Effects of Biodiesel on Aerosols in Underground Mine

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Objective

- NIOSH is identifying technically and economically feasible control technologies to reduce exposure of underground miners and other workers to diesel particulate matter (DPM) and gases.
- Evaluate potential of biodiesel fuels (with and without DOC) to reduce concentrations of aerosols in mine air.
- Characterized physical and chemical properties and toxicity of diesel and biodiesel aerosols in mine air.

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Fuels Used in the Study

Biodiesel (B100): Stepansol SB-W, Stepan Company (Northfield, IN)
Ultra low sulfur diesel (ULSD): Guttman Oil (Belle Vernon, PA)
Blend: B50 (50% Biodiesel & 50% ULSD)
Fuel analysis done by Core Laboratories, Houston, TX

Test	Method	Unit	B100	ULSD
Energy, Net	ASTM D-240	kJ/kg (BTU/lb)	39975 (17198)	46486 (19999)
Cetane Number	ASTM D-613	-	49.2	58.1
Density	ASTM D-4052	g/ml	0.8835	0.8050
Oxygen Content	ASTM D-5291M	Wt. %	10.54	0.51
Flash Point, PMCC	ASTM D-93A	°C (F)	138 (280)	61 (142)
Sulfur Content	ASTM D-5453	mg/kg	5.1	10.0

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Methodology

- Characterization of DPM in occupational setting:
  - NIOSH Mobile Engine Emissions Laboratory (MEEL) at Lake Lynn Laboratory (LLL);
  - Avoid laboratory uncertainties introduced with various simulations of processes;
  - Bridge gap between inherently inaccurate field and unrealistic laboratory experiments.
- Physical characterization:
  - Size distribution.
- Chemical characterization:
  - Carbon analysis.
- In-vitro genotoxicity analysis.

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Biodiesel Study
Test Matrix

Fuel	Test Mode	Exhaust Configuration	
		Muffler	DOC
ULSD	M1	8 hours	7.5 hours
	M2	8 hours	6.5 hours
	M3	6.5 hours	
	M4	5 hours	
B50	M1	3 hours	3 hours
	M2	3 hours	3 hours
	M3	3 hours	
	M4	3 hours	
B100	M1	8 hours	8 hours
	M2	8 hours	8 hours
	M3	8 hours	
	M4	6 hours	

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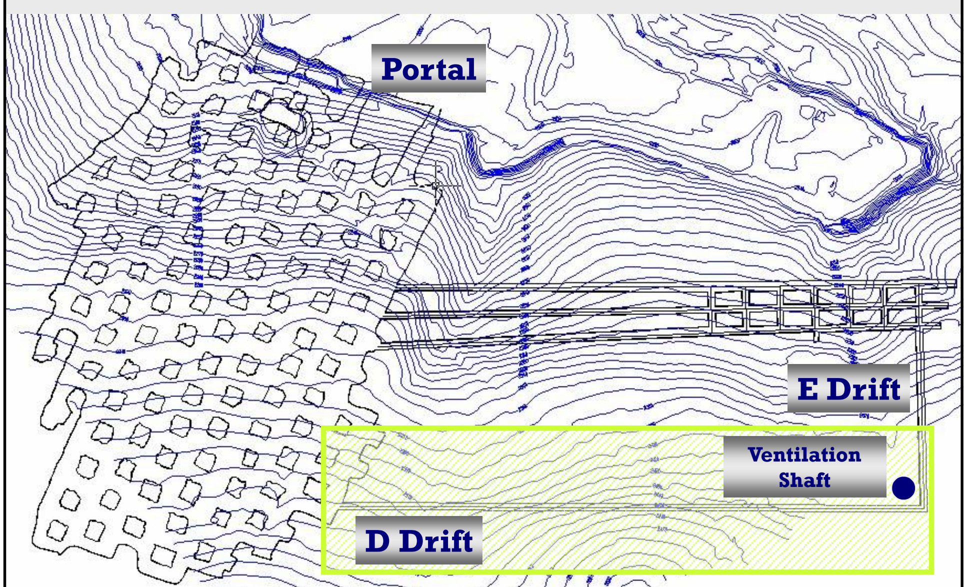
NIOSH Lake Lynn Laboratory (LLL)



