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

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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 (CO_2), 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.

Table 1. Test Schedule and 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 mine production

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 CO_2 with non-dispersive infra-red (NDIR) detectors. It does not require a separate moisture removal system for the CO and CO_2 NDIR detectors. The NO_X analyzer section consists of a chemilumenescence detector with an NO_2 / 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, CO_2, 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 (H_2O), 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 CO_2 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.

During the 12-hour in-use tests, as specified in SAE J1321, each truck pair was dispatched to perform the same duty cycle, one immediately after the other when possible, so they entered the loading and dumping queues in the same order. This ensured that each truck in the pair saw the same duty cycle throughout the shift and minimized the impacts of ambient conditions or varying roadway characteristics.

TEST RESULTS

PRE-TEST ENGINE BALANCE – Test personnel conducted one velocity traverse at each power setting at each exhaust pipe. An exhaust flow surrogate was calculated based on the exhaust temperature and flow pressure logged during the velocity traverses. The exhaust flow surrogate was:

$$Q_{surrogate} = \text{Mean}(\text{sqrt}(\Delta P)) * \text{sqrt}(\text{Mean } T_s) / \text{sqrt}(P_s)$$

Where: $Q_{surrogate}$ = exhaust gas flow surrogate
ΔP = velocity head of stack gas, "H_2O
T_s = absolute stack temperature, K
P_s = absolute stack gas pressure, psia

Table 3 shows the results from the velocity traverse engine balance performed on one test truck.

Table 3. Velocity Traverse Engine Balance

Power Setting	$Q_{surrogate}$		% Difference
	Port	Starboard	
25%	7.4	7.0	4.7
50%	12.7	12.3	3.7
75%	17.2	16.9	1.2
100%	21.1	20.8	1.4

Test personnel also screened the exhaust gas CO, CO_2, and NO_X concentrations for each exhaust pipe. Three readings of each pollutant concentration were taken from each exhaust pipe. Table 4 summarizes the results.

Table 4. Emissions Engine Balance

Power Setting	% Difference		
	CO	CO_2	NOx
25%	-14.1	-4.6	-0.8
50%	13.2	2.6	-0.3
75%	1.8	-1.4	-1.3
100%	3.5	0.6	0.6

Carbon monoxide concentrations were generally very low, so small absolute differences between the cylinder banks led to the large relative differences shown in Table 4. Carbon dioxide emissions, which are much more directly related to fuel consumption and engine performance, were very consistent and closely related to the exhaust gas flow rates. Analysts therefore concluded that the engine was well-balanced, based primarily on the exhaust gas flow, CO_2, and NO_X concentrations.

EXHAUST GAS FLOW CORRELATION – 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 instantaneous exhaust gas flow during the in-use tests based on the logged main alternator power data.

Analysts plotted the relationship between the volumetric flow rate and bhp observed at each power setting during load box tests. A polynomial trendline was added to the plot. The equation of the trendline served as the correlation equation for exhaust gas flow rate during the in-use tests. The R-squared value of the equation indicates how "well" the equation predicts the stack gas dry volumetric flow rate.

Figure 3 shows the resulting correlation equation for one of the test trucks.

