Isolated Zone Evaluation of Biodiesel Fuels

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17th MDEC Conference,
Toronto, October 3-7, 2011

Introduction

- Use of fatty acid methyl ester (FAME) biodiesel fuels plays an important role in the efforts of Newmont USA Ltd. and a large number of other underground mines in the U.S. to control exposures of miners to aerosols and gases emitted by diesel-powered vehicles.
- Previous studies conducted in underground mines showed that use of FAME fuels can have favorable effects on concentrations of total diesel particulate matter (DPM) and particularly elemental carbon (EC) in mine air (Bugarski et al. 2006, Bugarski et al. 2010).
- However, the effects of FAME biodiesel fuel on emissions vary widely as a function of FAME fuel type and content (Bugarski et al. 2006, Bugarski et al. 2010) and engine type and design (Durbin et al. 2007).
- Researchers from the National Institute for Occupational Safety and Health (NIOSH) and Newmont USA Limited – Nevada Leeville Complex conducted a study with the objective of quantifying and characterizing the effects of three blends of FAME fuels on aerosols and criteria gases emitted by a haulage truck powered by a late model heavy-duty diesel engine.

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Fuels

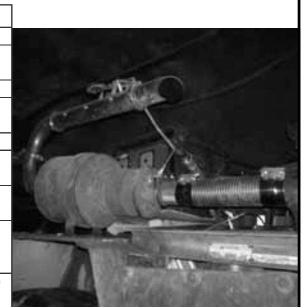
- The effects of three FAME biodiesel fuel blends (B20, B50, and B57) were compared with corresponding effects of ultralow sulfur diesel (ULSD).
- The neat FAME fuel (B100) was supplied by Renewable Energy Group (REG) (Ames IA , REG9000-10).
- The ULSD was supplied by Thomas Petroleum, Carlin, NV.
- The FAME blends with ULSD were supplied by Thomas Petroleum facility in Carlin, NV.
- The results of analysis performed on test fuels by Bently Tribology Services (Minden, NV) laboratory are shown below.

Fuel Property	Test Method	ULSD	B20	B50	B57	B100
Fatty Acid Methyl Ester Content [%]	ASTM 7371	N/A	22.76	48.56	56.5	100
Heat of Combustion [BTU/gal]	ASTM D240	133194	135286	131184	128118	126089
API Gravity @ 15.6 °C [°API]	ASTM D1298	38.1	35.8	34.6	32.2	29.8
Cetane Number	ASTM D613	60	50	50	53	52
Sulfur by UV [ppm]	ASTM D5453	11.07	2.74	5.06	6.04	8.36
Cloud Point [°C]	ASTM D2500	-9	-10	-8	1	10
Pour Point [°C]	ASTM D97	-24	-14	-13	-2	1
Flash Point, Closed Cup [°C]	ASTM D93	67	68	74	80	173
Lubricity, HFRR, Wear Scar Diameter [μm]	ASTM D6079	640	190	170	230	240

The evaluation was conducted in an active underground mine using a production vehicle.

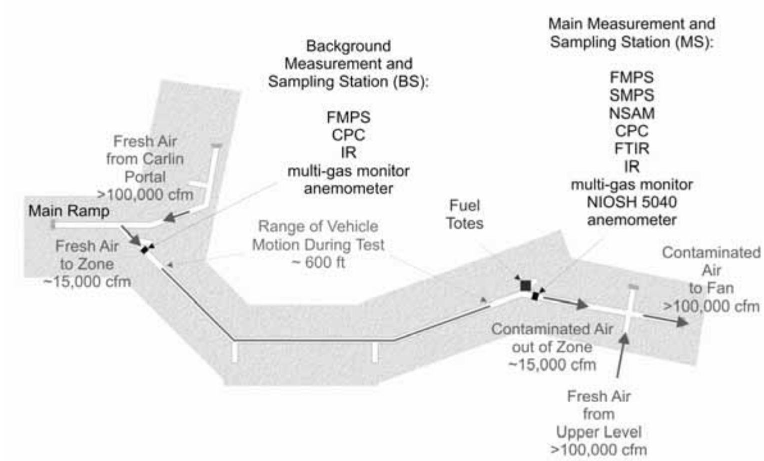
- Fully loaded 30-tonnes haulage truck (UHT051) manufactured by Sandvik Mining and Construction, Burlington, ON, Canada (Model EJC 30SX) was used as test vehicle;
- The truck was powered by Mercedes Benz OM 926 LA off highway engine (US Tier 3).
- Engine was retrofitted by diesel oxidation catalytic converter.