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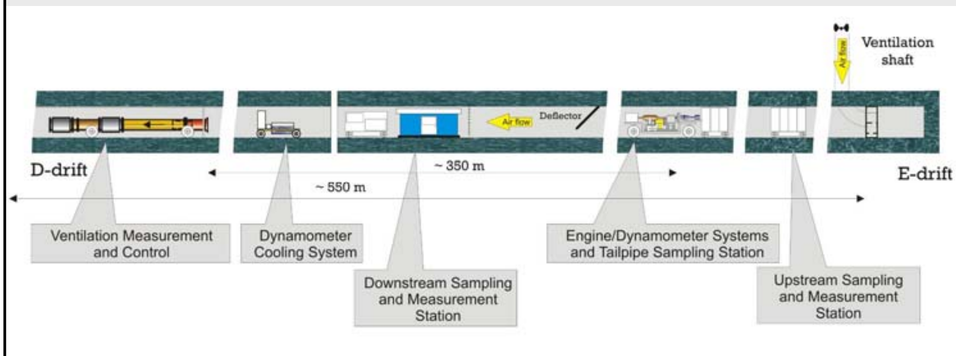
NIOSH Diesel Laboratory at LLL



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Engine/Dynamometer Systems: 150 kW Dynamometer Coupled to Isuzu C240 Engine (56hp)

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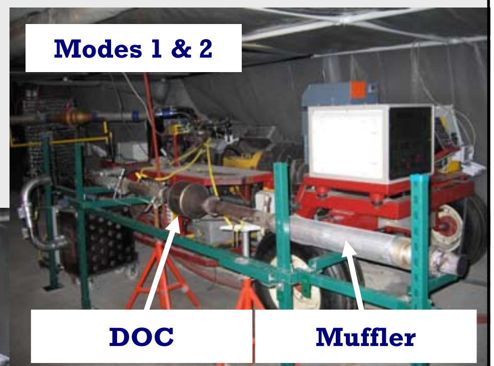
Exhaust Configuration



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Test Modes

Mode	Description	Engine Speed	Torque	Power
		rpm	Nm	kW
M1	Rated speed ~50% load	2950	55.6	17.2
M2	Rated speed ~100% load	2950	111.2	34.3
M3	Intermediate speed ~50% load	2100	69.1	14.9
M4	Intermediate speed ~100% load	2100	136.9	30.6

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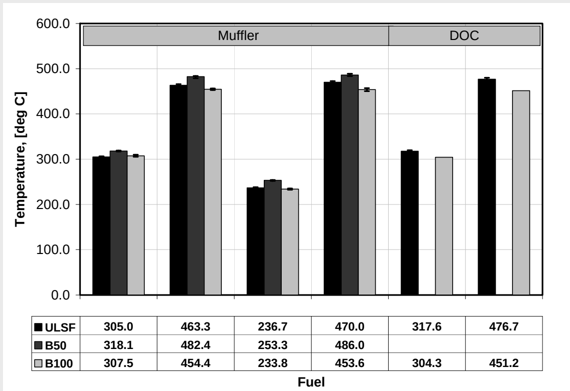
Average Exhaust Temperatures at Inlet to Muffler or DOC over Duration of the Tests



ULSF	305.0	463.3	236.7	470.0	317.6	476.7
B50	318.1	482.4	253.3	486.0		
B100	307.5	454.4	233.8	453.6	304.3	451.2

Mode	Average Exhaust Temperature [°C]
M1	304-318
M2	451-482
M3	233-253
M4	453-486

- Two light-load modes (M1 & M3)
- Two heavy-load modes (M2 & M4)

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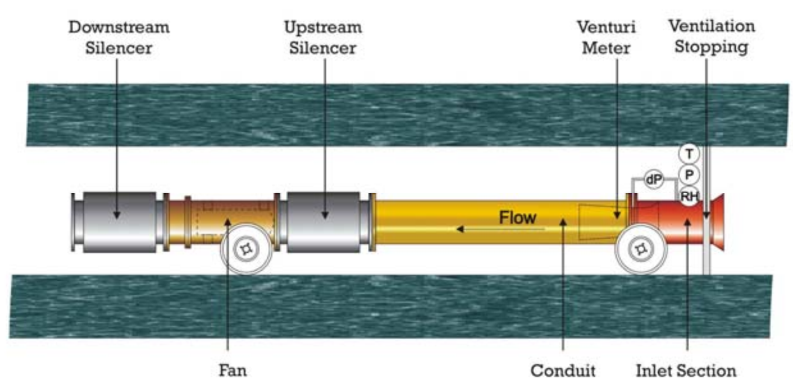
Ventilation Measurement and Control