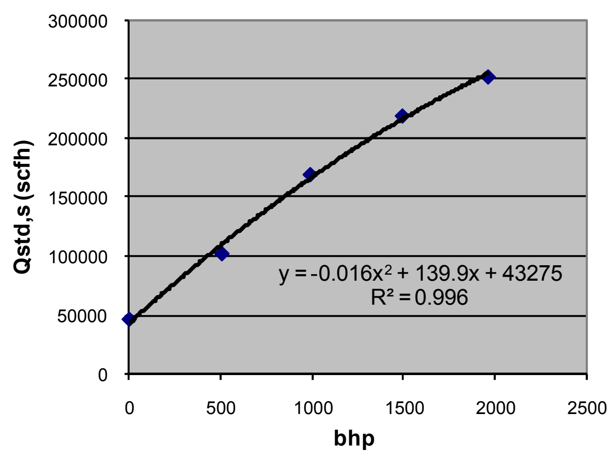

Figure 3. Example Exhaust Gas Correlation Equation

LOAD BOX EMISSIONS – Gaseous emissions changes for each individual truck were reported as the absolute difference in g/bhp-h during baseline and candidate testing. Brake-specific emissions results were based on the bhp signal supplied by the truck's diesel-electric generation system. The absolute accuracy of that system was uncertain because the signal or its contributing parameters (such as voltage and current) could not be referenced to any NIST-traceable standard. This means that absolute brake-specific comparisons between trucks may not be valid because the bhp definition may vary from truck to truck. Baseline and candidate comparisons within one truck, however, are valid because test personnel used the same sensors and processing algorithms for both test phases.

To calculate gaseous emissions, analysts:

- Calculated the overall mean mass emissions, generated power, and sample standard deviation (s_{n-1}) for each power setting and low idle, based on the mean PEMS concentrations and Method 2 flow rates for each individual run
- Calculated the overall mean brake-specific emission rate and s_{n-1} in (g/bhp-h) for each power setting
- Calculated the difference between the baseline and candidate mean results
- Evaluated the statistical significance of the difference
- Calculated the 95-percent confidence interval on the difference

Table 5 summarizes the baseline and candidate load box emissions results and their 95 percent confidence intervals for one test truck. This truck was run on No. 2 diesel during the baseline tests and No. 2 diesel with the fuel additive during candidate tests.

Table 5. Test Truck Load Box Emission Rates

Baseline Brake-Specific Emissions, g/bhp-h				
Power Setting	**25%**	**50%**	**75%**	**100%**
CO	ND	ND	ND	0.74 ± 0.01
CO_2	725 ± 19	601 ± 9	564 ± 7	565 ± 8
NO_X	10.7 ± 0.3	9.62 ± 0.15	11.22 ± 0.14	10.99 ± 0.17
THC	1.78 ± 0.04	1.09 ± 0.02	0.79 ± 0.01	0.59 ± 0.01
Candidate Brake-Specific Emissions, g/bhp-h				
Power Setting	**25%**	**50%**	**75%**	**100%**
CO	ND	ND	ND	1.11 ± 0.03
CO_2	692 ± 15	618 ± 4	560 ± 11	555 ± 13
NO_X	10.4 ± 0.2	9.64 ± 0.07	9.85 ± 0.19	9.98 ± 0.01
THC	1.74 ± 0.04	0.95 ± 0.01	0.63 ± 0.01	0.4 ± 0.2

"ND" for CO emissions indicates that concentrations were below the OBS-2200 detection limit.

IN-USE EMISSIONS – Southern calculated and reported emission rates, integrated over each duty cycle, as grams/duty cycle and as g/h, based on the 1 Hz PEMS concentrations and fixed pitot flow rates. Analysts then:

- Calculated the overall mean and s_{n-1} mass emissions for all similar duty cycles in grams/duty cycle
- Calculated the overall mean and s_{n-1} emission rate for all similar duty cycles in g/h

Duty cycles were considered "similar" if the lowest individual baseline result, for example, was within 2.0 percent of the highest individual baseline result. This is similar to the J1321 criteria described in the next section.

Direct comparison of the baseline and candidate cycle-specific emission rates was not especially meaningful because of changing conditions (for example, the shovel or dump locations may have changed between baseline and candidate tests). Analysts found that comparisons of duty cycle segments or "microtrips" were more meaningful. Those which remained similar between the baseline and candidate test periods were especially useful. Ascending the same major grade is an example. Southern used the in-use observations data as compared to the real-time rpm, ΔP, T_s, and other data to determine which microtrips were similar.

Table 6 shows the baseline and candidate in-use emissions results and their 95 percent confidence intervals for one test truck. This truck was run on No. 2 diesel during the baseline tests and No. 2 diesel with the fuel additive during candidate tests. Analysts used upbound microtrips for all in-use emissions calculations because their elapsed times, fuel consumption, and mean bhp were the most consistent. The data set included seven complete upbound runs. No in-use brake-specific emission rate changes were statistically significant.

