipped with two engines, and it was the rear bucket engine that was tested.

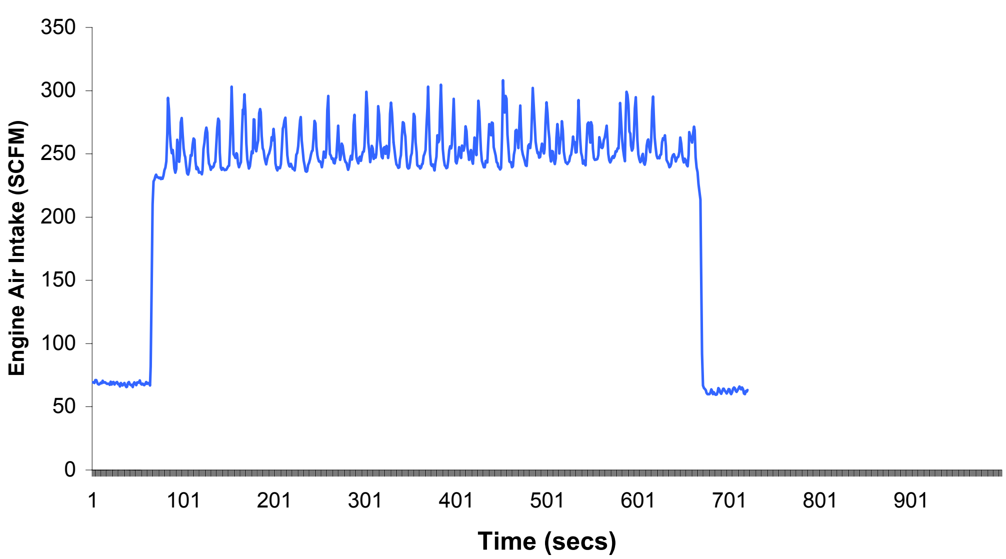


Figure 12. Typical Gradall XL5200 Engine Air Intake Profile

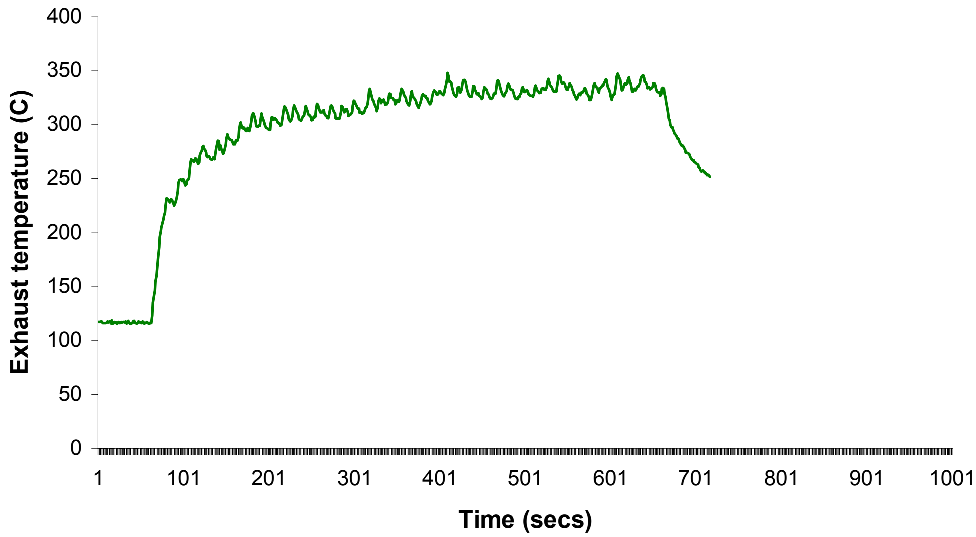


Figure 13. Typical Gradall XL5200 Exhaust Temperature Profile

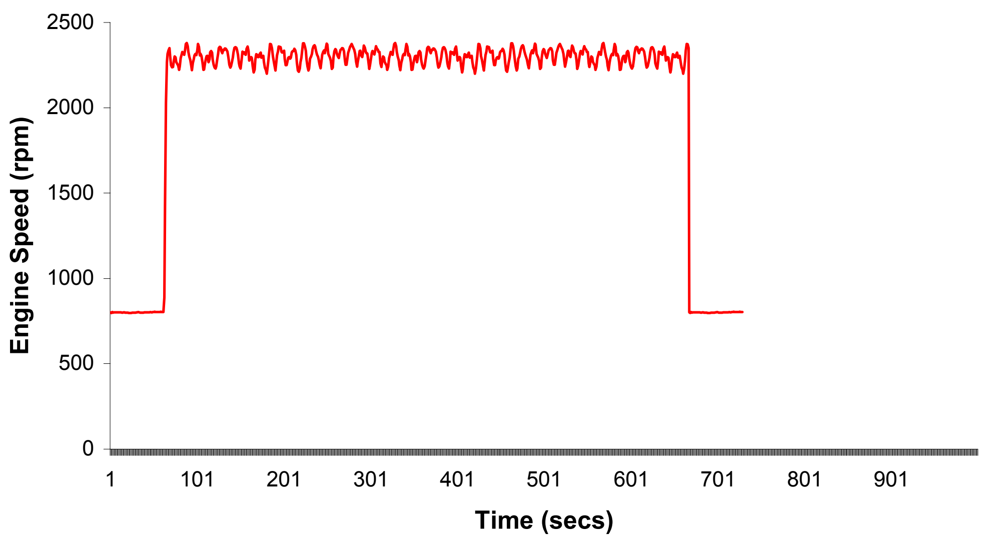


Figure 14. Typical Gradall XL5200 Engine Speed Profile

7.4 Dump Truck Test Cycle (from the Barbours Cut Cruise Terminal)

This test cycle took place entirely inside one of the container yards at the Port of Houston. The test vehicle would drive to the yard from the Cruise Terminal, which took approximately two minutes, idle for 15 seconds, and then start the first in a series of seven loops totaling 6.84 miles. During the loops the vehicle would quickly accelerate up to 40 mph. Once the test was finished the vehicle would proceed back to the Cruise Terminal.