UHT051	
Vehicle Type	30-tonnes haulage truck
Vehicle Manufacturer	Sandvik Mining and Construction
Vehicle Model	EJC30SX
Engine Manufacturer	Mercedes Benz
Engine Model	OM 926 LA, Tier 3
Number of Cylinders	6 (inline)
Engine Displacement	7.2 l
Engine Type	liquid cooled, turbocharged, electronically controlled
Engine Power	240 kW (322 hp) @ 2200 rpm
Engine Torque	1300 Nm (952 lb-ft) @ 1300-1600 rpm



The experimental part of the study was conducted in an isolated zone established in underground workings of Newmont's Leeville Mine.

- Fresh air was supplied from Carlin portal via main ramp.
- In order to prevent contamination of dilution air, the main ramp was closed for traffic during the tests.



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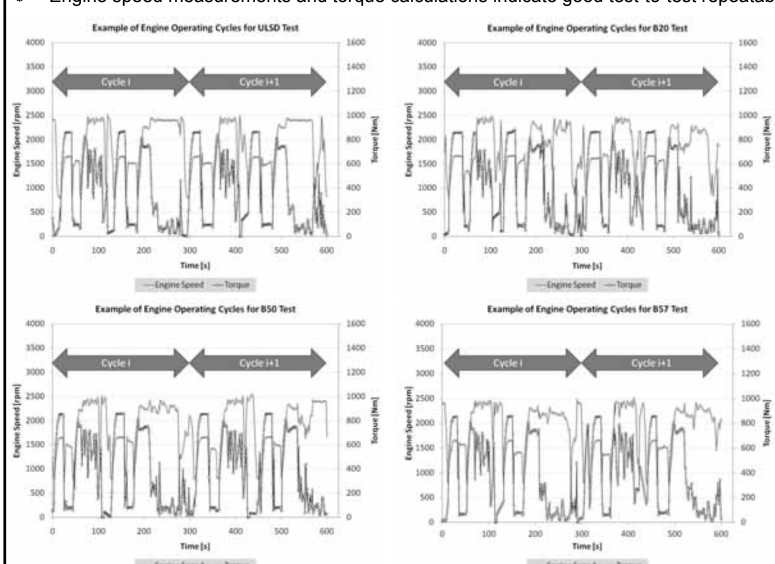
- For each of the tests, the vehicle/engine was operated for extended period of time in the 600 feet long section of main drift of the isolated zone.
- The vehicle/engine duty cycle consisted of several repetitions of a 300-second long simulated haulage-truck duty cycle.
- Engine speed measurements and torque calculations indicate good test-to-test repeatability.



Test	Average Torque [Nm]
ULSD	371.7
B20	376.0
B50	358.1
B57	370.9

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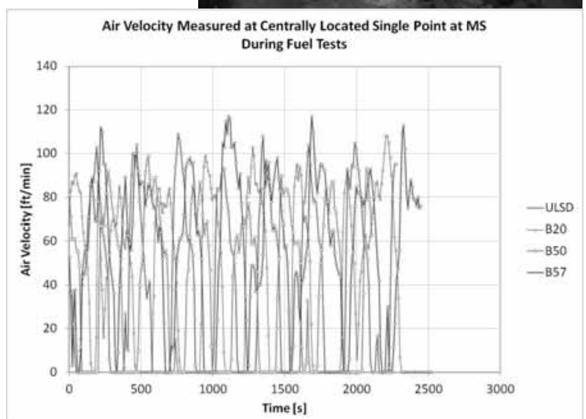
Ventilation Flow Rate

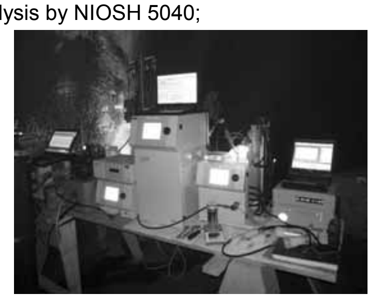
- According to the single point measurements performed continuously at the downstream end of the isolated zone, the ventilation air flow rates were very transient in nature.
- The flow was affected by vehicle movement and position.
- The actual average flow rates (~ 7,000 ft³/min) were substantially lower than the initially targeted nominal flow rate of 15,000 ft³/min.