Table 6. Test Truck In-Use Emission Rates

Brake-specific emissions, g/bhp-h		
	Baseline	**Candidate**
CO	0.82 ± 0.16	0.6 ± 0.2
CO_2	480 ± 30	487 ± 14
NO_X	7.9 ± 0.4	7.6 ± 0.4
THC	0.9 ± 0.06	0.96 ± 0.08

Results for tests using the lubricating oil re-burn system and the biodiesel blend showed results with similar levels of confidence.

FUEL CONSUMPTION – Baseline test runs established initial fuel consumption performance ratios between the test and control trucks. This test campaign compared the performance of the two test trucks (Test_1, Test_2) and the two control trucks (Cntrl_1, Cntrl_2). A test technology was then applied to trucks Test_1 and Test_2 over a break-in period. The candidate test runs established the final test truck to control truck fuel consumption performance ratios. The change in the ratio after the break-in period, as compared to the baseline ratio, is the change in fuel consumption.

SAE states that the J1321 fuel consumption method accuracy, when applied to on-highway vehicles, is approximately 1.0 percent. The SAE method requires that the T/C ratio for each test cycle be within 2.0 percent of all other valid runs to achieve this accuracy. Over a 12-hour shift, with each truck in the pair running as closely as possible to the other, sufficient runs were logged to enable reporting of the change between baseline and candidate fuel conditions to approximately 1.0 percent.

<u>Load Box Fuel Consumption</u> – Figures 4 and 5 show the load box T/C ratios for each truck pair. The published certified brake-specific fuel consumption (bsfc) for this engine family was 0.329 lb/bhp-h. Tests on other engines indicate bsfc between 0.365 and 0.444 lb/bhp-h, depending on make and model. In this test, bsfc ranged from 0.322 to 0.463 lb/bhp-h, depending on the power setting.

