Effects of Mining Continuously Regenerated Trap (Mining-CRT) System on the Aerosol and Gaseous Emissions from a Heavy-Duty Diesel Powered Underground Mining Vehicle

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Introduction

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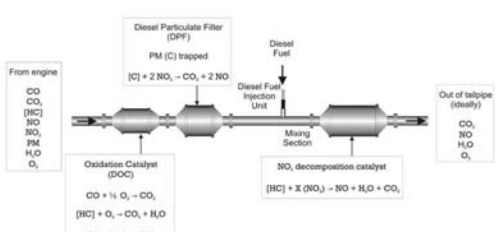
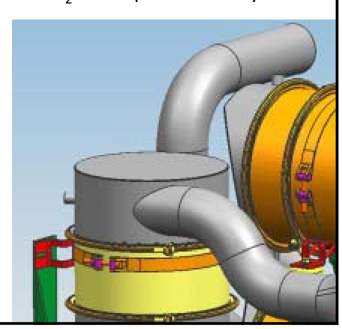
- Johnson Matthey GmbH, with assistance from NIOSH and Vale, developed and evaluated a passive DPF system suitable for controlling diesel particulate matter emissions from heavy-duty underground mining equipment operated over medium- and heavy-duty operating cycles.
- The result was the Mining Continuously Regenerated Trap (Mining-CRT) that can be continuously regenerated at exhaust temperatures of 220 ˚C (30 percent of time).
- The Mining-CRT system is designed to lower the level of energy required for filtration element regeneration by promoting soot oxidation by NO_2. Nitrogen dioxide is generated via catalytic oxidization of NO in a converter situated upstream of the filtration element.
- The potential for NO_2 slip is minimized by reacting catalytically remaining NO_2 with hydrocarbons injected downstream of the filtration element and upstream of the NO_2 decomposition catalyst.





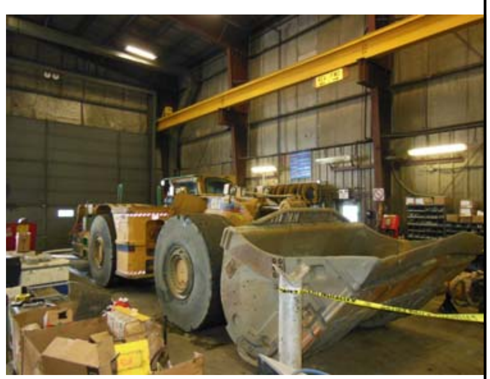
Introduction

- As a part of long term evaluation, the system was subjected to:
  - laboratory evaluation at CANMET;
  - long term evaluation at surface operations of Vale's Totten Mine;
  - long term evaluation in underground operations of Vale's Copper Cliff Mine (CCM).
- At CCM, the system was retrofitted to the load-haul-dump (LHD) vehicle #515 and used in the underground operation for approximately 1000 hours.

#515	
Vehicle	Caterpillar ScoopTram R1700G
Engine	Caterpillar C11 3176 DITA AAAC, EPA Tier 3
Engine displace.	11.1 L
Number of cylinders	6
Engine type	Turbocharged and aftercooled
Engine Power	263 kW (352 hp)

A series of tests was conducted at the surface shop of CCM to assess the effects of the system on gas and aerosol emissions from the Caterpillar C11 engine.

- The emissions were assessed while the LHD was parked in the high bay area of the surface shop, and the engine was operated at four different steady-state conditions:
  - low idle (LI),
  - high idle (HI),
  - hydraulic stall (HS),
  - torque converter and hydraulic stall (TCS&HS).



Methodology

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- The effects of the system were assessed using the results of a series of three sequential measurements performed on the exhaust drawn from ports located upstream (EOut) and downstream (FOut) of the system.
  - four-minute LI and HI tests and
  - two-minute HS and TCS&HS tests.

Instrumentation - Aerosols

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- A partial dilution system (Dekati, Model FPS4000) was used to dilute exhaust.
- Concentrations and size distributions of aerosols in the partially diluted exhaust were measured using a Fast Mobility Particle Sizer spectrometer (TSI, Model 3091 FMPS).
- Surface areas of aerosols deposited in alveolar region of human lungs were measured in the partially diluted exhaust using a Nanoparticle Surface Area Monitor (TSI, Model 3550 NSAM).

Instrumentation – Gases

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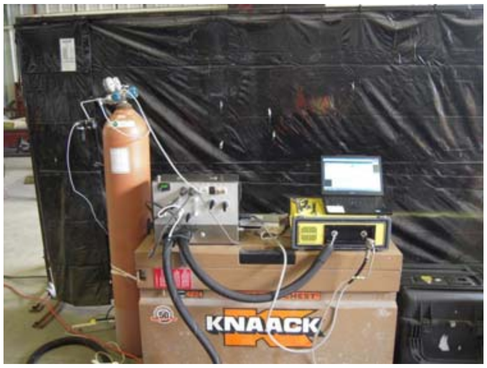
- The effects of the system on concentrations of CO, CO_2, NO, NO_2, N_2O, and hydrocarbons were determined using results of measurements made in undiluted exhaust using a Fourier transform infrared (FTIR) analyzer (Gasmet, dx-4000).
- The following hydrocarbons were summed to obtain total hydrocarbon concentrations (THC): ethane, propane, butane, pentane, hexane, octane, ethylene, acetylene, propene, 1,3-butadiene, formaldehyde, acetaldehyde, benzene, and toluene.



