West Virginia University
CAFEE
Center for Alternative Fuels, Engines & Emissions

Evaluation of a Partial Flow Dilution System for Transient Particulate Matter Emissions

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Abstract

A commercially available partial flow dilution system, the BG-3 manufactured by Sierra Instruments Emissions Systems, was evaluated against a 40 CFR Part 1065 designed constant volume sampling (CVS) system at West Virginia University over a suite of transient engine dynamometer tests. A 350hp John Deere engine was tested using cold and hot start cycles of the Non-Road Transient Cycle (NRTC). The engine was a laboratory engine reprogrammed for non-road Tier 4 levels retrofitted with a Caterpillar Johnson Matthey CCRT®. Particulate matter (PM) was collected on single 47 mm diameter TX40 filters for both the CVS and BG-3. Gaseous emissions were collected using the laboratory CVS full-scale tunnel with subsonic venturi flow control.

Repeatability of each system was high when considering the brake-specific PM results compared to a Tier 4 standard of 15 mg/bhp-hr. For 10 cold start non-road transient cycle (NRTC) tests of the John Deere engine equipped with the CCRT®, the CVS reported PM emissions as 2.05 ± 0.704 mg/bhp-hr (coefficient of variation of 34.3%), while the BG-3 reported PM emissions as 1.99 ± 0.453 mg/bhp-hr (coefficient of variation of 22.8%). Over fifty hot start NTRC tests of the same engine, the CVS reported PM emissions as 1.69 ± 0.558 mg/bhp-hr (coefficient of variation of 33.1%), while the BG-3 reported PM emissions as 1.58 ± 0.332 mg/bhp-hr (coefficient of variation of 20.4%). Based on the CVS results, the cold start tests had an average brake-specific PM level 86% below the Tier 4 standard, and for the hot start tests, the PM level was 89% below the Tier 4 standard.

Objectives

- To evaluate a commercially available partial flow particulate sampling system against a laboratory constant volume sampling system
- To conduct testing using an engine dynamometer to determine the particulate matter emission level of a heavy-duty diesel engine equipped with an exhaust gas aftertreatment system
- To assess the accuracy of the secondary dilution tunnel in the laboratory CVS system
- To evaluate particulate matter emissions from both cold start and hot start Non-Road Transient Cycle (NRTC) tests of a heavy-duty diesel engine

Laboratory Equipment

West Virginia University's SSV-CVS Installed at the CAFEE Engine and Emissions Testing Laboratory

West Virginia University's Particulate Matter Sampling System

The Constant Volume Sampling (CVS) system used during this study is shown in the above left figure. The 20 inch primary dilution tunnel is constructed of 316 stainless steel and consists of an entrance region, a mixing region, and a sampling region. The CVS also consists of a plenum, and two subsonic venturis (only one currently installed. The primary dilution air is HEPA filtered by a custom filter assembly and is ducted to the entrance region of the primary dilution tunnel. The exhaust and dilution air mixture is connected to a variable speed blower fan at the exit of the system that routes the exhaust mixture to the outdoor environment.

The secondary dilution tunnel system for particulate matter collection is shown in the above right figure. The system consists of a 1 inch heated line that serves as the secondary dilution tunnel, a heated enclosure that contains plumbing, a cyclone (2.5 μm cut size), 47 mm filter holders, a bypass system, solenoid valves, mass flow controllers, and electronics. Secondary dilution air can be used to control the filter face temperature to 47 ± 5 °C in accordance with 40 CFR §1065.140(e).

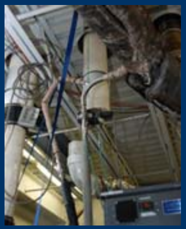
Sierra BG-3

Sierra BG-3 Cabinet

"The Model BG-3 with TDAC (Transient Dilution Airflow Control) system is a Particulate Partial Flow Sampling System (PPFSS) that provides accurate, repeatable Particulate Matter (PM) measurements for transient and steady-state engine and vehicle testing. More than three years of research, development and testing at Southwest Research Institute and Caterpillar, as part of the development of ISO 16183, have demonstrated BG-3's ability to maintain transient cycle PM correlation to within ± 5% of full tunnel (CVS) results. The state of the art system is designed for transient test cycles of diesel, gasoline or natural gas engines of any size to be used in both engine and chassis test cells. The Model BG-3 is exceptionally suited for steady-state test cycles as well.