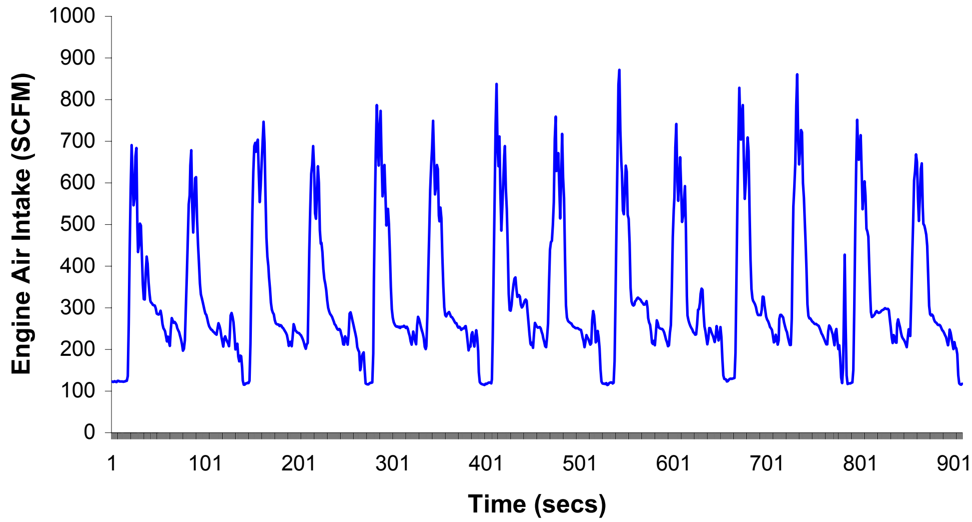


Figure 15. Typical Dump Truck (Barbours Cut Cruise Terminal) Air Intake Profile

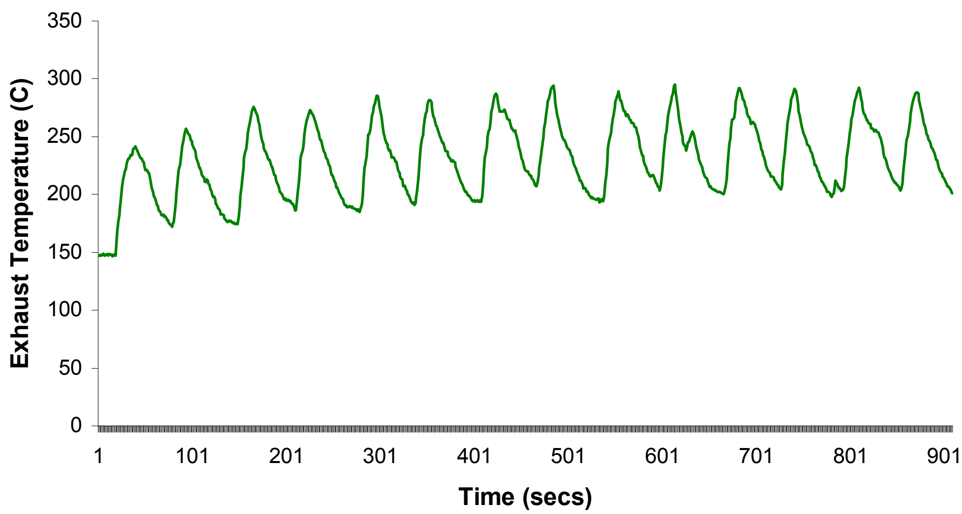


Figure 16. Typical Dump Truck (Barbours Cut Cruise Terminal) Exhaust Temperature Profile

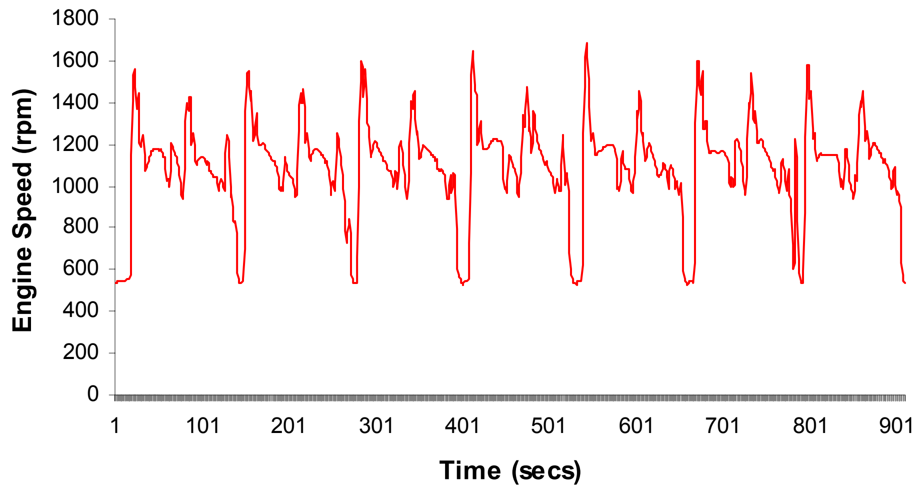


Figure 17. Typical Dump Truck (Barbours Cut Cruise Terminal) Engine Speed Profile

7.5 Vacuum Pump Test Cycle

The vacuum pump test cycle was composed of three segments. The first segment of the trace consisted of a driving portion around the grid of roads at Ellington Field. This driving portion lasted for approximately 6 minutes and was followed by a two-minute idle period. Subsequent to the idling time, was a pumping portion during which a red pylon was placed inside the vacuum hose to simulate load, while the engine was set to rev at 1300 rpm. The pumping portion lasted 8 minutes.