CDC NIOSH

Size Distribution and Concentrations of Aerosols

CDC NIOSH

Size Distributions and Concentrations of EOut Aerosols

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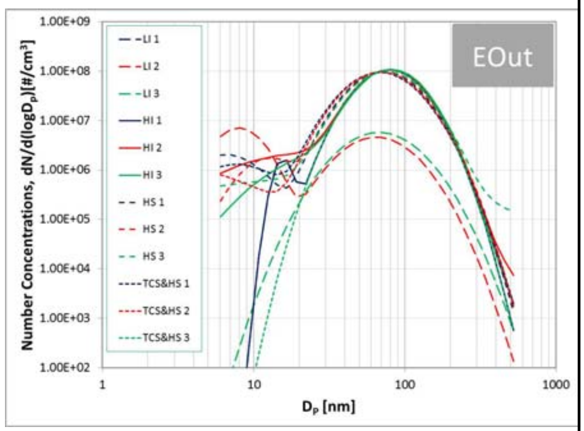
- The size distributions of EOut aerosols for all but two tests were found to be bimodal (the exceptions were single modal distributions for LI 3 and TCS&HS 3):
  - Median diameters for accumulation mode aerosols were between 56 and 82 nm;
  - Median diameters for nucleation mode aerosols were between 7 and 35 nm.



Size Distributions of FOut Aerosols

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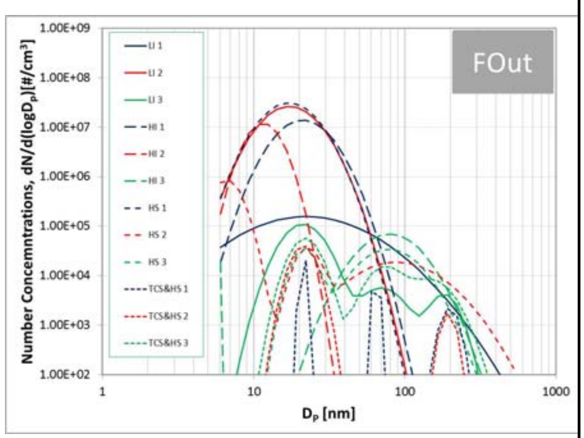
- The size distributions for FOut aerosols were single modal, bimodal, or trimodal:
  - Median diameters for the primary accumulation modes were between 65 and 89 nm;
  - Secondary accumulation modes with median diameters of 130-200 nm were observed for a number of tests;
  - Median diameters for nucleation mode aerosols was between 6 and 23 nm.



Effects of the System on Size Distributions for LI Conditions

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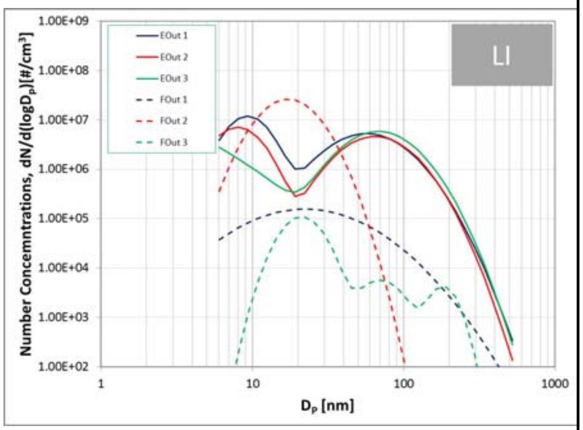
- For two out of three LI tests (FOut LI 1 and FOut LI 3), the system reduced concentrations of both accumulation and nucleation aerosols.
- For the third case (FOut LI 2), relatively high concentrations of nucleation aerosols were observed.
- Most probably those can be attributed to nucleation of fuel injected downstream of the filtration element.



Effects of the System on Size Distributions for HI Conditions

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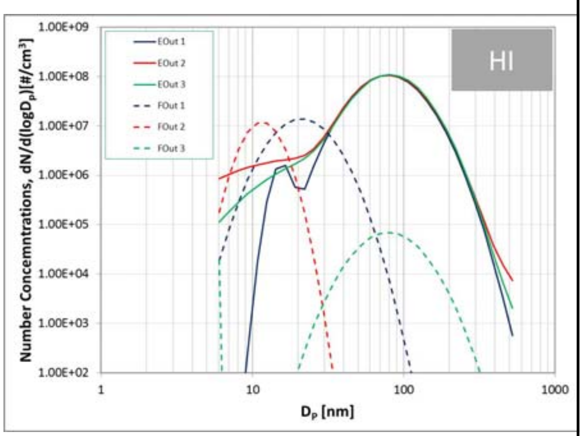
- In the case of HI conditions, relatively large concentrations of nucleation aerosols were observed during FOut HI 1 and FOut HI 2 tests.
- No nucleation aerosols were found in FOut exhaust for HI 3 test.
- Most probably those can also be attributed to the nucleation of HC that slip the decomposition catalyst.