Two ambient measurement/sampling stations were established in the isolated zone:
1. Background or upstream station (BS)
2. Main or downstream station (MS)

- Background Station (BS)
  - Gases:
    - CO_2 concentrations (Vaisala, Carboncap GM70IR)
    - CO, NO, and NO_2 (Industrial Scientific, iTX multi-gas monitor)
  - Aerosols:
    - Particle number concentrations (TSI, Condensation Particle Counter, CPC 3776 and Fast Mobility Particle Spectrometer, FMPS 3091)
    - Particle size distributions (Fast Mobility Particle Spectrometer, FMPS 3091).
  - Ventilation:
    - Air Velocity (TSI, Alnor RVA501)

- Main Station (MS)
  - Gases:
    - Furrier Transform Infrared (FTIR) analyzer (Gasmet, DX4000 FTIR);
    - Infrared (IR) CO_2 monitor (Vaisala, Carboncap GM70IR);
    - Electrochemical cells (ECC) based multi-gas monitor (Industrial Scientific, iTX).
  - Aerosols:
    - Condensation Particle Counter (TSI, CPC 3776), Fast Mobility Particle Spectrometer (TSI, FMPS 3091) and Scanning Mobility Particle Sizer (TSI, SMPS 3936) were used to measure particle number concentrations ;
    - FMPS (TSI 3091) and SMPS (TSI 3936) were used to measure particle size distributions;
    - Nanoparticle Surface Area Monitor (TSI, NSAM 3550) was used to measure surface area of particles deposited in alveolar region of lungs;
    - Elemental carbon concentrations were determined using filter sampling and thermal optical transmittance – evolve gas analysis by NIOSH 5040;
  - Ventilation:
    - Air velocity (TSI, Alnor RVA501).



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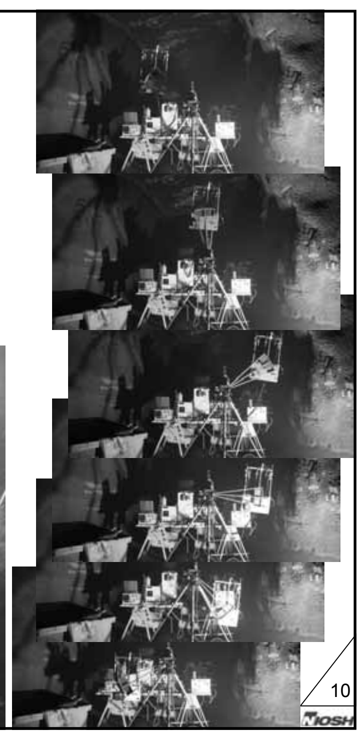
- At BS, all sampling and measurements were performed from single location centrally located in the drift.
- At MS, in order to minimize effects of stratification, certain samples were collected from a revolving platform ("Ferris wheel") that carried the sampling inlets for FTIR, FMPS, NSAM, complete CO_2 and multi-gas monitors, and complete sampling trains for DPM sampling.
- The geared motor was used to revolve the platform on 1 meter arm at radial speed of 1 rpm.



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The concentrations of criteria gases (CO, CO_2, NO, and NO_2) and a number of engine and ambient parameters were measured sequentially in the exhaust upstream and downstream of DOC using SEMTECH DS mobile emissions analyzer (Sensors Inc., Saline, MI).

- This portable emissions measurement analyzer system uses:
  - NDIR analyzer to measure CO and CO_2 concentrations;
  - NDUV analyzer to measure NO and NO_2 concentrations;
- Pitot tube was used to measure exhaust flow rate.
- The system also measured and recorded a number of engine parameters such as:
  - Engine speed and fuel consumption.
- and several ambient parameters such as:
  - Barometric pressure and atmospheric temperature.