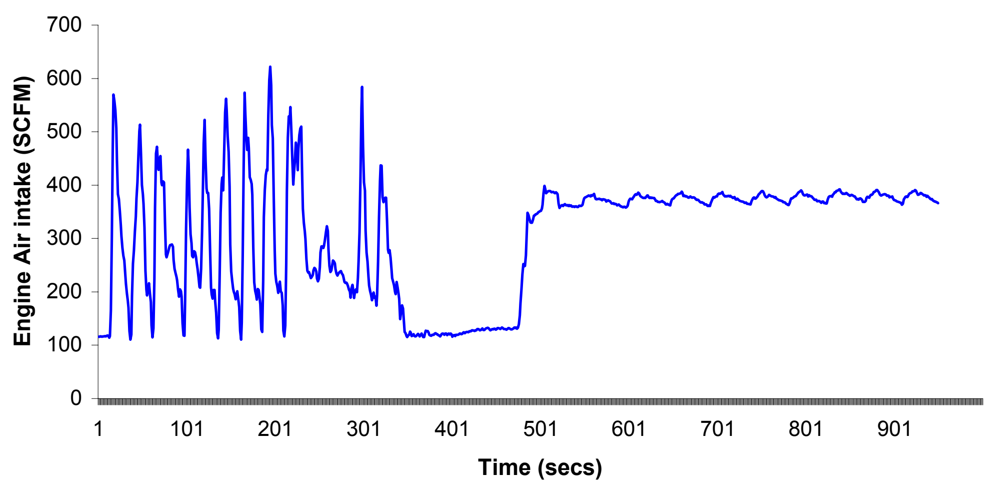


Figure 18. Typical Vacuum Pump Engine Air Intake Profile

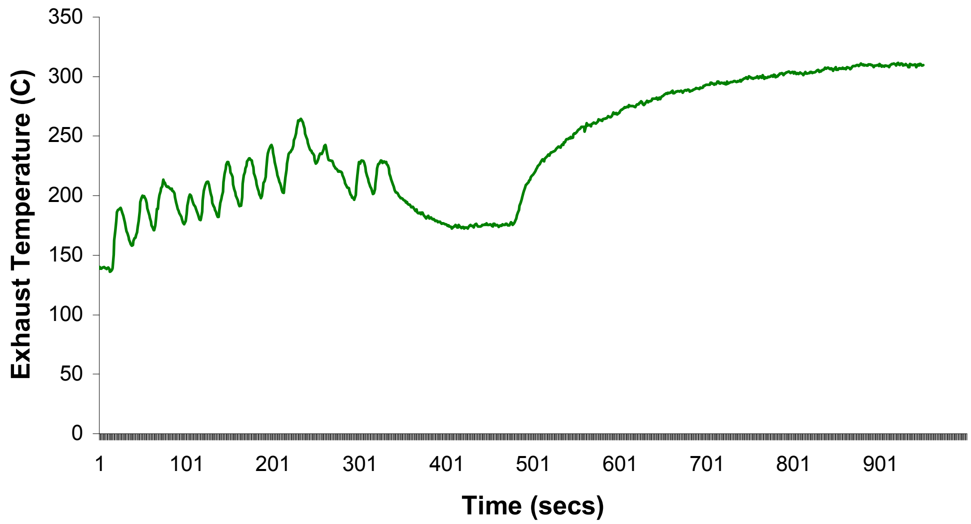


Figure 19. Typical Vacuum Pump Exhaust Temperature Profile

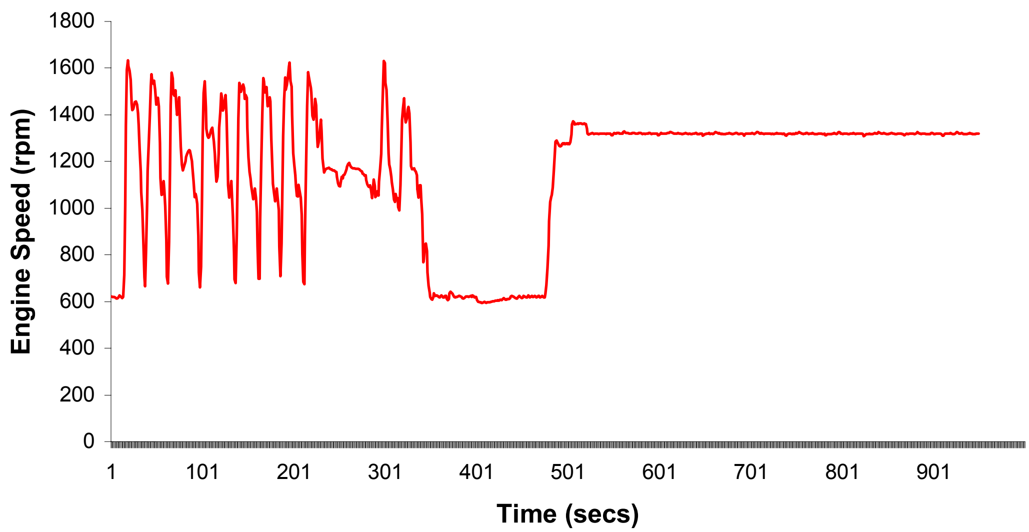


Figure20. Typical Vacuum Pump Engine Speed Profile

7.6 Automated Side loader Test Trace

The test cycle for the automated side loader consisted of two low speed loops within the Ellington Field grid. There were fourteen stops within each loop to simulate typical daily use.