Effects of the System on Size Distributions for HS Conditions

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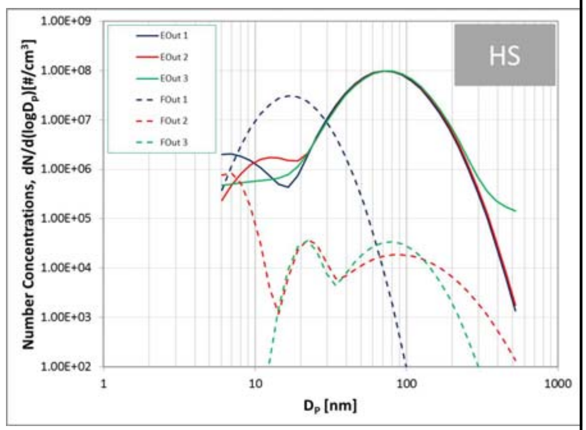
- In the case of HS conditions, relatively large concentrations of nucleation aerosols were observed during FOut HS 1 test.
- The concentrations of nucleation aerosols were relatively low for FOut HS 2 and HS 3 tests.
- Nucleation of fuel injected downstream of the filtration element was the most probably source of those aerosols.



Effects of the System on Size Distributions for TCS&HS Conditions

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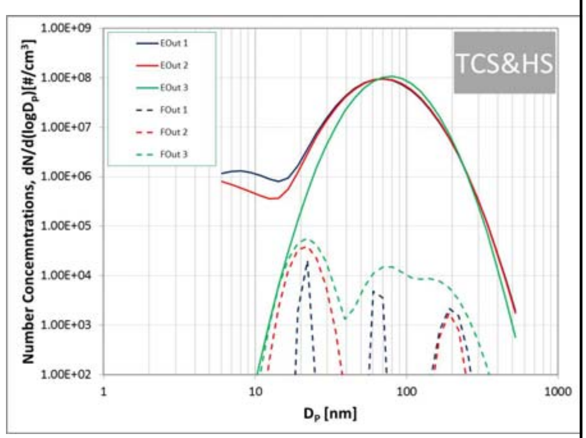
- For TCS&HS conditions, the FOUt aerosol concentrations were very low.
- It appears that the high exhaust temperatures characteristic for TCS&HS favorably affected reaction of the injected hydrocarbons with NO_2 over the decomposition catalyst and reduced propensity for formation of nucleation aerosols.
- As a result, for all TCS&HS tests the system reduced dramatically concentrations of both accumulation and nucleation aerosols.



Effects of the System on Total Number Concentrations: Averages Calculated for Data Collected During the Last 30 Seconds of the Tests

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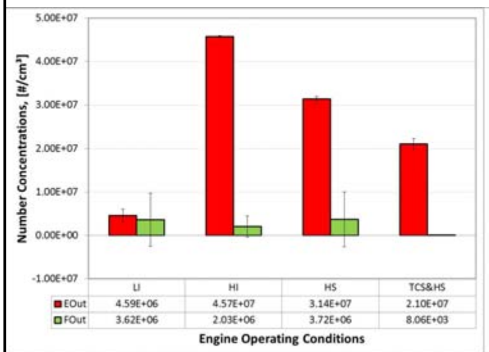
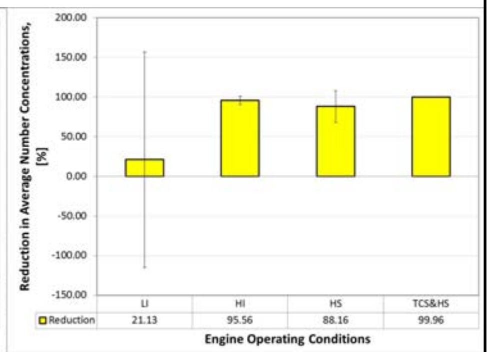
- For HI, HS, and TCS&HS conditions, the system reduced aerosol concentrations by 88 to 99 percent.
- The presence of relatively large concentrations of nucleation aerosols in the FOut LI 2 case, caused the average reductions for LI conditions to be more modest.





To advance understanding of the consequence of nucleation aerosols on the assessment of the effectiveness of the system in removal of aerosols, further analysis was performed using instantaneous data.