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Ventilation Rates (VR) & Dilution Ratios (DR)

- VR for Complete Test

VR = 5.814 m^3/s ± 0.050 m^3/s (12319 ft^3/min ± 106 ft^3/min)

- VR for Second Hour

VR = 5.813 m^3/s ± 0.049 m^3/s (12317 ft^3/min ± 104 ft^3/min)

Mode	Dilution Ratio (Complete test)	
	AVG	STD
M1	141.3	3.5
M2	139.9	3.6
M3	173.6	4.7
M4	175.9	2.7

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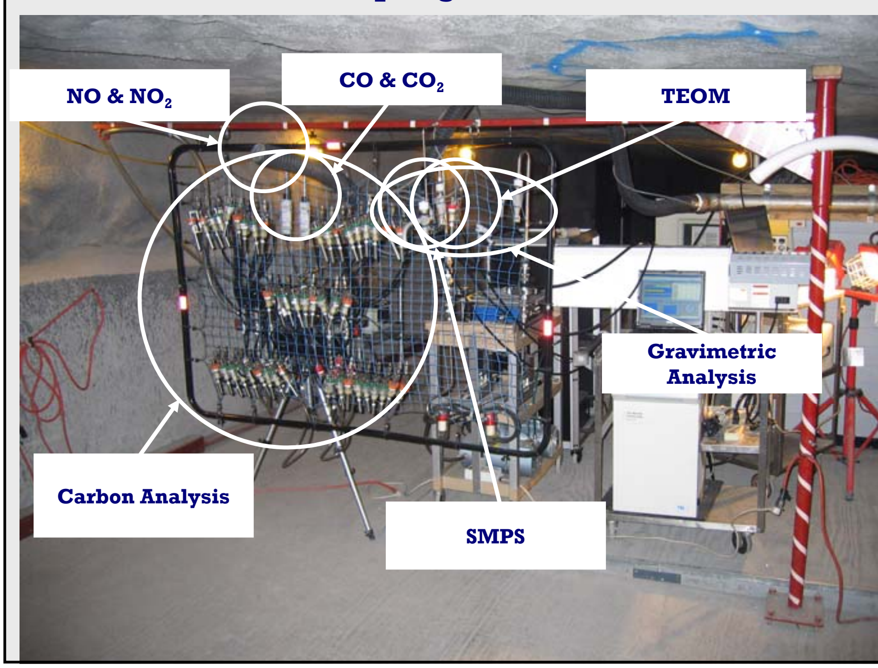
Downstream Sampling and Measurement Station



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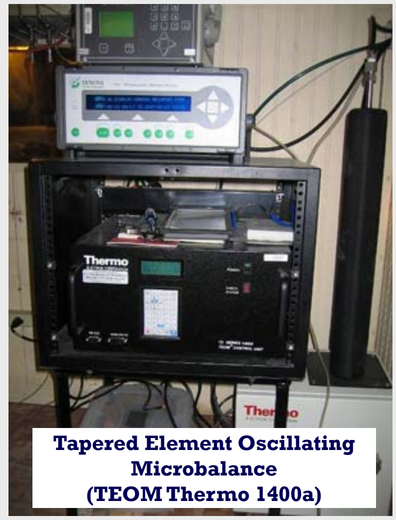
Instrumentation at Downstream Sampling and Measurement Station

Scanning Mobility Particle Sizer Spectrometer (SMPS TSI 3936)



Tapered Element Oscillating Microbalance (TEOM Thermo 1400a)

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Results

- Effects of the fuels (with & without DOC) and DOC on concentrations and size distribution of diesel aerosols in mine air (SMPS).
- Effects of the fuels (with & without DOC) and DOC on total aerosol number concentrations (SMPS).
- Effects of the fuels (with & without DOC) and DOC on total aerosol mass concentrations (gravimetric analysis).
- Effects of the fuels (with & without DOC) and DOC on total aerosol mass concentrations (TEOM).
- Effects of the fuels (with & without DOC) and DOC on elemental carbon (EC), organic carbon (OC), and total carbon (TC) (NIOSH 5040).