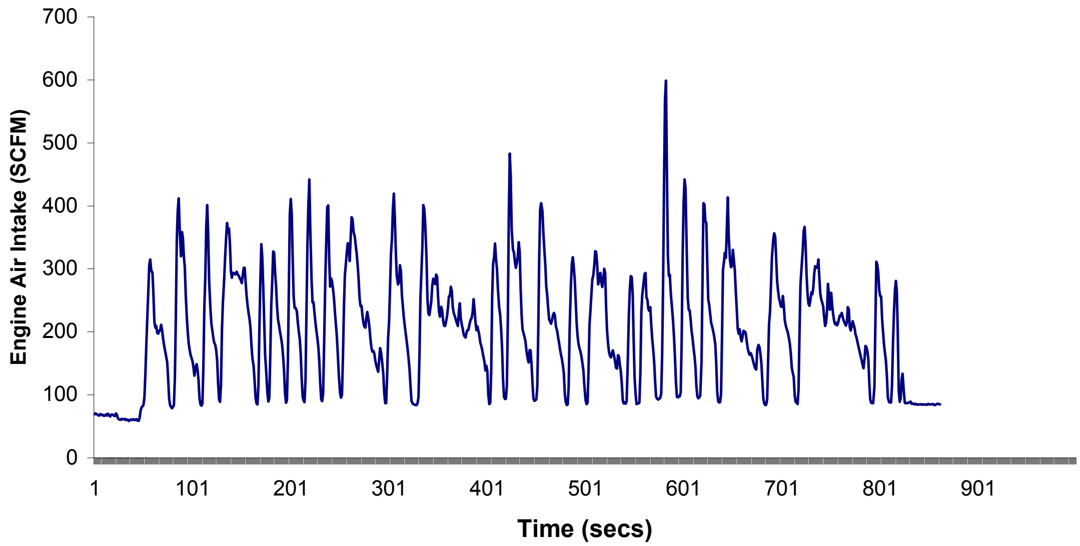


Figure 21. Typical Automated Side loader Engine Air intake Profile

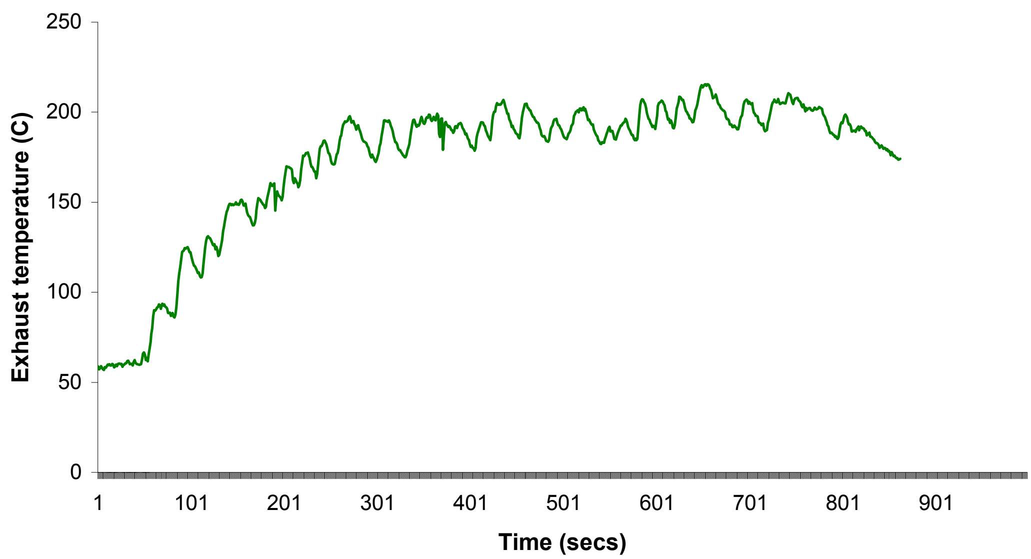


Figure 22. Typical Automated Side loader Exhaust Temperature Profile

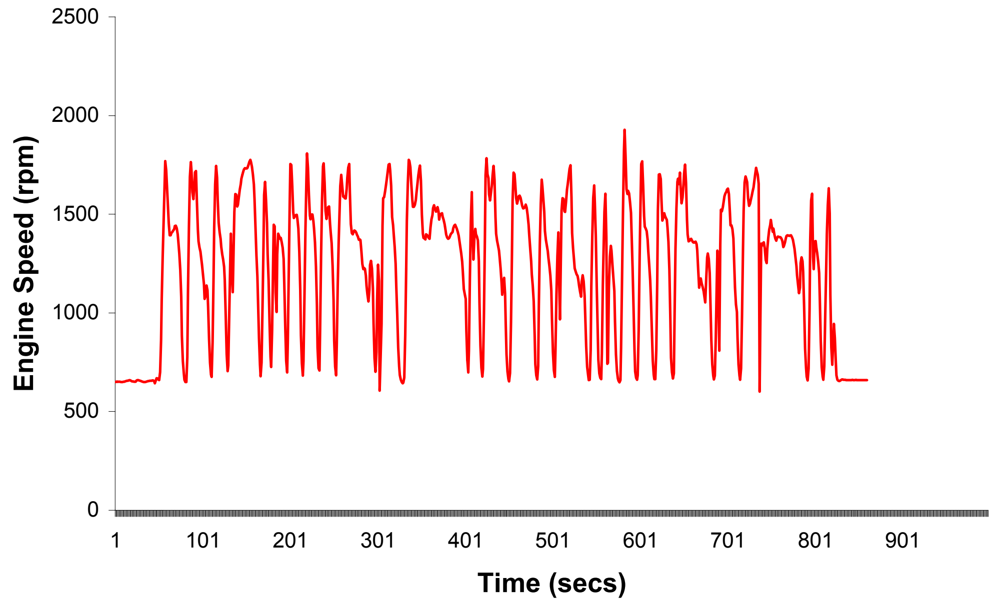


Figure 23. Typical Automated Side loader Engine Speed Profile

7.7 Test Repeatability

Throughout testing various parameters including engine air intake, time, engine speed, and exhaust temperature were compared and analyzed. Figure 24. shows a plot of the engine speed seen for each test run, baseline and retrofit, for dump truck # 31520. Figure 25. shows a plot of the engine air intake for each test run taken by dump truck #TXDot 20-5737-E. This route was on-road in real traffic versus that for #31520, which took place in a container yard with only a small number of external vehicles present. As time passes, traffic, driver error, and road signals contribute to variances in the trace.

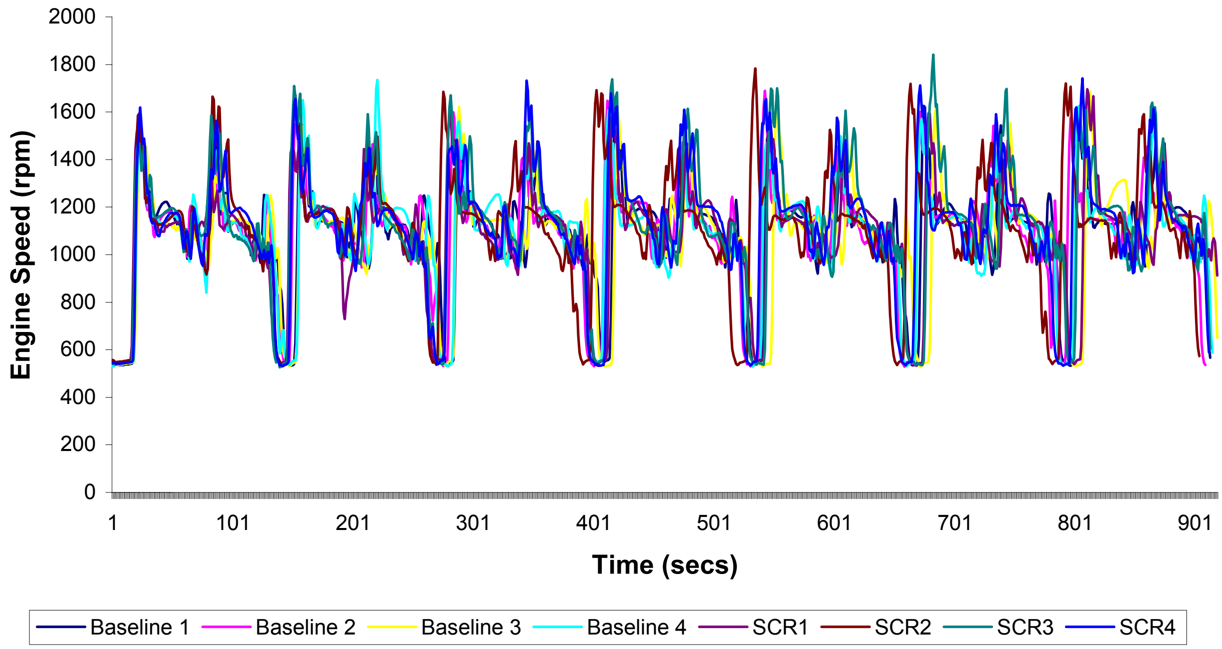


Figure 24. Engine Speed Over Four Baseline and Four Retrofit Tests (Dump Truck # 31520)

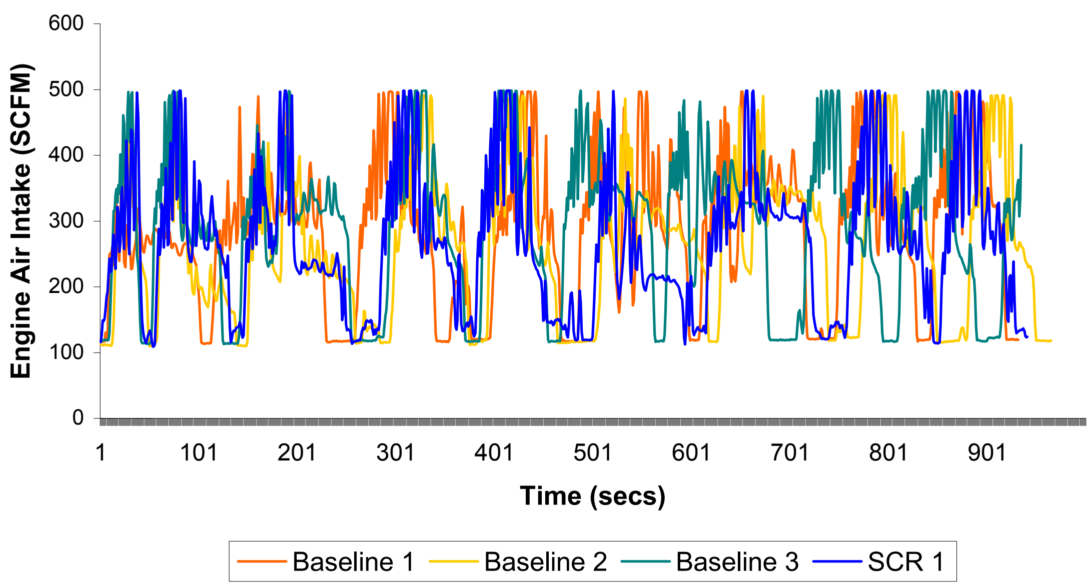


Figure 25. Engine Air Intake Baseline vs. Retrofit (Dump Truck TXDoT 20-5737-E)

Note that while the curves may not indicate an exact repeat of the driving pattern, the trends are the same, as are the average results for the different parameters as seen in Table 3.

Table 3. Operating Parameter Averages for Each Set of Tests for Dump TXDot 20-5737-E

	Total Flow (Qtot) lpm	Engine air intake (Qeng) scfm	Dilution air flow (Qdil) lpm	Exhaust flow (Qexh) lpm	Main flow (Qmain) lpm
Baseline #1	33.7	286	26.3	7.4	32.0
Baseline #2	32.8	265	25.7	7.1	31.1
Baseline #3	33.1	293	25.4	7.7	31.3
SCR #1	33.3	267	26.2	7.1	31.6

8.0 Test Procedures

Testing commenced once the DOES2 system and sensors were installed, allowed to warm up, and verified to be functioning correctly as read on the computer. New filters were installed in each of the filter holders and an evacuated Tedlar™ or Cali-5-Bond™ (5-layer) sampling bag was connected to the DOES2 sample line. The vehicle was then driven to the official start point, where it waited for the test to be initiated. Once at the start point after all the pumps were started, the sampling was initiated.