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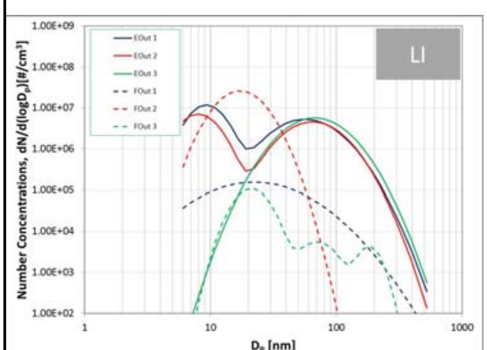
- The aerosol distributions were fitted with single modal, biomodal or trimodal lognormal curves using DistFit 2009.01 software (Chimera Technologies Inc.).
- The fit data were used to estimate the split between nucleation and accumulation modes (example provided for LI test conditions).



Meas. Location	TEST	Nucleation Mode	Accumula-tion Mode	All
		TNC	TNC	TNC
		#/cm³	#/cm³	#/cm³
EOut	LI 1	3.70E+06	2.93E+06	6.63E+06
	LI 2	2.43E+06	2.30E+06	4.73E+06
	LI 3	0.00E+00	2.98E+06	2.98E+06
FOut	LI 1	1.31E+05	0.00E+00	1.31E+05
	LI 2	1.03E+07	0.00E+00	1.03E+07
	LI 3	3.23E+04	2.74E+03	3.51E+04

Effects of the System on Total Number Concentrations (FMPS): Averages Calculated for Selected Instantaneous Data

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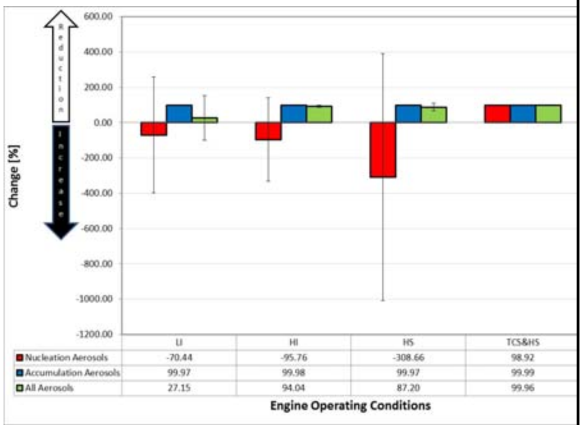
- The analysis of selected instantaneous data showed the following:
  - Efficiency in removal of accumulation aerosols: 99.97-99.99%
  - Efficiency in removal of all aerosols: 65.70-99.96 %
  - For all but TCS&HS conditions, the relatively large increases in concentrations of secondary nucleation aerosols resulted in lower overall efficiencies.



	LI	HI	HS	TCS&HS
Nucleation Aerosols	-70.44	-95.76	-308.66	98.92
Accumulation Aerosols	99.97	99.98	99.97	99.99
All Aerosols	27.15	94.04	87.20	99.96

Comparison of FOut Aerosols with Shop Air Aerosols

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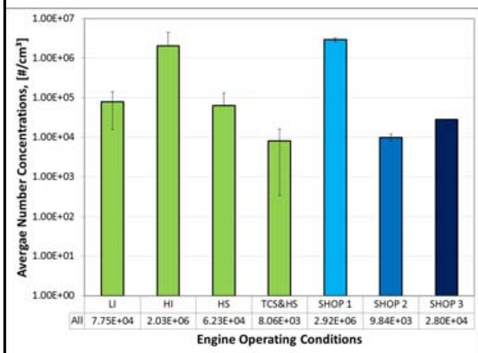
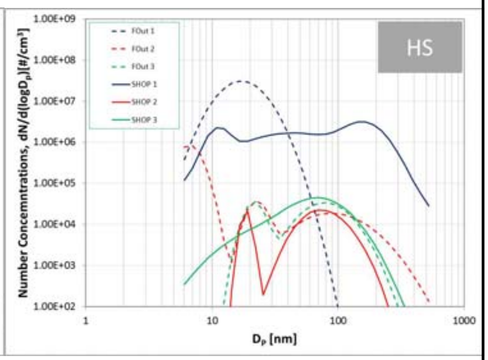
- For all four operating conditions, the total FOut concentrations were:
  - below concentrations of aerosols measured in the shop during welding and vehicle movement operations (SHOP 1), and
  - comparable to those measured in the shop during the tests with filtered exhaust ducted outside of the shop (SHOP 2 and SHOP 3).
- However, the makeup of those aerosols was most probably substantially different.