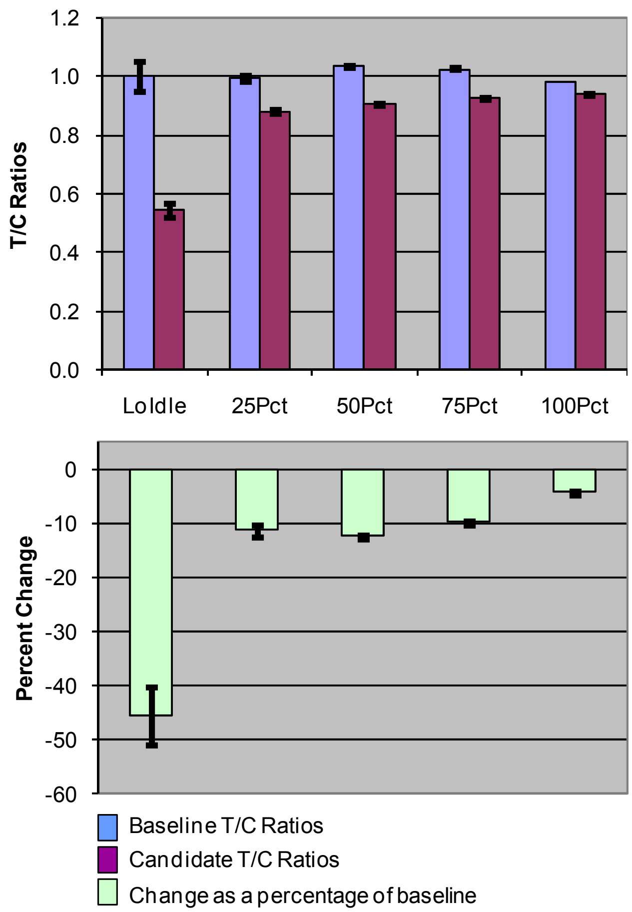

Figure 4. Load Box Fuel Consumption T/C Ratios, First Truck Pair

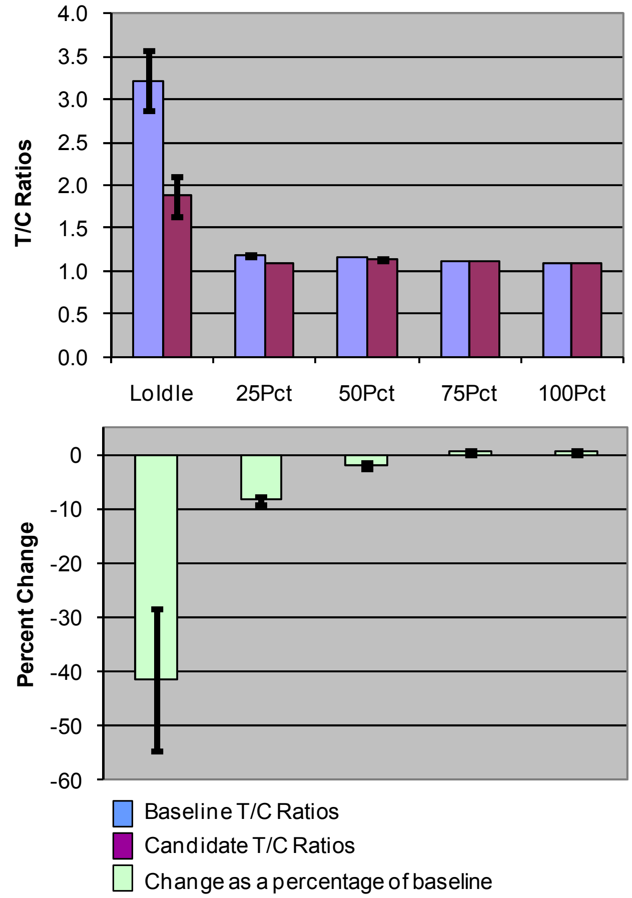

Figure 5. Load Box Fuel Consumption T/C Ratios, Second Truck Pair

Fuel consumption at low idle was in gallons per hour (gph), and both the truck pairs showed significant improvements. The results should be regarded with caution, however, because of the small fuel consumption rates. The low idle fuel consumption is the difference between two large, nearly similar, fuel flow rates. Slight injector performance, fuel piping, meter installation, or calibration changes which would not affect higher power fuel consumption determinations can profoundly change the low idle results.

<u>In-Use Fuel Consumption</u> – Southern test personnel logged in-use duty cycle events while riding the trucks during baseline and candidate test phases. The in-use duty cycles consisted of a series of events, such as departing the shovel, driving past certain mine locations, dumping the load, etc. Analysts determined that the repeatability of an event series, and the resulting confidence intervals, varied widely depending on the event or duty cycle types. Queuing behavior, for example, caused large variability in the round trip duty cycles. Variability was much smaller during the initial 8 percent upgrade events as the trucks left the shovel.
In-use duty cycle definitions were:

- Round trip: began when the truck left the dump, ended when the truck arrived back at the dump
- Upbound: began when the truck left the shovel loaded, ended just before the truck dumped the load

- Mid-mine: mid-mine upbound travel
- 8 percent upgrade: data extracted from the middle of the initial (loaded) climb as the truck left the shovel

Figure 6 shows engine rpm, fuel consumption in gph, bhp as measured by the diesel-electric generation system, and truck ground speed in miles per hour (mph) for a representative upbound duty cycle. Such depictions can be useful for examining mine haul road layout, operator behavior, or other effects. Haul road grades controlled truck operations at points A and B. The graphs show high bhp, rpm, and gph with decreasing ground speed. The ground speed dip at A corresponded to an approximately 6 percent grade while the grade at B was about 8 percent. The two very strong retarder applications at C, which show as negative bhp, were operator-controlled and could indicate the sudden avoidance of a road hazard. Repeated heavy retarder use may indicate the need for better operator training.