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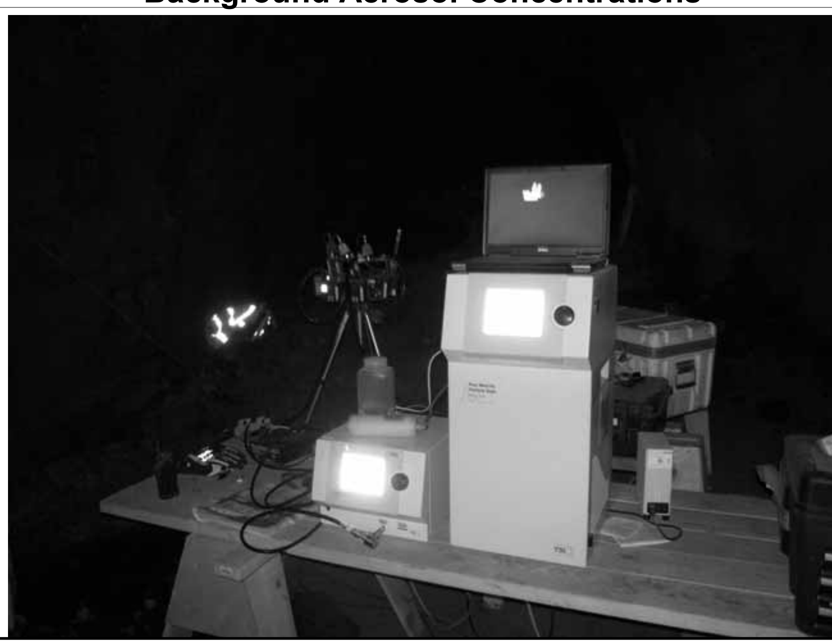
Results:
Background Aerosol Concentrations



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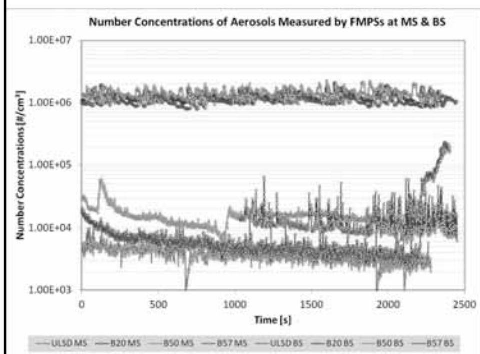
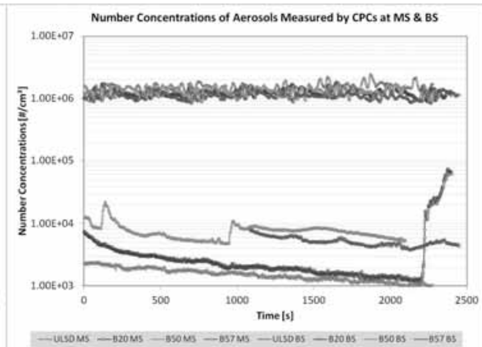
- Analysis of results of measurements of total aerosol concentration with FMPSs and CPCs and results of carbon analysis showed that contribution of background activities to aerosol concentrations were negligible.





FMPS	TS_{BS} in TC_{MS} [%]
ULSD	0.26
B20	1.12
B50	1.22
B57	1.24

CPC	TSBS in TCMS [%]
ULSD	0.10
B20	0.39
B50	0.58
B57	0.46

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CO_2 Concentrations in the Exhaust (NDIR) and Ambient Air at MS (FTIR & IR)

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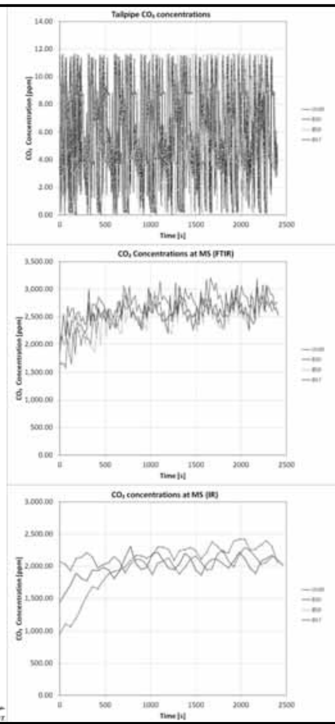
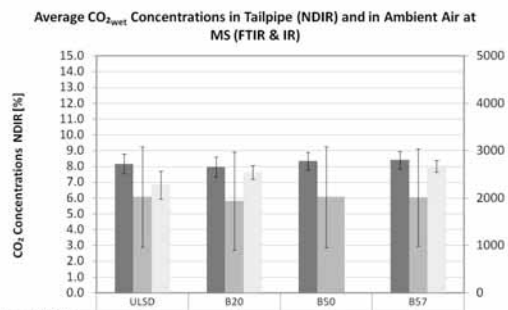


- The results of continuous measurements of CO_2 concentrations in tailpipe (NDIR) and at MS (FTIR and IR) showed good repeatability of vehicle/engine duty cycle.
- The results of CO_2 measurements in the exhaust downstream of DOC (NDIR) and MS (FTIR) were also used to determine dilution rates and test-to-test correction factors.