Upon completion of the test cycle, the loaded PM filter was removed from the filter holder and placed in a petri dish that was sealed with paraffin tape before transport back to the ERMD lab. Particulate mass was determined gravimetrically by weighing the filter on a Sartorius model M5P-000V001 balance upon its return to the ERMD. Before the final filter weight was taken the filters were conditioned at 40% ± 10% RH, and 20 to 25 degrees Celsius for a minimum of 8 hours.

The bag of gaseous sample was removed from the DOES2 and brought to the analysis area where it was read on the analyzers, which had all been zeroed and calibrated using standard reference gases. After the sample bag was analysed, it was evacuated, flushed with nitrogen, and then evacuated again. After each test, the data from the on board computer was downloaded onto a diskette and examined on a separate laptop that provided emission results in grams per minute.

The heated sample line was disconnected from the DOES2 for the initial run of each configuration. This initial run ensured that the equipment was warmed up prior to conducting a test, and also served as a measurement of the ambient air levels of these exhaust components. The concentrations of the emissions found in the sample bag represented the level of the ambient air pollutants found at the site. These ambient values were used in the mass emission calculations.

8.1 System Verification and Repeatability

After every test, the DOES2 operation was verified by ensuring that expected trend lines were observed for various flow rates. Plots of the engine air intake (Qeng), dilution air (Qdil), raw exhaust (Qexh) and the main flow through the dilution tunnel (Qmain) were created after each test. The plots provided an easy tool to verify that Qmain remained constant throughout the run, and that Qeng and Qexh varied proportionally while the Qdil curve varied inversely to Qeng (or Qexh). Should Qdil have reached low constant values of approximately 5 L/min, the test parameters would have been adjusted since the DOES2 cannot restrict the dilution flow to less than 5 L/min. The dilution flow in the DOES2 was verified, as it should remain between approximately 10 L/min and 35 L/min. The thermocouples and pressure transducers were also verified, as they are expected to give ambient (verifiable) values. For example, the dilution air temperature (Tdil) should be close to the ambient air temperature. Figure 26. shows a typical plot examined between tests to verify that the DOES 2 system was performing as expected.

The emission rates for a test configuration were averaged and a coefficient of variation was calculated. A minimum of three tests were conducted per test configuration but more tests were repeated as required.

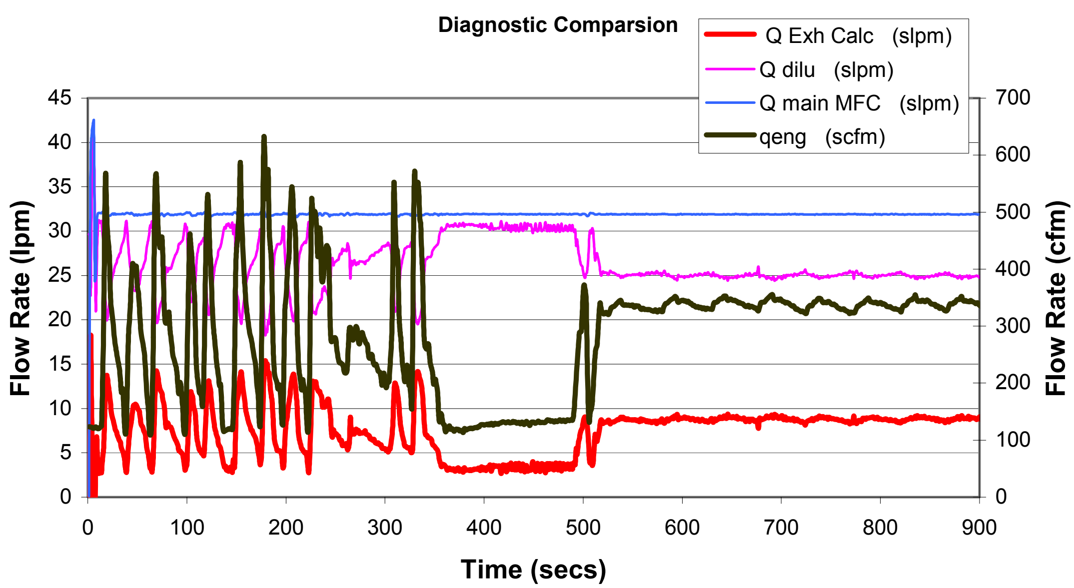


Figure 26. DOES2 System Verification Diagnostic Chart

9.0 Results and Discussions

Testing for the different configurations took place over the course of an 8-month period. Between the baseline and retrofit testing, vehicles returned to their fleets where they continued operating within their regular scope of duty.

The DOES2 system enables the measurement of certain parameters (such as the measured concentrations of gaseous emissions, total flow through the tunnel, engine air intake, dilution air flow, etc.), which in turn provide for the calculation of the mass emission rates (in grams of pollutant / min). The total exhaust flow rate was obtained from a mass balance on the air intake of the engine.

The mass of each pollutant was determined based on the following equations*:*

Hydrocarbon mass:
*THC mass = Vmix * Density HC * (Sample HC (ppm)- (Ambient HC (ppm)*(1-1/DF)))/10*^{6}

Oxides of nitrogen mass:
NO_X *mass = Vmix* Density* NO_2 **KH* (Sample* NO_X *(ppm)- (Ambient* NO_X *(ppm)*(1-1/DF)))/10*^{6}

Carbon monoxide mass:
*CO mass = Vmix * Density CO * (Sample CO (ppm)- (Ambient CO (ppm)*(1-1/DF)))/10*^{6}

Carbon Dioxide mass:
CO_2 *mass = Vmix * Density* CO_2 ** (Sample* CO_2 *(ppm)- (Ambient* CO_2 *(ppm)*(1-1/DF)))/10*^{2}

Where:

Vmix = total dilute exhaust volume in ft^3 per test.
DF = dilution factor
KH = humidity correction factor used for NO_x emissions
Density CO: 32.97 g/ft^3
Density CO_2: 51.81 g/ft^3
Density THC: 16.33 g/ft^3
Density NO_2: 54.16 g/ft^3

Emissions data from the testing of the vehicles in their original configuration, and then with an emission control technology, are listed in the following tables. These tables show the mass emission rates of CO, CO_2, NOx, THC, and Particulate Matter (PM) on a time basis for each test. The average value used to evaluate the percent change in emissions from each configuration is also shown with the percent coefficient of variation

(COV %), which indicates how much the results from each run deviated from the average.

The difference in emission rates between the baseline and the retrofit are shown in tables following the mass emissions rate for each vehicle. The percent reduction values are based on the average emission rates in g/min calculated from the following equation:

$$\%\ \text{Change} = \frac{\text{Emission Rate [g/min]}_{\text{retrofit}} - \text{Emission Rate [g/min]}_{\text{baseline}}}{\text{Emission Rate [g/min]}_{\text{baseline}}}$$

Statistical analysis in the form of a student's t-distribution test was performed to verify that comparing two sets of emission data, which contained a certain degree of variability, was statistically significant. The shaded cells in the tables represent values that do not have statistical significance since the "t" distribution was less than the 95% confidence level. This implies that the calculated percent change is lower than the error expected based on the standard deviation of the test sets that were compared. At times, variance within the sample, high ambient levels, and/or low readings, contributed to the lack of statistical significance although the % change appeared to be substantial.