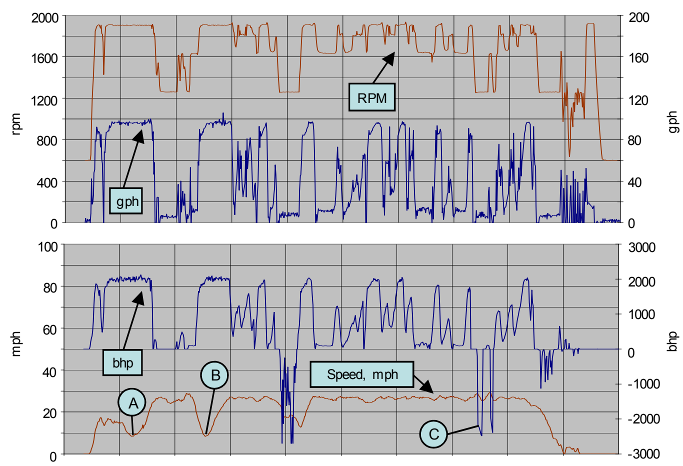

Figure 6. Example Upbound Duty Cycle

The following tables provide in-use bsfc results and their 95 percent confidence intervals for both truck pairs.

Table 7. In-Use bsfc T/C Ratios for First Truck Pair

Duty cycle	Round Trip	Upbound	Upbound, Mid-Mine	8 % Upgrade
Baseline T/C ratio	1.07 ± 0.10	1.02 ± 0.06	1.03 ± 0.03	0.989 ± 0.007
Candidate T/C ratio	0.92 ± 0.06	0.93 ± 0.03	0.931 ± 0.010	0.953 ± 0.007
T/C ratio change	-0.15 ± 0.12	-0.09 ± 0.07	-0.10 ± 0.04	-0.035 ± 0.010
Change as Percentage of Baseline	-14 ± 11	-9 ± 6	-9 ± 3	-3.6 ± 1.0

Table 8. In-Use bsfc T/C Ratios for Second Truck Pair

Duty cycle	Round Trip	Upbound	Upbound, Mid-Mine	8 % Upgrade
Baseline T/C ratio	1.17 ± 0.05	1.11 ± 0.02	1.126 ± 0.013	1.116 ± 0.010
Candidate T/C ratio	1.14 ± 0.03	1.110 ±0.016	1.110 ± 0.015	1.108 ± 0.011
T/C ratio change	*	*	*	*

*Not statistically significant

Analysis of J1321 Procedures – SAE J1321 procedures require the use of paired “test” and “control” units. The results can be analyzed two ways: as the absolute performance change “within” a particular test truck; and as the change in the T/C ratio.

Southern has generally paired a single test truck with a single control truck, although multiple test trucks could be compared to a single control truck. A review of the recently-concluded mining haul truck study shows that the J1321 method did bring value to the test campaign, but evaluation of absolute performance changes within a test truck are also valuable. The conclusion is that complete reliance on either method exclusively may not give a true picture of what is really happening.

The following tables summarize results for the load box tests.

Table 9. Absolute bsfc Percentage Change, Load Box

Truck	25 % Load	50 % Load	75 % Load	100 % Load
Test_1	-3.7	-7.7	-7.7	-3.4
Test_2	-10.2	-4.2	-1.6	-1.1
Cntrl_1	8.7	5.4	2.3	0.9
Cntrl_2	-1.9	-2.3	-2.0	-1.6

Table 10. T/C Ratio Percentage Change, Load Box

Truck	25 % Load	50 % Load	75 % Load	100 % Load
Test_1 / Cntrl_1	-11.3	-12.5	-9.8	-4.2
Test_2 / Cntrl_2	-8.4	-1.9	0.5	0.5

For the load box tests, both Test_1 and Test_2 performance improved between the baseline and candidate tests. Cntrl_1 performance declined which drove the Test_1 / Cntrl_1 T/C ratio towards improved performance. Cntrl_2 performance improved which drove the Test_2 / Cntrl_2 T/C ratio towards neutral performance change in the higher power settings. The J1321 procedure therefore was “conservative” for the Test_2 / Cntrl_2 pair and “liberal” for the Test_1 / Cntrl_1 pair.