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Number Size Distributions
SMPS

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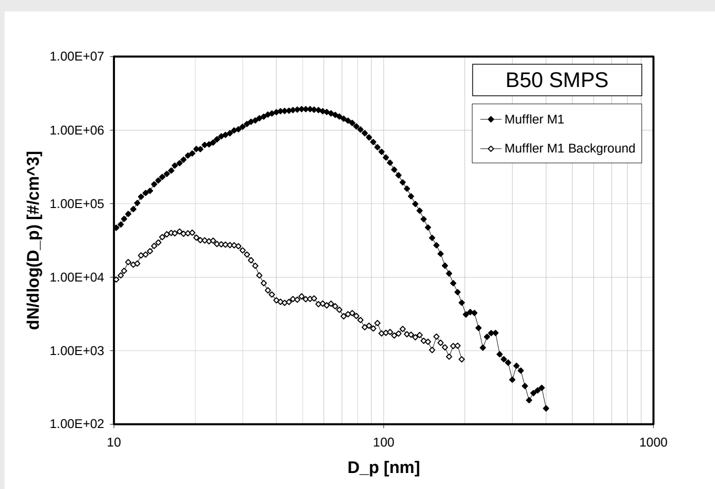
Number Size Distributions
Biodiesel B50, SMPS



- Background concentrations of nano and ultrafine aerosols were app. three order of magnitude lower then aerosol concentrations measured at the downstream station.

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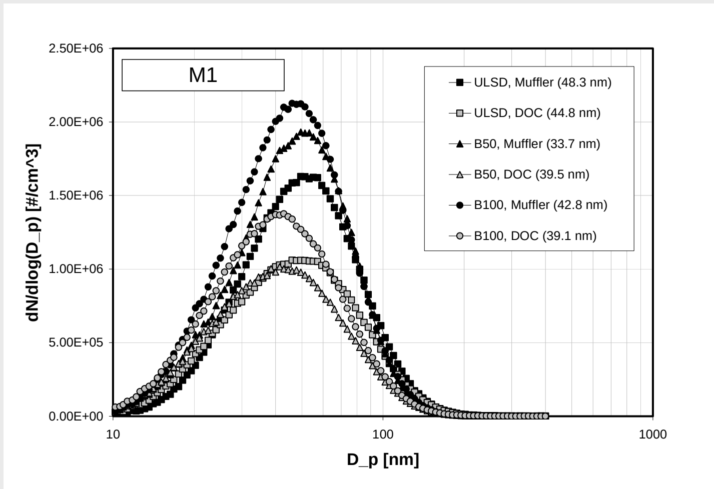
Effects of Fuel Formulation and DOC on Number Size Distributions Mode 1 (M1)



- In the case of M1, peak concentrations increased with fraction of biodiesel in the fuels, and
- median diameter ($_{50}d_{em}$) decreased with fraction of biodiesel in the fuels.
- DOC reduced substantially peak concentrations and somewhat $_{50}d_{em}$.

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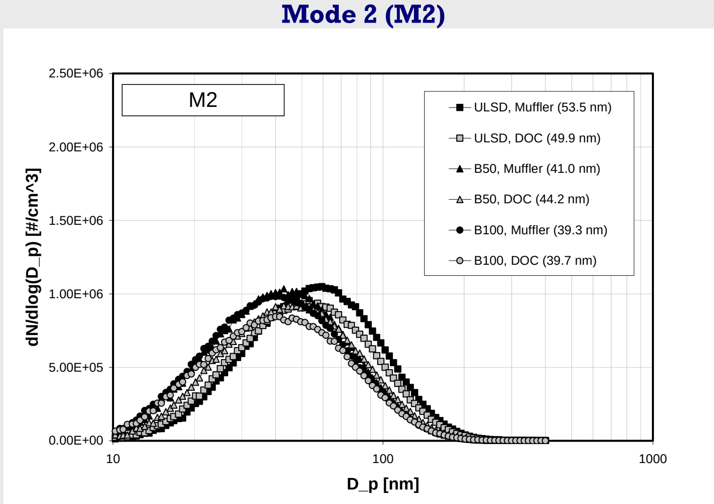
Effects of Fuel Formulations and DOC on Number Size Distributions Mode 2 (M2)



- In the case of M2, fraction of biodiesel in the fuels did not changed substantially peak concentrations, but
- $_{50}d_{em}$ decreased with fraction of biodiesel in the fuels.
- DOC had less pronounced effects on peak concentrations and $_{50}d_{em}$ for M2 then for M1.