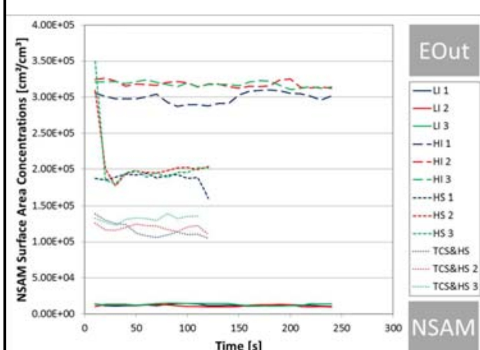
	LI	HI	HS	TCS&HS	SHOP 1	SHOP 2	SHOP 3
All	7.75E+04	2.03E+06	6.23E+04	8.06E+03	2.92E+06	9.84E+03	2.80E+04

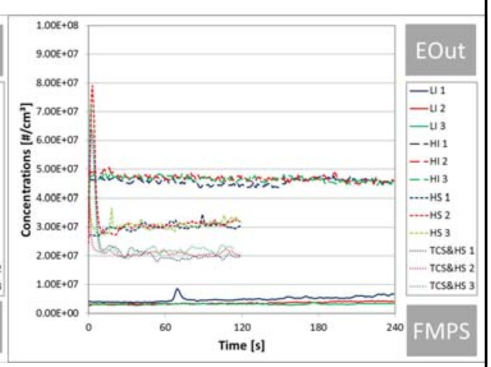


Surface Area of Aerosols Deposited in Alveolar Region

Surface Area of Aerosols Deposited in Alveolar Region (NSAM)

- For all four steady-state test conditions , uncertainty of the triplicate measurements of EOut NSAM concentrations was relatively low.
- The NSAM data (left graph) exhibited similar qualitative properties as FMPS data (right graph).
- With respect to the surface area concentrations in EOut exhaust the test modes can be ranked in the following order: HI>HS>TCS&HS>LI.
- To minimize uncertainty associated with transient effects at the beginning of the each test only data collected during the last 60 seconds of tests were used for statistical analysis.





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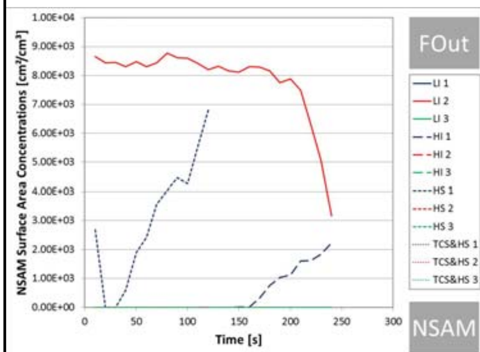
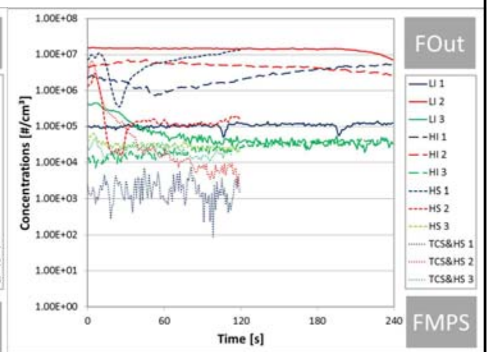
Surface Area of Aerosols Deposited in Alveolar Region (NSAM)

- For all but LI 2, HI 1, and HS 1 tests the concentrations of FOut aerosols in the diluted exhaust proved to be below detection limit of the NSAM.
- Apparently, the NSAM was found to be inadequately sensitive to quantify the low number (right graph, FMPS) and surface area concentrations of aerosols leaving the JM MCRT system.





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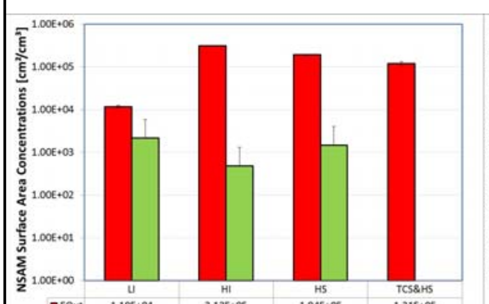
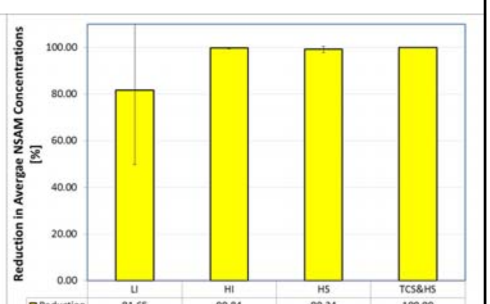
Surface Area of Aerosols Deposited in Alveolar Region (NSAM)

- The efficiencies of the JM MCRT system in removal of NSAM surface area were tentatively estimated below.



