

In-Use Evaluation of Fuel Economy and Emissions from Coal Haul Trucks Using Modified SAE J1321 Procedures and PEMS

Staci F. Haggis, Timothy A. Hansen, Kevin D. Hicks and Robert G. Richards

Southern Research Institute

Rodger Marx

Manager of Fuel Programs

Copyright © 2008 SAE International

ABSTRACT

Diesel equipment owners often desire knowledge of the direct feasibility and impacts of different technologies, retrofits, or fuels on their fleet under their specific operating conditions. This is now possible with the advent of portable emissions measurement systems and other in-use measurement technologies. The SAE J1321 Fuel Economy Test and Title 40 CFR 1065 in-use emissions testing procedures were adapted for use in an off-road mining haul truck environment over long time periods. Fuel consumption was directly measured using coriolis mass flow meters on two pairs of test and control trucks. Gaseous emissions were also measured with a Horiba OBS-2200 portable emissions measurement system. Testing was completed under steady state loads analogous to laboratory dynamometer modal tests and during normal in-use operations for 12 hour test periods with real-time emissions and fuel consumption data obtained. Fuel consumption and nitrogen oxides, carbon monoxide, and total hydrocarbon emissions correlated well with typical levels and the manufacturer's certifications for this engine family. Analysts also compared engine control module fuel consumption data to coriolis meter fuel consumption data, and found reasonable agreement at high power settings. The in-use data also allowed evaluation of fuel consumption and emissions profiles over entire vehicle duty cycles. This provides indicators to help train operators and plan mine layouts to minimize driving conditions where high emissions or fuel consumption occur.

INTRODUCTION

Original equipment manufacturers (OEMs), engine manufacturers, emission control strategy developers, fleet managers, and other stakeholders increasingly see the need for realtime in-use fuel consumption and engine emissions determinations. Some of the influences driving the desire for such testing are:

- Governmental mandates for in-use on-highway heavy truck testing, the potential for similar requirements for non-road applications, and the development of accurate measurement technologies that can be applied to in-use equipment [1, 2]
- Lack of meaningful correlation between common laboratory engine or vehicle dynamometer test cycles and real world operating conditions [3, 4, 5]
- Individual driving or operating style impacts on emissions and fuel consumption which cannot be duplicated in a laboratory setting [6]
- Profound effects of different duty cycles on control strategy feasibility, design, or proper operations [7, 8]
- Laboratory testing or equipment downtime expenses, especially for large-engine applications or the wide variety of possible emissions control or fuel consumption improvement strategy combinations within a given fleet

Southern Research Institute (Southern) recently tested the effects of three diesel fuel technologies on two pairs of 240-ton diesel-electric haul trucks at a mining facility. The diesel fuel technologies tested were a fuel additive, a lubricating oil re-burn system, and a biodiesel blend. The prime mover for each truck was a Detroit Diesel / MTU 12V4000 engine with a nominal rating of 2000

brake horsepower (bhp) at 1900 revolutions per minute (rpm). The pairs were designated Cntrl_1 and Test_1, and Cntrl_2 and Test_2. Tests quantified fuel consumption and gaseous emissions by direct measurement utilizing normal in-use test cycles and steady-state “load box” operations.

The implementation of portable emissions measurement systems (PEMS), improved fuel consumption instrumentation, on-board datalogging, and other in-use measurement technologies has made such testing more feasible. This project demonstrated that a PEMS in conjunction with coriolis mass flow meters can provide equipment owners with the ability to evaluate fleet emissions and fuel consumption in real time. The applicability and performance of different technologies, retrofits, or fuels under their specific operating conditions can be assessed with known accuracy.

TEST PROCEDURES

Test objectives were to quantify truck emissions and fuel consumption during normal in-use service, as well as collection of performance data under steady-state operations while the truck was at a stationary location and operated in load box mode.

The primary test goal was the quantification of the performance change between baseline and candidate test conditions resulting from implementation of the various technologies. The performance parameters determined during this test campaign were the changes in:

- Carbon monoxide (CO), carbon dioxide (CO₂), nitrogen oxides (NO_x), and total hydrocarbon (THC) exhaust emissions in parts per million by volume (ppmv), grams per hour (g/h), and grams per brake horsepower-hour (g/bhp-h)
- Fuel consumption in pounds per hour (lb/h) and pounds per brake-horsepower hour (lb/bhp-h)

Baseline test runs established initial emissions and fuel consumption performance. Test personnel immediately evaluated candidate performance for the lubricating oil re-burn system and the biodiesel blend because of their prompt impact. The fuel additive required a four to eight week break-in period before candidate testing. The additive was dosed in two ratios: a preliminary dose of 625 gallons of diesel fuel to 1 gallon of additive (625:1); and then a maintenance dose of 1250:1. The additive was dosed at 625:1 for approximately half of the break-in period and then dosed at 1250:1 for the remainder of the break-in period and during candidate testing. The candidate test runs after the break-in period then established final emissions and fuel consumption performance. Table 1 summarizes the testing schedule and diesel technologies tested.