	ULSD	B20	B50	B57
Tailpipe (NDIR) [%]	6.07	5.82	6.06	6.03
Ambient (FTIR) [ppm]	2723.23	2656.49	2779.59	2807.53
Ambient (IR) [ppm]	2278.50	2540.98		2673.09

Fuel

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Effects of DOC on Concentrations of CO, NO, NO_2, and NO_X in the Exhaust (Engine-Out and DOC-Out Measurements with NDIR and NDUV) and Ambient Air at MS (FTIR and IR)

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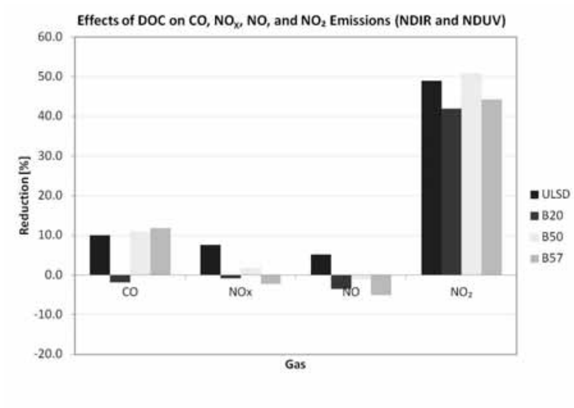
- The results of measurements performed in the exhaust upstream and downstream of DOC (NDIR and NDUV) showed that the effects of DOC on CO, NO_X, and NO were minor.
- The reductions in NO_2 concentrations were probably result of reaction of that gas with soot deposited on the walls of DOC.
- It appears that the catalyst in this vintage DOC was deactivated sometimes during its life prior to this study.
- Therefore, since DOC did not affect the emissions, the majority of observed effects on ambient concentrations of criteria gases can be attributed to tested fuels.



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Effects of Fuels on Concentrations of CO, NO, NO_2, and NO_X in Engine Exhaust (Engine-Out and DOC-Out Measurements using NDIR and NDUV) and in Ambient Air at MS (FTIR and IR)

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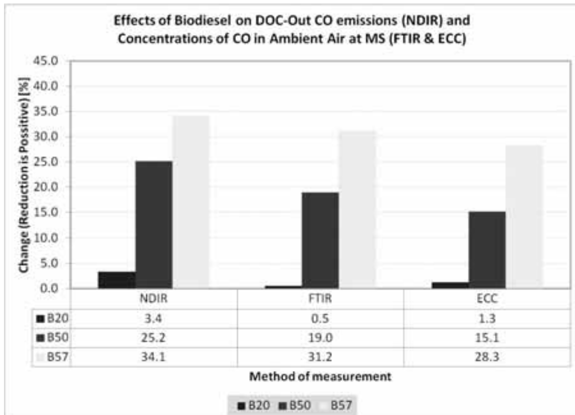
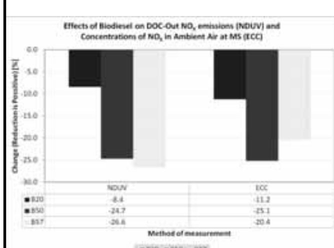
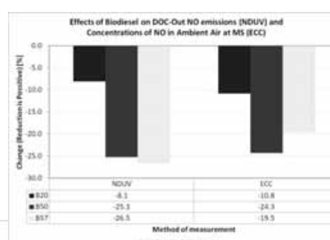
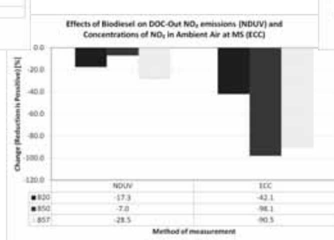
- The CO measurements performed in the exhaust of the test engine (upstream and downstream of DOC) and in ambient at MS showed that the biodiesel reduced CO emissions.
- Reductions in CO concentrations in the tailpipe and in the ambient air were found to directly correlate with biodiesel content in the blends.