	LI	HI	HS	TCS&HS
EOut	1.19E+04	3.12E+05	1.94E+05	1.21E+05
FOut	2.18E+03	4.86E+02	1.48E+03	0.00E+00

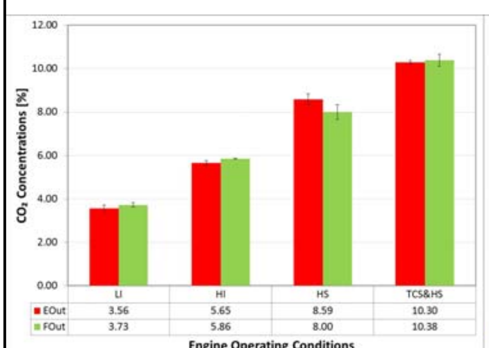


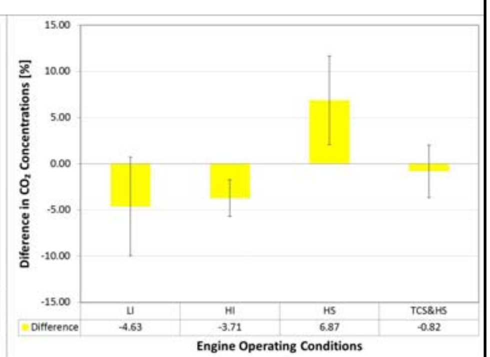
	LI	HI	HS	TCS&HS
Reduction	81.65	99.84	99.24	100.00

Concentrations of CO_2, CO, NO_X, NO, NO_2, N_2O and THC

Carbon Dioxide- CO_2 (FTIR)

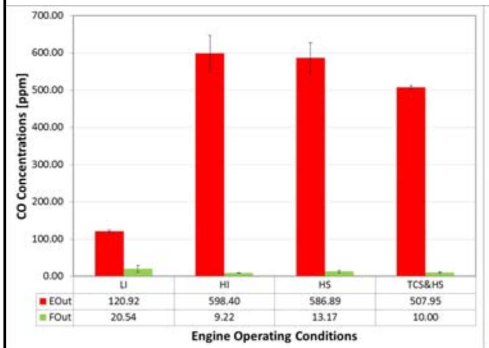
- The CO_2 results confirmed that selected test methodology provided repeatable test conditions between triplicates.
- However, some uncertainties were expected due to transient operation of the system.
- The primarily source of uncertainty would be post-DPF fuel injection that was managed by system and was not manipulated externally in this study.

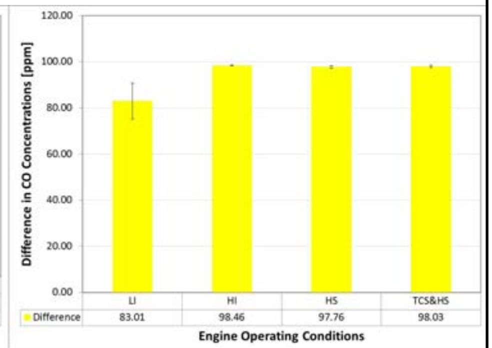




Carbon Monoxide (CO)

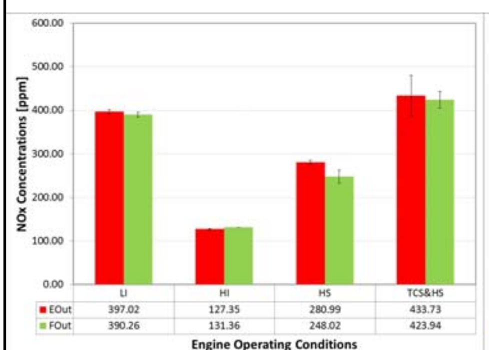
- The system was very effective in controlling CO emissions at HI, HS, and TCS&HS conditions.
- Due to the relatively low exhaust temperatures, the reductions were somewhat lower at LI conditions.

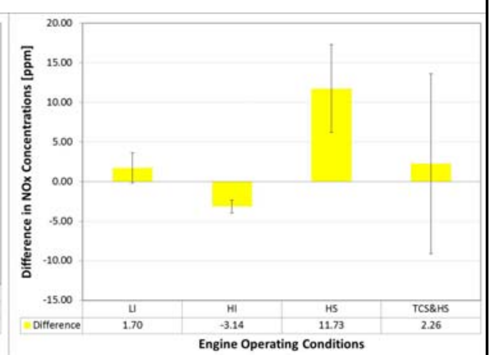




Nitric Oxides (NOx= NO + NO_2 + N_2O)

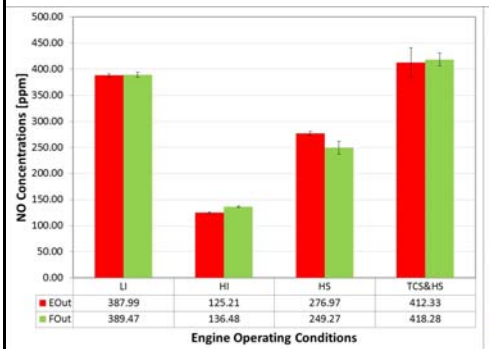
- The system had a relatively minor effect on NOx emissions.