Tables 11 and 12 for the in-use tests show results for microtrips that were selected based on the in-use observations data.

Table 11. Absolute bsfc Percentage Change, In-Use				
Truck	**Round Trip**	**Upbound**	**Mid-Mine**	**8% Upgrade**
Test_1	-11.0	-14.5	-6.6	-1.2
Test_2	-8.2	-1.7	-2.6	-1.3
Cntrl_1	3.6	-6.7	2.7	2.4
Cntrl_2	-5.2	-2.1	-1.3	-0.7

Table 12. T/C Ratio Percentage Change, In-Use				
Truck	**Round Trip**	**Upbound**	**Mid-Mine**	**8% Upgrade**
Test_1 / Cntrl_1	-14	-9	-9	-3.6
Test_2 / Cntrl_2	*	*	*	*
* Not statistically significant				

Both Test_1 and Test_2 performance improved between the in-use baseline and candidate tests. Cntrl_1 performance change was mixed but generally declined, which drove the Test_1 / Cntrl_1 T/C ratio towards improved performance. Cntrl_2 performance improved almost exactly in pace with Test_2. This drove the Test_2 / Cntrl_2 T/C ratios to be not statistically significant. Again, the J1321 procedure was “conservative” for the Test_2 / Cntrl_2 pair and generally “liberal” for the Test_1 / Cntrl_1 pair.

OPERATIONS LOGGING

DUTY CYCLE COMPARISONS – Based on in-use observational data collected by Southern test personnel, analysts were able to identify microtrips within the 12-hour in-use test runs. Identifying these microtrips facilitated the assessment of mine duty cycles and truck operator variability. Analysts found that truck scheduling and queuing at the shovel or dump were important overall performance factors. Southern focused duty cycle analyses and comparisons on upbound (loaded) cycles because they were fundamentally less variable, presumably because of the load’s inertia.

Southern test personnel stressed that the truck operators drive as consistently as possible from run to run in order to minimize run to run variability and the resulting confidence intervals. Even so, each truck, operator, and the combination of the two had their own “signature” as shown by acceleration, braking, cruising, and other behaviors. Figure 7 shows bhp traces for three upbound runs by a single operator (Operator A). The figure shows how remarkably repeatable the driver is from run to run. Trends in bhp behavior were nearly identical for each run. This shows that making direct comparisons of runs from a single truck / operator combination is a valid approach resulting in minimal variability and small confidence intervals.

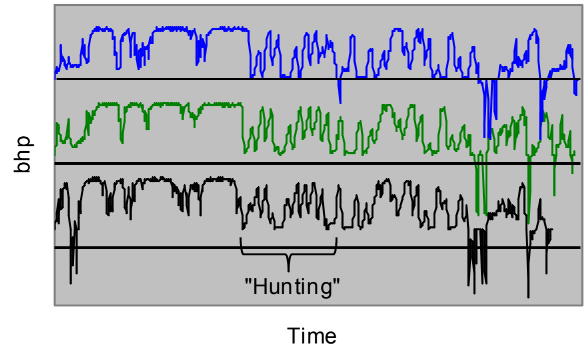

Figure 7. Operator A Upbound Duty Cycles

Figure 8 shows bhp traces for three upbound cycles from another truck operator (Operator B). Operator B is also very repeatable with respect to her own runs, but differences are apparent between the two operators. A notable feature is the difference in acceleration and retard patterns. At the beginning of each run, for example, the bhp traces were very similar during the initial climb from the loading site. However, Operator B tended to more frequently cycle between maximum and low bhp (as compared to Operator A). Brake-horsepower is directly related to rpm and fuel consumption, so this implies that Operator B was on and off the accelerator more frequently, or had a “heavier foot” than Operator A. Retard events were also more numerous and lasted longer for Operator B. Analysts observed that these patterns and differences were repeatable and specific to a particular operator / truck combination.