9.1 Engelhard EGR System with a DPX Particulate Filter

Exhaust gas recirculation systems work on the principle that the portion of exhaust gas being recirculated back to the engine air intake has a depleted oxygen content, which therefore lowers the burn temperature, and in turn, reduces the production of NO_x emissions. Three vehicles equipped with Englehard's EGR/DPX emission control technology were tested as part this program. Automated side loader #30319 and vacuum pump #30491 were baseline and retrofit tested while operating on regular #2 diesel fuel. Vacuum pump #30490, which was running on TexLed fuel, was tested in order to evaluate the durability of the system. It had been baseline and retrofit tested, in December 2000 and October 2001 respectively, while running on BP Amoco fuel (30 ppm sulfur), as part of Phase I of this study[9].

The system showed a 27% to 68% reduction in NO_x emissions, a 56% to 95% reduction in CO emissions, a 26% to 32% reduction in THC, and a 56% to 76% reduction in TPM. It should be noted that the low-end number for each compound was from the testing of vehicle # 30319 that had a noticeable change in CO_2. The length of time each trace took, as well as the arrival at each stop, was the same for each set of testing, however the speed for retrofit testing was on average higher and this could be due to engine shift, harder acceleration/decelerations, or other operator impacts.

The durability testing of the system on vacuum pump #30490 showed that the percent reductions in THC, NOx, and TPM all decreased when compared to the original retrofit

[9] Environment Canada. Emissions research and Measurement Division. "City of Houston Diesel Demonstration Project." ERMD Report # 01-36.

testing. The percent reduction from the baseline, due to the EGR/DPX system, was larger in CO during the durability testing than during the original retrofit testing, see Figure 27. The durability testing took place over a two year time period.

Table 4. Automated Side Loader # 30319 Emissions Rates (g/min)

Run	THC (g/min)	NOx (g/min)	CO (g/min)	CO_2 (g/min)	PM (g/min)
Baseline Dec.11_02					
Test #1	0.042	3.55	0.581	397	0.048
Test #2	0.041	3.65	0.565	417	0.058
Test #3	0.047	3.60	0.617	405	0.051
Average	**0.043**	**3.60**	**0.588**	**406**	**0.052**
COV (%)	6.6	1.5	4.5	2.5	9.2
Retrofit Mar 30_03					
Test #1	0.030	2.97	0.223	486	0.025
Test #2	0.034	2.67	0.231	478	0.029
Test #3	0.031	2.48	0.304	450	0.021
Test #4	0.035	2.50	0.350	476	0.014
Test #5	0.028	2.57	0.193	468	0.027
Average	**0.032**	**2.64**	**0.260**	**468**	**0.023**
COV (%)	8.7	7.6	24.8	3.6	26.0

Table 5. Percent Difference in Emissions (g/min) Between the Baseline and Retrofit Average Results (From Table 4)

Test id.		THC	NOx	CO	CO_2	PM
Automatic Side Loader #30319	**% change due to EGR**	-25.6	-26.7	-55.8	15.3	-55.8

Table 6. Vacuum Pump #30491 Emissions Rates (g/min)

Run	HC (g/min)	NOx (g/min)	CO (g/mile)	CO_2 (g/min)	PM (g/min)
Baseline Nov.14_02					
Test #1	0.065	8.62	0.752	944	0.115
Test #2	0.058	9.39	0.770	1021	0.115
Test #3	0.041	8.54	0.734	890	0.103
Test #4	0.032	8.29	0.798	936	0.108
Average	**0.049**	**8.71**	**0.763**	**948**	**0.110**
COV (%)	31.4	5.5	3.6	5.8	5.2
Retrofit Dec.14_02					
Test #1	0.020	2.73	0.173	806	0.029
Test #2	N/A	2.86	0.158	862	0.022
Test #3	0.033	2.74	0.264	836	0.028
Test #4	0.021	2.86	0.151	866	0.026
Average	**0.025**	**2.80**	**0.187**	**842**	**0.026**
COV (%)	28.4	2.7	28.2	3.3	12.0

Table 7. Percent Difference in Emissions (g/min) Between the Baseline and Retrofit Average Results (From Table 6)

Test id.		THC	NOx	CO	CO_2	PM
Vacuum Pump #30491	**% change due to EGR**	-49.0	-67.9	-75.5	-11.2	-76.4

Table 8. Vacuum Pump #30490 Emissions Rates (g/min) Durability with Engelhard EGR/DPX

Run	HC (g/min	NOx (g/min)	CO (g/min)	CO_2 (g/min)	PM (g/min)
Retrofit Durability Dec.17_02					
Test #1	0.040	3.05	0.046	935	0.051
Test #2	0.029	2.80	0.024	842	0.034
Test #3	0.031	2.97	0.077	894	0.034
Test #4	0.027	2.84	0.045	893	0.050
Average	**0.032**	**2.92**	**0.048**	**891**	**0.042**
COV (%)	18.1	4.1	45.3	4.3	22.3
The following baseline, and retrofit data was collected during a previous testing program					
Baseline Dec. 11_00					
Test #1	0.050	8.54	0.990	827	0.128
Test #2	0.050	8.32	1.030	828	0.126
Test #3	0.040	8.58	0.910	824	0.122
Average	**0.047**	**8.48**	**0.977**	**826**	**0.125**
COV (%)	12.4	1.7	6.3	0.3	2.4
Retrofit Oct.29_01					
Test #1	0.010	1.57	0.240	820	0.030
Test #2	0.010	1.62	0.240	826	0.030
Test #3	0.010	1.68	0.220	824	0.030
Average	**0.010**	**1.62**	**0.233**	**823**	**0.030**
COV (%)	0.0	3.4	5.0	7.0	0.0

Table 9. Percent Difference in Emissions (g/min) Between the Baseline and the Retrofit Average Results (From Table 8)

Test id.	Vacuum Pump #30490	THC	NO_x	CO	CO_2	PM
Retrofit Durability Dec.17_02	% change from baseline due to EGR	-31.9	-65.6	-95.1	7.9	-66.4
Retrofit Oct.29_01	% change from baseline due to EGR	-80.0	-81.0	-76.0	-0.4	-76.0