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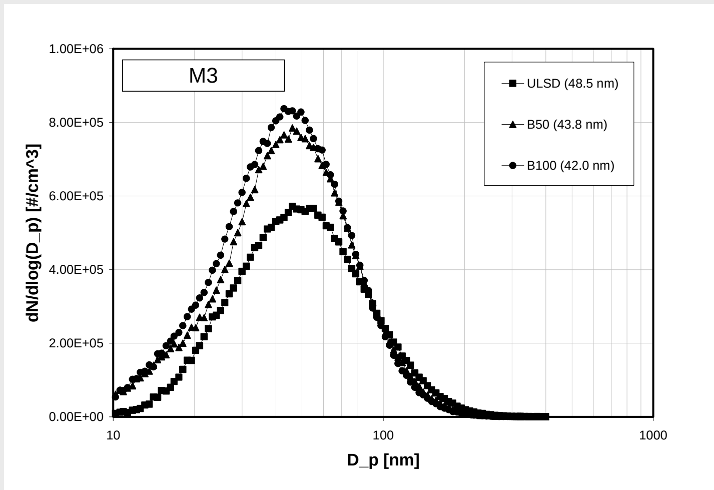
Effects of Fuel Formulations on Number Size Distributions Mode 3 (M3)



- In the case of M3, peak concentrations increased with fraction of biodiesel in the fuels, and
- ${}_{50}d_{em}$ decreased with fraction biodiesel in the fuels.

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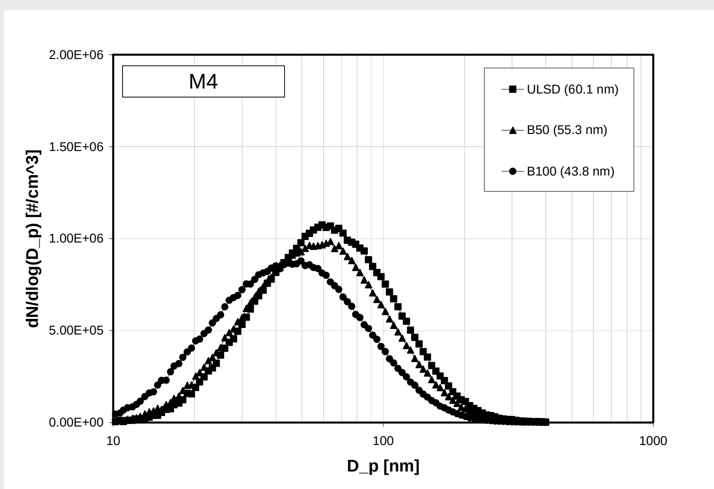
Effects of Fuel Formulation on Number Size Distributions Mode 4 (M4)



- In the case of M4, peak concentrations and ${}_{50}d_{em}$ decreased with fraction of biodiesel in the fuels.

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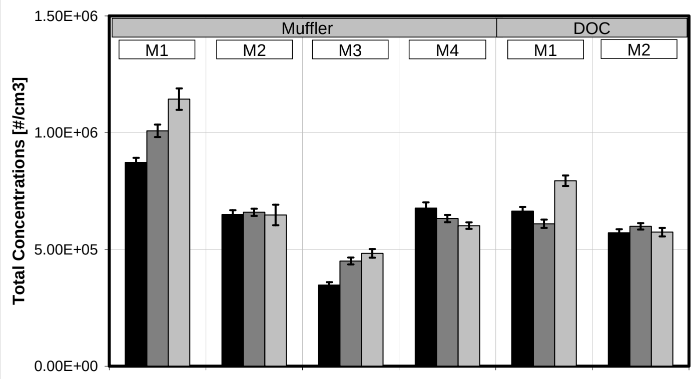
Effects of Fuel and DOC on Total Number Concentrations with $_{50}d_{em}$ between 10 and 400 nm (SMPS)



	M1	M2	M3	M4	M1	M2
ULSD	872800	649600	347500	677300	664300	571500
B50	1008000	659100	450500	632000	610100	599000
B100	1144000	647200	483500	602100	794100	574100

Mode/Exhaust System

- Biodiesel fuels increased total number concentrations of aerosols for M1 and M3, but
- total number concentrations of aerosols remained unchanged for M2 and decreased slightly for M4.