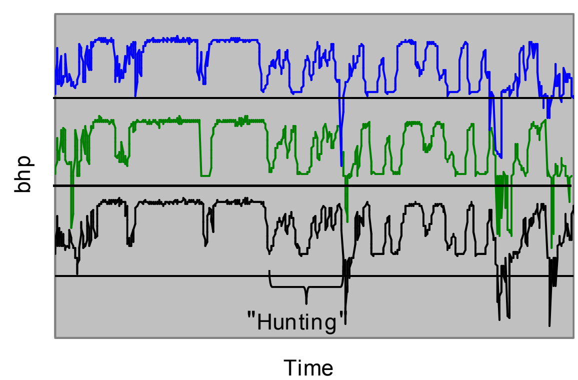

Figure 8. Operator B Upbound Duty Cycles

Both operators experienced surging ("hunting") while running along certain level or slight downgrades in the mine. The diesel-electric generation system would oscillate uncontrollably between full and reduced power even though truck speeds, throttle pedal positions, and operator practices were steady and consistent. Figures 7 and 8 indicate this behavior with brackets. Better control system integration or more refined damping coefficients could represent an opportunity for fuel savings under these conditions.

TRUCK OPERATING CHARACTERISTICS – Analysts examined the in-use observations data to identify operating characteristics during typical 12-hour truck shifts. Analysts utilized plots of the logged data to classify certain types of truck behavior. Of particular interest to equipment owners for this project were:

- Periods of time during shifts where trucks were off
- Hauling periods
- Periods of truck idling while dumping
- Periods of truck idling while queuing or for other reasons

Analysts examined the logged rpm and truck speed data to identify these periods. All instances of non-zero truck speed were designated as truck hauling. Engine off conditions were characterized by zero truck speed and zero rpm. Periods of zero truck speed and non-zero rpm were identified as truck idling. During idle time, truck operation was classified as either "dumping" or "non-dumping." Non-dumping includes time spent queuing at the shovel or dump location and idling for other reasons (possibly driver breaks throughout the shift, time spent waiting at mine intersections, etc.). Dumping events were characterized by zero truck speed, zero alternator power, and rpm of over 680. Non-dumping events were characterized by zero truck speed and rpm of less than 680. Observations by test personnel were the source of the rpm criterion. In general, truck operators raised the engine speed more than 680 rpm during dumping because the hydraulic system operated the bed too slowly otherwise.

Figure 9 summarizes the results for three trucks as percentage of total truck time. Data included:

- Truck 1: 99 hours over 8.25 shifts
- Truck 2: 118 hours over 9.8 shifts
- Truck 3: 58.8 hours over 4.9 shifts

The figure shows that the majority of truck time was spent hauling, but a significant portion of truck time was spent idling while not dumping.

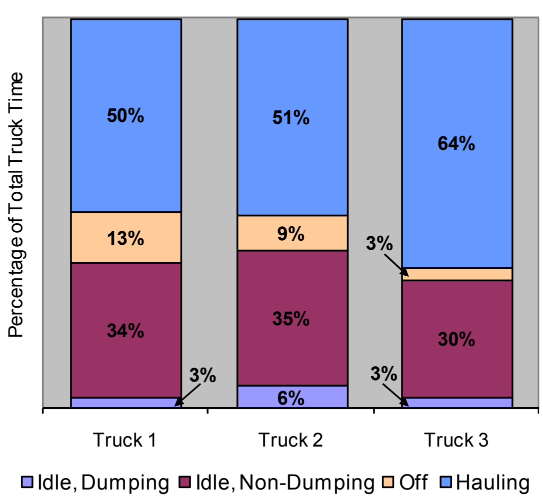

Figure 9. In-Use Truck Operating Characteristics

ECM COMPARISONS

Southern recorded ECM outputs during load box and in-use testing on the trucks. ECM validation consisted of the difference between the mean of a given parameter and that developed from other data sources. These were:

1. Coriolis meters for fuel consumption comparisons
2. Diesel-electric generation system engine speed signal for rpm comparisons
3. Diesel-electric generation system bhp signal for ECM bhp comparisons

Analysts first aligned the ECM and data logger 1-second data, based on rpm spikes or other engine events during load box tests. Stable operating time periods were then selected at each power setting and the mean for each parameter was computed for that time period. The difference and the 95 percent confidence interval on the difference were then calculated at each power setting between the ECM and the other data sources.