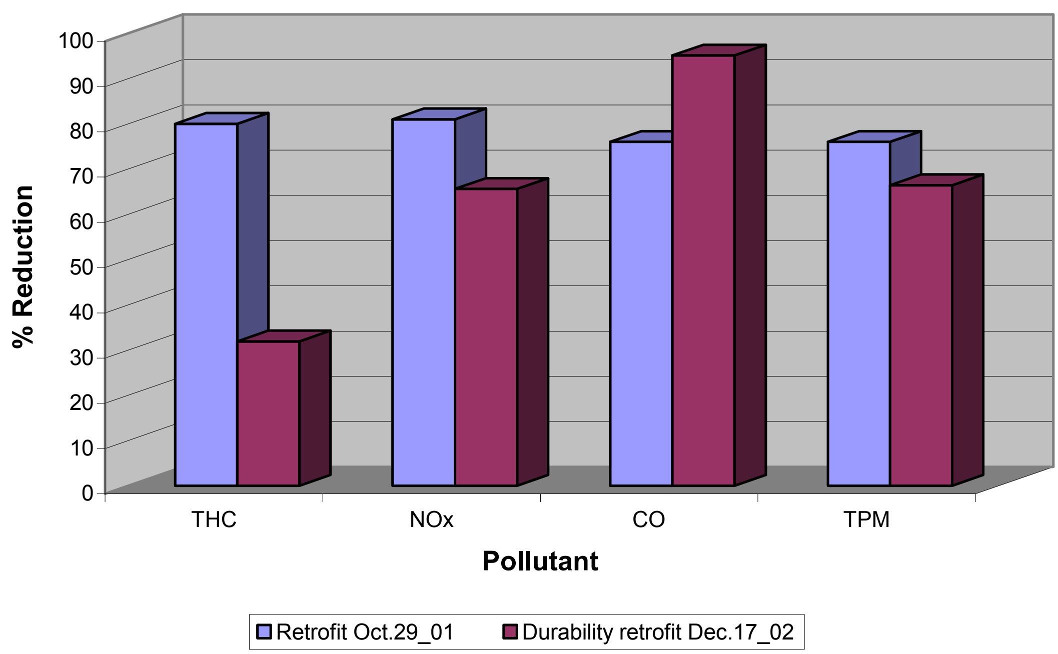


Figure 27. Percent Reductions From Baseline: Retrofit vs. Durability

9.2 Extengine SCR System

The Extengine SCR (selective catalytic reduction) System was composed of a diesel oxidation catalyst (DOC), a particulate filter, and finally, the anhydrous ammonia SCR. The exhaust passes first over the DOC and particulate trap where NO_x, mainly composed of NO, is oxidized to NO_2, which is then mixed with the injected reducing agent, NH_3, ideally giving end products of H_2O and N_2.

While SCR (selective catalytic reduction) technology has been used in the treatment of exhaust from stationary sources for sometime, the application of this technology for the reduction of NOx from mobile sources is relatively new. Various challenges to retrofitting vehicles with this system include having an onboard supply of ammonia or urea (studies have shown the amount needed could be up to 3-6 % of fuel burned leading to fairly frequent refilling[10]), and the fact that vehicle performance is generally not affected by the lack of ammonia thereby leaving the vehicle operator unaware as to whether the system is functioning or not, as well as lacking incentive to replenish the ammonia supply. One concern when using an SCR system is the potential for unreacted ammonia to pass through the control system and be emitted into the atmosphere. This is referred to as 'ammonia slip'.

Four Gradalls, and two dump trucks, running on regular #2 diesel, were tested with the SCR system in place. Each compound exhibited a wide range of reductions from the baseline measurements. THC showed reductions of up to 72%, while CO showed reductions of 51% to 89%, TPM was reduced up to 56%, and NOx up to 67% reductions.

[10] Heavy Duty Standards / Diesel Fuel RIA. Chapter III – Emissions Standards Feasibility. December 2000. EPA420-R-00-026.

Table 10. Gradall #23505 Emissions Rates (g/min)

Run	HC (g/min)	NOx (g/min)	CO (g/min)	CO_2 (g/min)	PM (g/min)
Baseline **Oct.30_02**					
Test #1	0.251	9.43	2.084	594	0.278
Test #2	0.266	10.94	2.329	631	0.297
Test #3	0.289	9.32	1.793	613	0.240
Test #4	0.280	9.29	1.536	563	0.213
Test #5	0.274	10.05	1.587	589	0.250
Average	**0.272**	**9.81**	**1.866**	**598**	**0.255**
COV (%)	5.3	7.2	10.1	4.3	12.8
Retrofit May02_03					
Test #1	0.120	3.61	0.891	561	0.115
Test #2	0.125	3.46	0.876	557	0.113
Test #3	0.129	3.60	0.915	567	0.113
Average	**0.125**	**3.56**	**0.894**	**561**	**0.114**
COV (%)	3.5	2.4	2.15	0.9	1.3

Table 11. Percent Difference in Emissions (g/min) Between the Baseline and Retrofit Average Results (From Table 10)

Test id.		THC	NOx	CO	CO_2	PM
Gradall #23505	**% change due to SCR**	-54.0	-63.7	-52.1	-6.6	-55.3

Table 12. Gradall #26795 Emissions Rates (g/min)

Run	HC (g/min)	NOx (g/min)	CO (g/min)	CO_2 (g/min)	PM (g/min)
Baseline Nov.05_02					
Test #1	0.210	9.60	1.950	671	0.245
Test #2	0.227	10.34	1.949	662	0.238
Test #3	0.250	10.28	1.681	639	0.180
Test #4	0.289	10.01	1.831	628	0.231
Test #5	0.268	10.02	1.657	620	0.189
Average	**0.249**	**10.05**	**1.814**	**644**	**0.216**
COV (%)	12.7	2.9	7.8	3.4	13.8
Retrofit May06_03					
Test #1	0.070	3.68	0.673	583	0.112
Test #2	0.095	3.30	0.940	542	0.068
Test #3	0.103	3.42	1.055	529	0.104
Average	**0.089**	**3.47**	**0.889**	**552**	**0.095**
COV (%)	19.3	5.6	22.0	5.1	24.5

Table 13. Percent Difference in Emissions (g/min) Between the Baseline and Retrofit Average Results (From Table 12)

Test id.		THC	NOx	CO	CO_2	PM
Gradall #26795	**% change due to SCR**	-64.3	-65.5	-51.0	-14.3	-56.0

Table 14. Gradall #30665 Emissions Rates (g/min)

Run	HC (g/min)	NOx (g/min)	CO (g/min)	CO_2 (g/min)	PM (g/min)
Baseline Oct31_02					
Test #1	0.077	3.88	0.839	626	0.056
Test #2	0.086	3.83	0.832	635	0.057
Test #3	0.087	3.70	0.897	645	0.059
Average	**0.083**	**3.80**	**0.856**	**635**	**0.057**
COV (%)	6.8	2.4	4.1	1.5	2.6
Retrofit Apr30_03					
Test #1	0.070	1.79	0.100	621	0.034
Test #2	0.071	1.89	0.105	622	0.033
Test #3	0.074	1.98	0.103	641	0.034
Average	**0.072**	**1.89**	**0.103**	**628**	**0.033**
COV (%)	2.6	5.2	2.5	1.8	1.8

Table 15. Percent Difference in Emissions (g/min) Between the Baseline and Retrofit Average Results (From Table 14)

Test id.		THC	NOx	CO	CO_2	PM
Gradall #30665	**% change due to SCR**	-13.3	-50.3	-88.0	-1.1	-42.1

Table 16. Dump Truck # 31520 Emissions Rates (g/min)

Run	HC (g/min)	NOx (g/min)	CO (g/min)	CO_2 (g/min)	PM (g/min)
Baseline June06_03					
Test #1	0.133	5.63	1.727	927	0.133
Test #2	0.147	5.99	1.738	968	0.129
Test #3	0.119	5.57	1.786	953	0.120
Test #4	0.131	5.66	1.920	962	0.116
Average	**0.133**	**5.71**	**1.793**	**952**	**0.124**
COV (%)	8.6	3.3	4.9	1.9	6.2
Retrofit June 07_03					
Test #1	0.059	5.60	0.221	940	0.083
Test #2	0.028	5.59	0.206	987	0.112
Test #3	0.036	5.52	0.202	986	0.106
Test #4	0.027	5.66	0.190	997	0.103
Average	**0.037**	**5.59**	**0.205**	**978**	**0.101**
COV (%)	40.4	1.1	6.21	2.6	12.44

Table 17. Percent Difference in Emissions (g/min) Between the Baseline and Retrofit Average Results (From Table 16)

Test id.		THC	NOx	CO	CO_2	PM
Dump Truck # 31520	**% change due to SCR**	-72.1	-2.1	-88.6	2.7	-18.5

Note: The SCR developer believes that system was not properly activated throughout the retrofit testing.