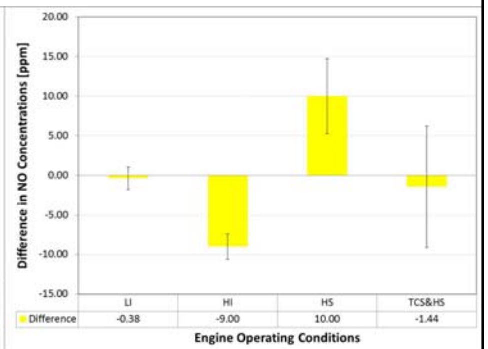




Nitric Oxide (NO)

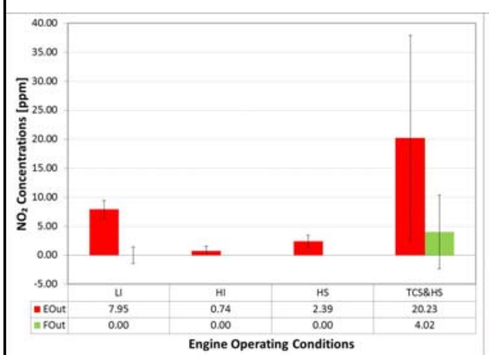
- Similarly, the system had a minor effect on NO emissions (NO comprised the majority of NO_X emissions).

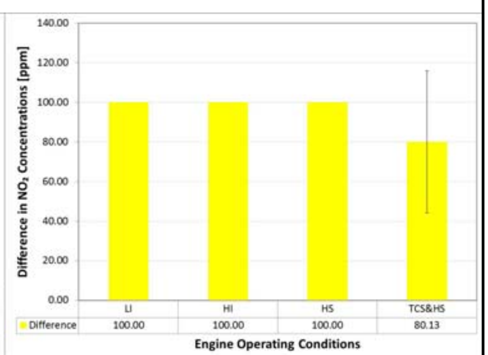




Nitrogen Dioxide (NO_2)

- The CAT C11 engine produced very low NO_2 emissions (0.5-4.7 percent of NO_X emissions).
- The NO_2 emissions were further reduced by the system (up to 1.0 percent of NO_X emissions).
- Due to undetectable FOut concentrations the reductions in NO_2 emissions for LI, HI, and HS conditions were estimated at 100 percent.





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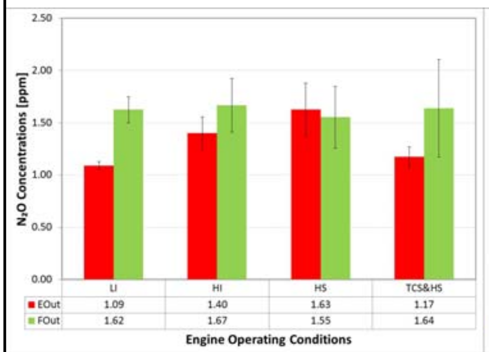
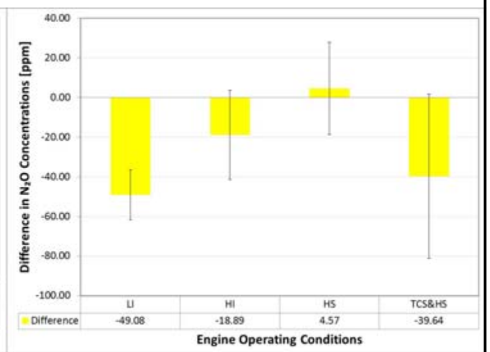
Nitrous Oxide-N_2O (FTIR)

- In general , the CAT C11 engine produced very low N_2O emissions.
- For LI, HI, and TCS&HS conditions the system increased average N_2O emissions up to 50 percent.
- For HS conditions the effects of the system on N_2O emissions were within quantification limits.





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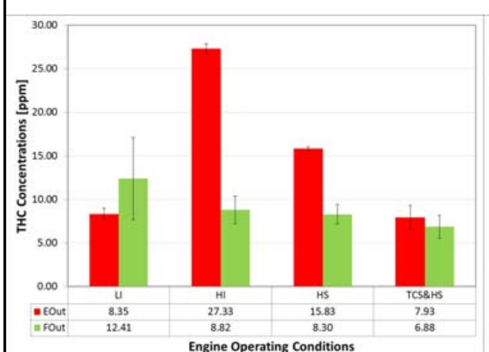
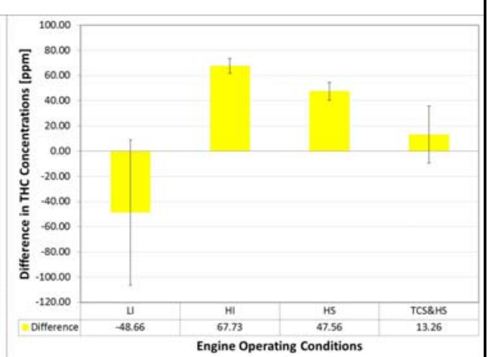
Total hydrocarbons (THC)

- For HI, HS, and TCS&HS conditions the system reduced THC emissions.
- For LI conditions, the effects of the system (most probably the HC injection) adversely affected the THC emissions.