- The NO and NO_2 measurements performed in the exhaust downstream of DOC and in ambient at MS showed that use of the biodiesel blends increased NO, NO_2, and NO_X (NO_X = NO + NO_2) emissions from the levels observed for ULSD.
- The relation between biodiesel content in the blends and NO, NO_2, and NO_X concentrations in the tailpipe and in the ambient air is not clear as in the case of CO concentrations.
- Due to low concentrations, the uncertainty of NO_2 measurements was high. Therefore, the increases estimated from results of ECC measurements appear to be high.







Effects of Fuels on Elemental Carbon Concentrations in the Ambient Air (TOT-EGA, NIOSH 5040)

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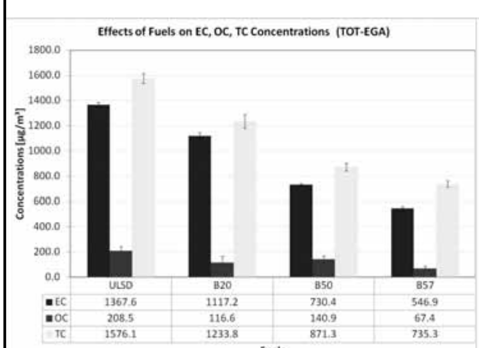
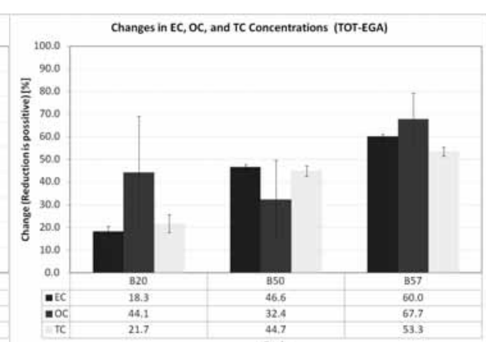
- The TOT-EGA analysis of the DPM samples collected at BS and MS showed that:
  - The background EC and TC concentrations were negligible and therefore those were not used to correct data.
  - Use of biodiesel resulted in substantial reductions in EC and TC concentrations downstream of the isolated zone.
  - The reductions in EC and TC (dominated by EC) concentrations were directly related to biodiesel content in the blends.
  - The relation between biodiesel content and OC concentrations was less clear.



	ULSD	B20	B50	B57
EC	1367.6	1117.2	730.4	546.9
OC	208.5	116.6	140.9	67.4
TC	1576.1	1233.8	871.3	735.3



	B20	B50	B57
EC	18.3	46.6	60.0
OC	44.1	32.4	67.7
TC	21.7	44.7	53.3

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Effects of Fuel Formulations on Total Number Concentrations of Aerosols (FMPS & SMPS)

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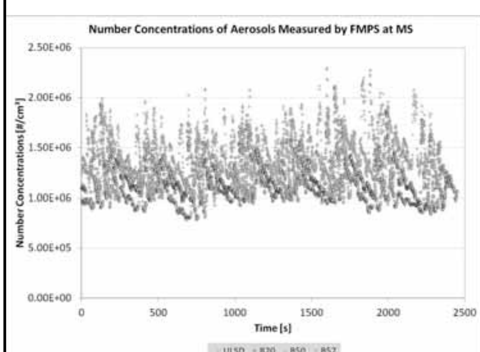
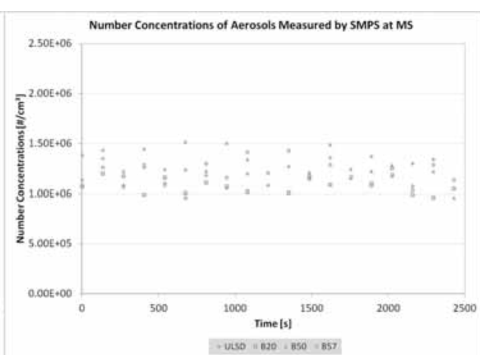
- The number concentrations of aerosols in ambient air at MS were simultaneously measured using FMPS (one measurement per second from sampling port located on the “Ferries wheel”) and SMPS (one measurement per 120 seconds from the fixed location in the central part of the drift).
- Since measurements were made from different locations and using different methodology direct comparison of the FMPS and SMPS data was not possible.
- However, the results of FMPS and SMPS measurements were found to be in general agreement.