The ECM fuel rate signal was compared to the fuel consumption reported by the coriolis meters for four runs (two baseline and two candidate) for two different trucks. ECM behavior appeared to change between the baseline and candidate tests. Overall, the accuracy of ECM fuel consumption was approximately $\pm$ 5.7 gph for one of the trucks and $\pm$ 4.7 gph for the other truck.

The ECM rpm signal was consistently biased low, as compared to the diesel-electric generation system rpm signal. All biases were less than 4 rpm, or approximately 0.3 percent of the diesel-electric generation system signal, except at low idle. The ECM signal bias at low idle was 22 rpm high for one test run. This may have been an artifact of the data extraction. Other low idle readings were biased low, between -1 and -2 rpm, which appears to be consistent with the higher power settings.

The ECM bhp signal showed significant negative bias as compared to the diesel-electric generation system signal for all test runs. The bias tended to decrease at higher power settings, and ECM behavior changed between the baseline and candidate test phases, similar to the fuel consumption data.

CONCLUSION

Real-time emissions and fuel consumption data measured during normal, in-use equipment operation may be highly useful to equipment owners. With this data, owners can reasonably and accurately evaluate new technologies, retrofits, and fuels on their fleets in their own operating conditions.

The SAE J1321 protocol provides a standard procedure for comparing in-use fuel consumption of two conditions.

However, comparing the absolute performance change "within" a particular test unit versus the change in the T/C ratio shows that complete reliance on either method exclusively may not give a true picture of what is really happening. For long term evaluations, using the T/C ratio approach may not be wise. Over a long period of time, it is difficult to tell how the control engine will change and if it does, why. In these cases, it may make the most sense to utilize the absolute performance change within a single test unit. Over short term testing, though, the T/C ratio approach works well. In either case, repeatability of test cycles and drivers is critical to getting results with minimal variance.

In addition to emissions and fuel consumption data, in-use operations logging can also be very useful to equipment owners. Owners can use information derived from in-use duty cycles to identify trends in their daily operations and driving characteristics. For example, information for operations logging may provide indicators to help train operators and plan layouts to minimize driving conditions where high emissions or fuel consumption occur (for instance, points of excessive idling).

Utilizing PEMS and real-time independent fuel metering for emissions and fuel consumption testing is widely applicable. Limits to using these methods really only include having the necessary space to mount equipment. This type of testing provides equipment owners and other interested parties with the opportunity to fully evaluate their equipment under real world conditions.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

bhp: brake-horsepower

bsfc: brake-specific fuel consumption

CO: carbon monoxide

CO_2: carbon dioxide

dscfm: dry standard cubic feet per minute

ECM: electronic control module

FID: flame ionization detector

g/bhp-h: grams per brake-horsepower hour

g/h: grams per hour

gph: gallons per hour

H_2O: water

Hz: hertz

K: degrees Kelvin

lb/bhp-h: pounds per brake-horsepower hour

lb/h: pounds per hour

mph: miles per hour

NDIR: non-dispersive infra-red

NO_X: nitrogen oxides

OEM: original equipment manufacturer

PEMS: portable emissions measurement system

ppmv: parts per million by volume

P_s: stack static pressure, "H_2O

psia: pounds per square inch, absolute

rpm: revolutions per minute

s_{n-1}: standard deviation

Southern: Southern Research Institute

T/C ratio: test truck to control truck ratio

THC: total hydrocarbon

T_s: stack gas temperature, K

ΔP: pitot tube velocity pressure, "H_2O