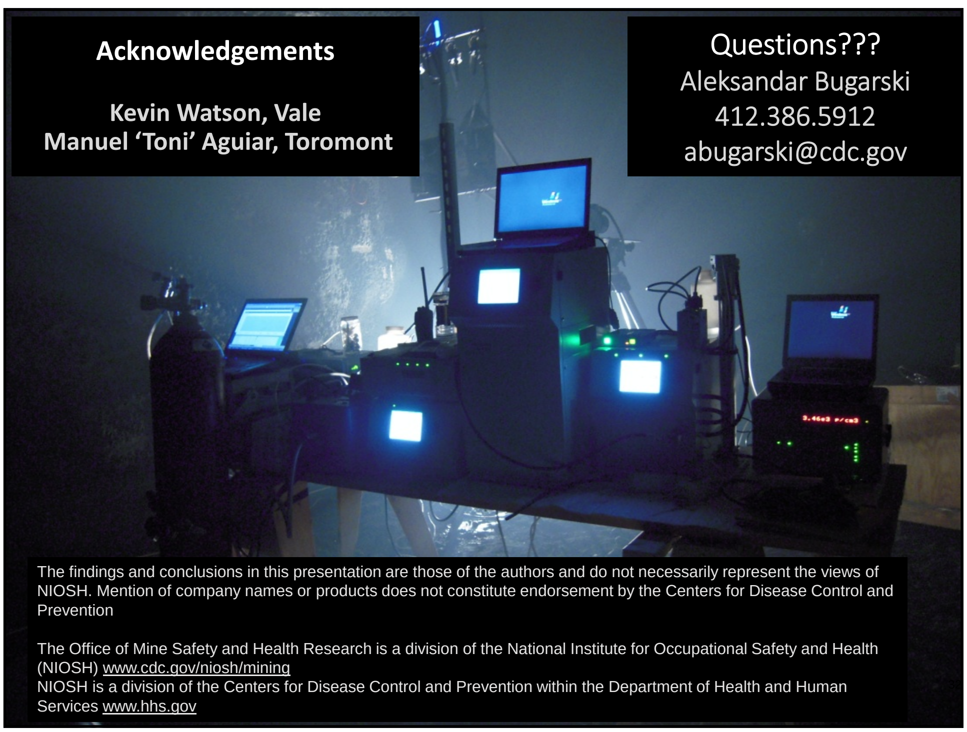


Summary and Future Work

- This testing showed that for the majority of test conditions the JM Mining-CRT system was very effective in reducing the number and surface area concentrations of aerosols emitted by the tested engine.

- Test conditions where measurements coincided with post-DPF fuel injection, resulted in a relatively high and temporary increase in concentrations of nucleation mode aerosols. In the case of the LI test, this was corroborated with an increase in concentrations of THC in FOut exhaust.

- The JM MCRT system was very effective in reducing CO emissions. The system had very minor effects on NO and NO_X emissions, adverse effects on N_2O, and favorable effects on NO_2 emissions. For all but LI conditions, the system had favorable effects on THC emissions.



Abstract

The results of a series of emissions tests conducted at a mine surface shop were used to assess the effects of the in-use Mining Continuously Regenerated trap (Mining-CRT) systems, on the aerosols and criteria gases emitted by a heavy-duty diesel powered vehicle. These measurements were carried out for torque converter/hydraulic stall, hydraulic stall, high idle, and low idle conditions. The effects of this system on particulate and gaseous emissions were quantitatively determined using measurements performed in the exhaust, both upstream and downstream of the system. The effects on number concentration and size distribution of aerosols in the diluted exhaust were assessed using measurements obtained from a fast mobility particle size spectrometer. The results of measurements performed in the diluted exhaust with a nanoparticle surface area monitor, were used to establish the effects of this system on the surface area of particles deposited in the alveolar region of lungs. The effects on CO, CO_2, NO_X, NO, NO_2, N_2O, and hydrocarbons were assessed using measurements performed sequentially in the raw exhaust, both upstream and downstream of the Mining-CRT system, using a Fourier transform infrared (FTIR) analyzer. For all test conditions, the Mining-CRT system was found to be very effective in reducing the number and surface area of aerosols, and CO emissions from the tested engine. The system had very minor effects on NO and NO_X emissions, adverse effects on N_2O, and favorable effects on NO_2 emissions. For all but low idle conditions, the system had favorable effects on total hydrocarbon emissions. The findings from this study contributed to a better understanding of the benefits and challenges of using Mining-CRT system to control exposures of underground miners to diesel aerosols and gases.

Reference

- Bugarski, AD; Hummer, J.A.; Stachulak, J.S. (2015). Effects of Mining Continuously Regenerated Trap (Mining-CRT) System on the Aerosol and Gaseous Emissions from a Heavy-Duty Diesel Powered Underground Mining Vehicle. 21st Annual Mining Diesel Emissions Council (MDEC) Conference.