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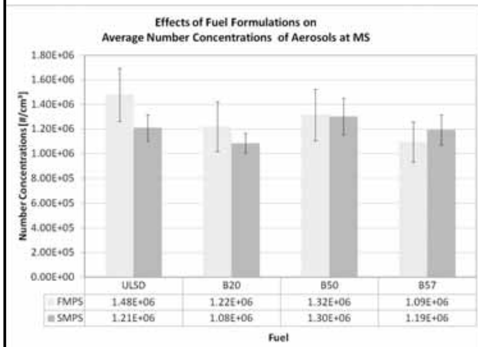
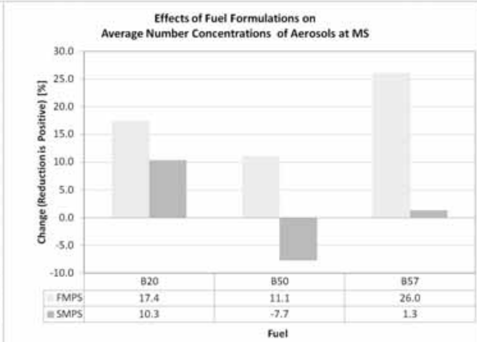
- The results of continuous measurements with FMPS and SMPS were used to calculate average total aerosol number concentrations.
- According to the results of FMPS measurements, the biodiesel blends produced 11% to 26 % reduction in number concentrations of aerosols in the air at MS.
- Those reductions were found to be substantially lower than those observed for EC and TC.
- According to SMPS measurements the changes in total number concentrations due to use of biodiesel blends were found to be within ± 10 %.
- The relationship between biodiesel content and changes in number concentrations is not clear from results of FMPS and SMPS measurements.





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Effects of Fuel Formulations on Size Distributions of Aerosols (FMPS & SMPS)

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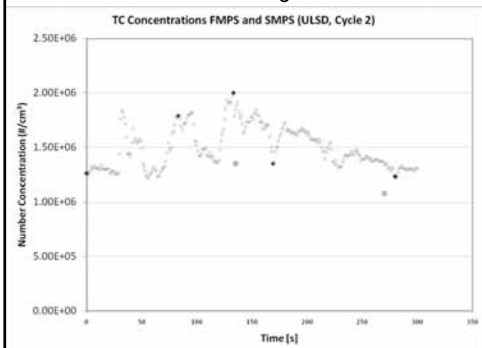
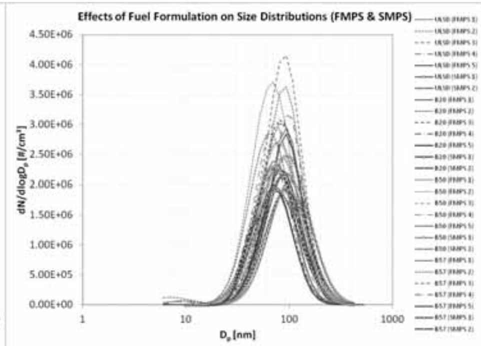
- Due to transient nature of the engine operating conditions, processes occurring in isolated zone, and movement of "Ferris wheel" in the case of FMPS, the concentrations of aerosols were changing constantly.
- The effects of fuel formulations on size distributions of aerosols are examined on the results of measurements made for selected instances of a single cycle for each of the tests. The instances were selected using results of continuous measurement of number concentrations by FMPS.
- 5 instances were examined for each of the tests using FMPS results and 2 instances were examined using SMPS results.





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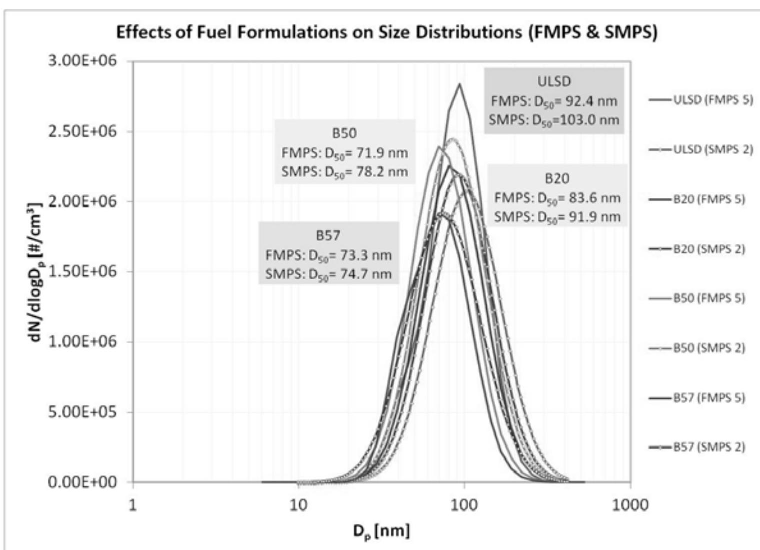
- The size distributions of aerosols generated by biodiesel blends were found to be characterized with smaller median diameters than the size distributions observed for ULSD.
- In general, the median diameter decreases with amount of biodiesel in the blend.