During a transient test cycle, engine speed, load, airflow and fuel flow values exhibit high rates of change over very short time frames. Because of these ever changing variables, the BG-3 with TDAC is the only system up to the task. The magnitude of engine inlet air mass flow excursions can approach 10:1 within less than two seconds. The challenge for a PPFSS is to maintain constant proportional flow from an exhaust stream with a highly variable mass flow rate."*

*Sierra Instruments Emissions Systems BG-3 Technical Data Sheet (Available at http://sierraemissions.com/pdf/bg3_data.pdf)



Sierra BG-3 Sample Probe and Dilution Tunnel

Sierra BG-3 Control Software*

Test Engine

John Deere Test Engine Equipped with Johnson Matthey CCRT® Installed on Engine Dynamometer Testing Platform

Engine Specifications:

Displacement:	9 L
Configuration:	Inline 6 cylinder
Model:	6081HRW27
Serial Number:	RG6081H231741
Engine Family:	JDXL08.1037
Rated Power:	350 hp @ 2200 rpm
Rated Torque:	1415 N-m @ 1600 rpm
Idle Speed:	1200 rpm

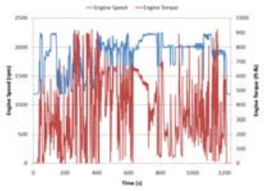
Engine retrofitted with Johnson Matthey Passive CCRT® exhaust aftertreatment system

Test Cycle

The test cycle used was the Non-Road Transient Cycle (NRTC). The speed and torque traces for the NRTC for the John Deere test engine used in this study are shown in the figure to the right.

NRTC Statistics:

Duration:	1239 s
Average Speed:	1874 rpm
Average Torque:	345 ft-lb
Reference Work:	44.2 bhp-hr

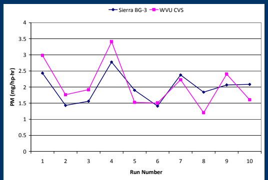


PM Sampling System Parameters

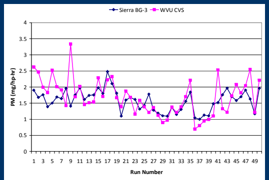
CVS Nominal Flowrate:	2295 scfm
Total PM Sample Flowrate:	2.332 scfm
Secondary Dilution Air Flowrate:	1.332 scfm
Filter Face Velocity:	96.2 cm/s
Minimum Dilution Ratio (at filter):	7.0:1

Results

The figures below show the results for each of the 10 cold start NRTC tests and the 50 hot start NRTC tests of the John Deere test engine equipped a Johnson Matthey CCRT®. As can be seen in the figures, there exists no distinct trend in either the CVS or BG-3 PM results.



PM Results of 10 Cold Start NRTC Tests



PM Results of 50 Hot Start NRTC Tests

	Cold Start (mg/bhp-hr)	Hot Start (mg/bhp-hr)	Composite+ (mg/bhp-hr)
WVU CVS	2.05 ± 0.704	1.69 ± 0.558	1.74 ± 0.430
Sierra BG-3	1.99 ± 0.453	1.58 ± 0.332	1.64 ± 0.223
Difference	-3.3%	-6.3%	-5.8%

+Average Composite results based on 1/7 * (Cold Start Result) + 6/7 * (Average of 5 Hot Start Results)

In order to further clarify the PM results obtained from the laboratory CVS, the PM sample flow from the CVS system (Vsf, obtained from two identical thermal mass flow controllers) was compared to the flow calculated from a reference laminar flow element (LFE). The resulting error was approximately 1 % low, which was deemed insignificant and within the tolerances of the mass flow controllers.

Vsf_{LFE} (scfm)	$Vsf_{\Delta MFC}$ (scfm)	Error
20.93	20.69	-1.16%

Conclusions

- PM results of 10 Cold Start NRTC tests yielded a coefficient of variation of 34.3 % (CVS) and 22.8 % (BG-3).
- PM results of 50 Hot Start NRTC tests yielded a coefficient of variation of 33.1 % (CVS) and 20.4 % (BG-3).
- A partial flow particulate sampling system can accurately measure PM emissions , with less variability, from a heavy-duty diesel engine over transient operation when compared to a laboratory CVS system.
- A 40 CFR Part 1065 designed PM sampling system can accurately measure PM emissions within 35% repeatability at a PM level over 85% below the PM emission standard.
- Laboratory CVS PM emissions can be strongly influenced by the responses of thermal mass flow controllers. It is necessary to perform verification checks to confirm accuracy of MFC signals.
- Test results of the study show that the Sierra BG-3 passes unpaired t and F-test statistical evaluation for alternate system approval per 40 CFR 1065.12.

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