Table 18. Dump Truck # TXDot 20-5737-E Emissions Rates (g/min)

Run	HC (g/min)	NOx (g/min)	CO (g/min)	CO_2 (g/min)	PM (g/min)
Baseline May07_03					
Test #1	0.094	4.60	2.789	844	0.276
Test #2	0.058	4.70	2.962	806	0.266
Test #3	0.053	5.03	3.040	864	0.269
Average	**0.068**	**4.78**	**2.930**	**838**	**0.270**
COV (%)	33.1	4.7	4.4	3.6	1.8
Retrofit May09_03					
Test #1	0.046	1.59	0.399	777	0.271
Average	**0.046**	**1.59**	**0.399**	**777**	**0.271**
COV (%)					

Table 19. Percent Difference in Emissions (g/min) Between the Baseline and Retrofit Average Results (From Table 18)

Test id.		THC	NOx	CO	CO_2	PM
Dump Truck # TXDot 20-5737-E	**% change due to SCR**	-32.4	-66.7	-86.4	-7.3	0.4

The following three tables have been included for information purposes only as the data is such that there is no opportunity for direct comparison between baseline and retrofit testing. During retrofit testing of Gradall # 20025, it was thought by the SCR developer, Extengine, that there were problems with the ammonia injection system. Various changes were made by Extengine throughout numerous tests in order to explore and isolate the problem. Retrofit testing on Gradalls # 19546 and 26609 was not completed due to various constraints.

Table 20. Gradall #20025 Emissions Rates (g/min)

Run	HC (g/min)	NOx (g/min)	CO (g/min)	CO_2 (g/min)	PM (g/min)	
Baseline Oct29_02						
Test #1	0.212	4.69	1.161	918	0.335	
Test #2	0.184	4.69	1.120	903	0.300	
Test #3	0.213	4.83	1.144	936	0.356	
Average	**0.203**	**4.74**	**1.142**	**919**	**0.330**	
COV (%)	8.2	1.7	1.8	1.8	8.6	
Retrofit	**HC (g/min)**	**NOx (g/min)**	**CO (g/min)**	**CO_2 (g/min)**	**PM (g/min)**	
May 01_03						
Test #1	0.069	4.68	0.156	971	0.148	No pressure
Test #2	0.068	5.13	0.239	1068	0.182	From NH_3 cylinder
May 05_03						
Test #1	0.103	5.12	0.151	904	0.123	No pressure
Test #2	0.082	3.89	0.178	902	0.119	45 psi
Test #3	0.073	4.16	0.196	975	0.123	45 psi
Test #4	0.070	4.24	0.186	871	0.145	Pressure increased
Test #5	0.074	4.55	0.239	1056	0.148	Pressure changed to original ,approx.
May 06_03	There was potentially a wiring problem for the previous tests (system not powered during full test cycle). Problem possibly fixed for May 6_03 testing					
Test #1	0.064	2.78	0.299	1006	0.166	
Test #2	0.054	4.30	0.221	990	0.140	Increased psi

Table 21. Gradall #19546 Emissions Rates (g/min)

Run	HC (g/min)	NOx (g/min)	CO (g/min)	CO_2 (g/min)	PM (g/min)
Baseline Oct21_02					
Test #1	0.236	4.83	1.695	756	0.270
Test #2	0.225	4.59	1.714	743	0.275
Test #3	0.218	4.82	1.654	766	0.271
Average	**0.226**	**4.75**	**1.687**	**755**	**0.272**
COV (%)	4.1	2.8	1.8	1.5	1.0

Table 22. Gradall #26609 Emissions Rates (g/min)

Run	HC (g/min)	NOx (g/min)	CO (g/min)	CO_2 (g/min)	PM (g/min)
Baseline Nov01_02					
Test #1	0.120	4.73	0.873	767	0.106
Test #2	0.123	4.23	0.808	702	0.100
Test #3	0.123	4.46	0.793	729	0.108
Test #4	0.130	4.46	0.914	703	0.123
Average	**0.124**	**4.47**	**0.847**	**726**	**0.109**
COV (%)	3.4	4.6	6.7	4.2	8.9

9.2.1 Ammonia Slip

Ammonia can be released not only as a by-product of incomplete combustion, but can also be emitted as the result of the use of an emission control technology.[11] One of the biggest concerns with possible ammonia slip is the potential production of ammonium sulphate or ammonium bisulphate which produces a white haze contributing to reductions in visibility, and which can also act as a lung irritant.[12] For the purposes of measuring ammonia slip throughout this project, 70mm cellulose filters were coated with citric acid and placed in the lower tier of the particulate filter holder in the diluted exhaust stream. The filters were transported back to the ERMD where they were to be analysed by the Ambient Air Quality Division using ion chromatography. Unfortunately final results of ammonia measurements are unavailable due to degradation of the samples while in storage awaiting analysis.

[11] Battye, R., et al. "Development and Selection of Ammonia Emission Factors - Final Report." US Environmental protection Agency. Office of Research and Development. August, 1994.

[12] Environment Canada. Emissions Research and Technology Division. "Gaseous and Particulate Matter Emissions from In-Use Light Duty Gasoline Motor Vehicles." ERMD report #99-67. 1999

10.0 Conclusions

The following conclusions were reached as a result of this emissions testing program:

Effects of Englehard's EGR/DPX system

- 27% to 68% NO_x emissions reduction
- 56% to 95% CO emissions reduction
- 26% to 32% THC emissions reduction
- 56% to 76% TPM emissions reduction

Effects of Extengine's SCR system

- Up to 67% NO_x emissions reduction
- 51% to 89% CO emissions reduction
- Up to 72% THC emissions reduction
- Up to 56% TPM emissions reduction

Neither system appeared to have a negative effect on vehicle emissions. Quite often there is a trade off between NO_x and TPM emissions, and this can pose a problem when dealing with equipment implementation decisions. Due to the large role mobile source emissions play in the release of NO_x, in particular, to the atmosphere, it is important to move forward with the implementation of emission control technologies if the Houston-Galveston area hopes to reach attainment levels by 2007.

Acknowledgements

The author would like to acknowledge the excellent support received from Steve Dornak with the City of Houston Mayor's Office of Environmental Policy. In addition, the author would also like to acknowledge the contributions of the following;

- Mary Case, Airport manager at Ellington Field; and associates
- The Port of Houston Authority, particularly Jerry Rhame, for permission to use their property
- City of Houston vehicle operators and their supervisors

as well as the staff of the ERMD who contributed to set up, analysis, and testing.