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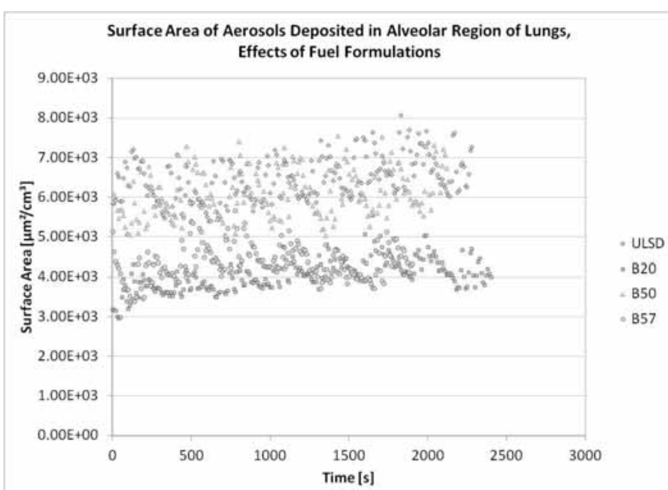
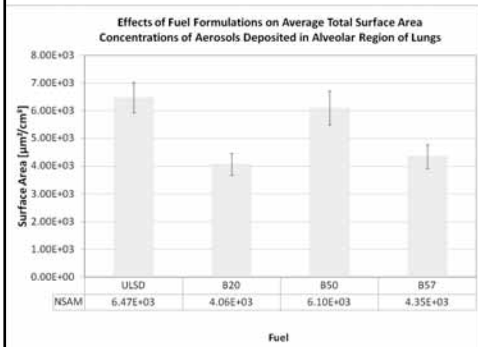
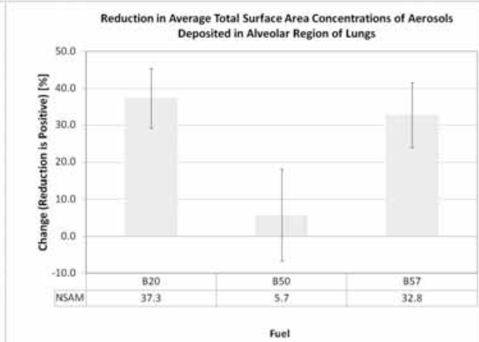
Effects of Fuel Formulations on Total Surface Area of Aerosols Deposited in Alveolar Region (NSAM)

- The surface area concentrations of aerosols deposited in alveolar region of lungs were also found to change constantly during the tests due to transient nature of numerous processes controlling formation and transformation of aerosols.
- The effects of fuel formulations on surface area concentrations of aerosols deposited in alveolar region of lungs were examined on the averages calculated for duration of each of the test.



- The results of NSAM measurements show that the biodiesel blends produced measurable reductions in average surface area concentrations of aerosols in the air at MS.
- Depending on content of biodiesel in the blends, the average reductions were ranging between 6% and 37%.
- The direct relation between biodiesel content and changes in average surface area concentrations is not clear from results of those measurements.





Summary

- This study showed that use of FAME biodiesel can result in substantial reductions in EC and TC concentrations in underground mine environment.
- In this particular case, those reductions were found to be direct function of biodiesel content.
- The reductions in EC and TC concentrations were found to be accompanied by measurable reductions in surface area concentrations of aerosol deposited in alveolar region of lung and somewhat more moderate reductions in number concentrations of the same aerosols.
- The FAME blends used in this study produced the aerosol size distributions that are characterized with smaller median diameters than the size distributions observed for ULSD.
- FAME blends were also found to measurably reduce CO and increase NO_X concentrations.

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