Test Date	Diesel Technology	Fuel Type	Test Condition
Aug., 2006	Additive	No. 2 Diesel	Baseline
Nov., 2006		No. 2 Diesel w/ additive	Candidate
Aug., 2006	None	No. 2 Diesel	Baseline
Nov., 2006		No. 2 Diesel	Candidate
Nov., 2006	Additive	No. 2 Diesel	Baseline
Feb., 2007		No. 2 Diesel w/ additive	Candidate
Nov., 2006	None	No. 2 Diesel	Baseline
Feb., 2007		No. 2 Diesel	Candidate
Feb., 2007	Lubricating oil re-burn system & Additive	No. 2 Diesel w/ additive, oil re-burn system off	Baseline
		No. 2 Diesel w/ additive, oil re-burn system on	Candidate
Feb., 2007	Biodiesel blend	No. 2 Diesel w/ additive	Baseline
		Biodiesel blend	Candidate
Feb., 2007	Lubricating oil re-burn system	No. 2 Diesel, oil re-burn system off	Baseline
		No. 2 Diesel, oil re-burn system on	Candidate
Feb., 2007	Biodiesel blend	No. 2 Diesel	Baseline
		Biodiesel blend	Candidate

The diesel fuel technologies were also evaluated via a modified SAE J1321 test procedure [9] which compares “test truck” performance against a “control truck.” The unchanging control truck is run in tandem with the test truck to provide a reference for fuel consumption data. The results can be analyzed two ways:

- As the absolute performance change “within” a particular test truck
- As the change in the test truck / control truck ratio (T/C ratio)

The T/C ratio for this evaluation is the ratio of fuel consumed by the test truck to the fuel consumed by the control truck during one test run.

Modifications to the as-published J1321 procedures included:

- Use of individual mass flow meters on the engine fuel supply and return lines, with fuel consumption consisting of the difference between the two, rather than a day-tank and gravimetric fuel consumption measurements
- Application to non-road duty cycles rather than a known on-highway travel route
- Operation of vehicles in a non-tandem manner, although within the same duty cycle and time periods, to minimize impacts on emissions

TEST EQUIPMENT – A Horiba OBS-2200 PEMS measured gaseous pollutant emissions. The OBS-2200 is essentially a miniaturized laboratory analyzer bench which has been optimized for portable use. It meets or exceeds Title 40 CFR 1065 [10] requirements for in-use testing of engine emissions. The OBS-2200 measures CO and CO₂ with non-dispersive infra-red (NDIR) detectors. It does not require a separate moisture removal system for the CO and CO₂ NDIR detectors. The NO_x analyzer section consists of a chemiluminescence detector with an NO₂ / NO converter. This is the kind of system specified in Title 40 CFR 60, Appendix A, Method 7E, “Determination of Nitrogen Oxides Emissions from Stationary Sources”, which is a reference method for NO_x. THC emissions are measured with a flame ionization detector (FID). This method corresponds to the system specified in Title 40 CFR 60 Appendix A, Method 25, “Determination of Total Gaseous Non-Methane Organic Emissions as Carbon”, which is a reference method for THC. The OBS-2200 sample pump conveys all samples through a heated umbilical directly to heated analyzer sections, which eliminates the need to remove moisture and eliminates possible moisture scavenging.

Test personnel placed the OBS-2200 in a shock-mounted case with vibration damping and powered the unit from the truck's 24 VDC electrical system while underway.



Figure 1. The Horiba OBS-2200 PEMS Installed on a Haul Truck

A Type-S pitot was used to conduct all velocity traverses. The pitot was calibrated prior to testing and was found to have a pitot coefficient of 0.805.

Truck-mounted Krohne Optimass 15T coriolis mass flow meters were installed on the engine fuel supply and return lines to directly measure fuel consumption as the instantaneous difference between the supply and return flow rates.



Figure 2. Truck-Mounted Krohne Coriolis Mass Flow Meters

Sensor outputs from the diesel-electric generation system provided truck speed, rpm, and bhp. The engine electronic control module (ECM) provided redundant fuel consumption data for comparison with the coriolis meters, as well as redundant rpm and bhp data. Each instrument reported to data loggers which recorded realtime data at 1 Hertz (Hz) throughout all test periods.

Table 2 lists the measurement accuracies of the major test instruments.

Table 2. Measurement Accuracies			
Instrument or Sensor	Accuracy		
Horiba OBS-2200 PEMS			
Pressure transducers	5.0 % of point or 5.0 % of max ^a		
Ambient barometric pressure	0.07 "Hg (250 Pa)		
Temperature transducers (T _{turb} , T _{out} , T _{amb})	1.0 % of point or 5.0 °C		
Instrumental analyzer concentration	4.0 % of point		
Other Instruments			
Exhaust flow	5.0 % of point		
Magnehelic gages	1.0 % of point		
Testo Model 350	CO, NO _x : 5.0 % of point CO ₂ : 0.4 % of point		
ΔP sensors	0.25 % of point		
Coriolis meters, net accuracy ^b	100 % power	50 % power	Low Idle
	0.5 %	1.2 %	8.8 %
Fuel temperature	0.6 °F		
Diesel-electric generation system wheel motor current sensors	± 0.5 % of point ^c		
Diesel-electric generation system wheel motor voltage sensor	± 1.0 % of point ^c		
Diesel-electric generation system bhp signal	Unknown ^d		
Diesel-electric generation system main alternator shaft speed signal	Unknown ^d		
Diesel-electric generation system truck speed signal	Unknown ^d		
^a "max" refers to the maximum value expected during testing			
^b Individual coriolis meter accuracy is 0.2 % of point at full RPM, ≈ 0.5% of point at low idle			
^c Provided verbally by diesel-electric generation system manufacturer			
^d Results based on these sensors are not valid for inter-truck comparisons unless accuracy, drift, and alternator mechanical efficiency specifications are available			

PRE-TEST ENGINE BALANCE – The tested engines have two cylinder banks which exhaust through separate turbochargers and exhaust pipes, one on port and the other on starboard. Combining the two exhaust flows into a single stream was impractical for this test, so engine emissions were determined for one exhaust pipe only. Total engine exhaust emissions were then the single exhaust pipe emission rate multiplied by two.

Test personnel conducted one exhaust gas velocity traverse according to EPA Method 2 for velocity and volume [11] at each of four power settings (25, 50, 75, and 100 percent) at each exhaust pipe. They also screened the exhaust gas CO, CO₂, and NO_x concentrations with a Testo 350 multi-gas analyzer.

Southern considered the engine to be acceptable for testing if exhaust gas flow rates in dry standard cubic feet per minute (dscfm) and gaseous emissions concentrations in ppmv at each exhaust pipe were within 5.0 percent of each other at each of the four power settings.

LOAD BOX OPERATIONS – Load box testing was necessary to:

- Characterize the engine exhaust flow under different loads, which was required to determine mass emission rates during in-use testing
- Screen the exhaust gas concentrations to establish that the engine's two cylinder banks were operating equally
- Acquire steady-state fuel consumption and emissions data at four power settings and low idle

The load box tests allowed for an evaluation that is more comparable to laboratory data than the in-use tests and generally resulted in narrower confidence intervals.

Load box tests were conducted while the main diesel-electric alternator power output was shunted to the truck's dynamic braking grid. This allowed steady-state engine loading at known power outputs. The load box results are analogous to modal test cycles such as those specified in Title 40 CFR 89 Subpart E [12].

Test personnel established four engine power levels evenly spaced between low idle and full speed for emissions and fuel consumption evaluations under load box operations. Fuel consumption and emissions data were acquired at these four power settings, plus low idle.

Test personnel conducted three test runs at each of the four power settings (25, 50, 75, and 100 percent) plus low idle for both the baseline and candidate test conditions. The PEMS gaseous emissions concentrations were correlated with the exhaust gas flow rate in dscfm to yield g/h emission rates at each power setting.

Test personnel conducted Method 2 exhaust flow traverses concurrently with each PEMS test run to determine exhaust gas flow rates. Calculation of exhaust flow in dscfm required correction for exhaust gas water (H₂O), as supplied by the PEMS, and exhaust gas temperature, as obtained during the traverse. Exhaust gas flow rate could not be measured directly by the PEMS because the exhaust pipe size on the trucks exceeded the size of the largest PEMS flow tube.

Calculation of the exhaust gas molecular weight was also required. For this test campaign, oxygen concentration was 20.9 minus the mean CO₂ concentration, as supplied by the PEMS, in volume percent. Nitrogen concentration was 79.1 volume percent.

IN-USE OPERATIONS – In-use operations consisted of monitoring a 12-hour shift with each truck operating over its normal duty cycle. This is an important concept because laboratory dynamometer measurements, such as those performed for haul truck engine certification, rarely reflect actual in-use accelerations, loading, or duty cycles. Also, laboratory equipment and procedures often cannot be employed in practical field test campaigns.

For the purposes of this test campaign, the definition of a "normal duty cycle" was one round trip as follows:

- Truck begins at the start of loading at the shovel
- Continues as the truck drives to the dump point and enters the dumping queue
- Continues as the truck returns to the loading shovel and enters the loading queue
- Ends when the shovel starts to load the truck for the next cycle

The PEMS provided gaseous emissions concentrations at 1 Hz intervals. Southern's data logger recorded the main alternator power output in kilowatts during the 12-hour in-use tests at 1 Hz intervals. It was impossible to conduct Method 2 traverses during the in-use test runs, so analysts correlated the Method 2 traverse flow rates with the main alternator power output at each power setting observed during the load box tests. This enabled determination of in-use instantaneous exhaust gas flow based on the logged main alternator power data. The resulting exhaust gas flow rates, correlated with PEMS emission concentrations seen during the in-use tests, yielded emission rates in g/h during the 12-hour in-use tests.

Test personnel observed the test trucks during at least three complete duty cycles during the 12-hour in-use test periods. From this in-use observations data they compiled a list of events, approximate truck speed, and elapsed times for the duty cycle. This aided later analysis of correlations between logged ECM, sensor, and emissions data and truck operations.