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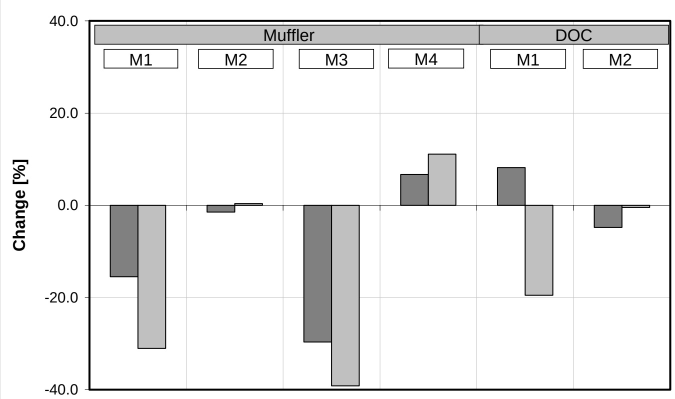
Effects of Fuel on Total Number Concentrations SMPS



	M1	M2	M3	M4	M1	M2
B50	-15.5	-1.5	-29.6	6.7	8.2	-4.8
B100	-31.0	0.4	-39.1	11.1	-19.5	-0.5

Exhaust/Mode

- Increases in total number concentrations for M1 and M3 were augmented with increase in fraction of biodiesel in the fuels.
- Reductions in total number concentrations for M4 were augmented with increase in fraction of biodiesel in the fuels.

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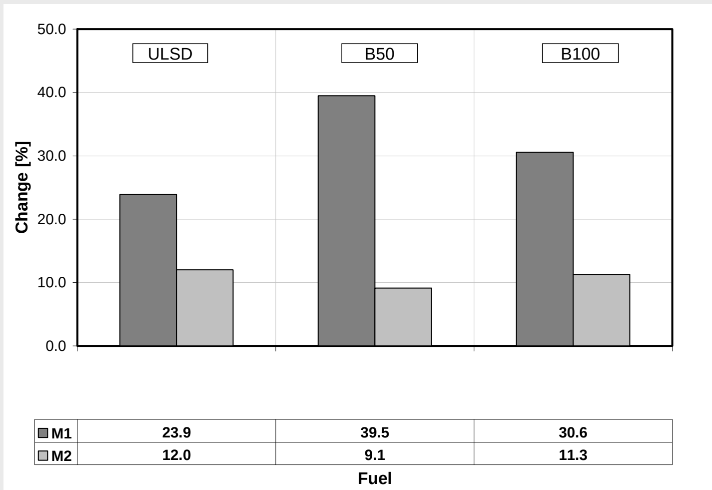
Effects of DOC on Total Number Concentrations SMPS



- DOC reduced total number concentrations for M1 and M2.
- Reductions in total number concentrations were substantially higher for M1 then for M2, probably due to substantially higher organic fraction emitted for M1 then for M2.

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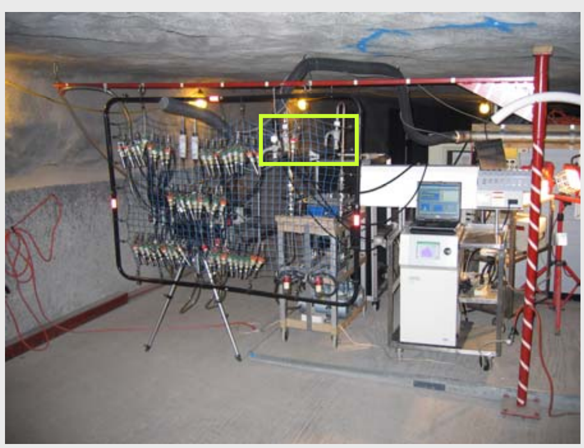
Effects of Fuels on Total Particulate Mass Gravimetric Analysis



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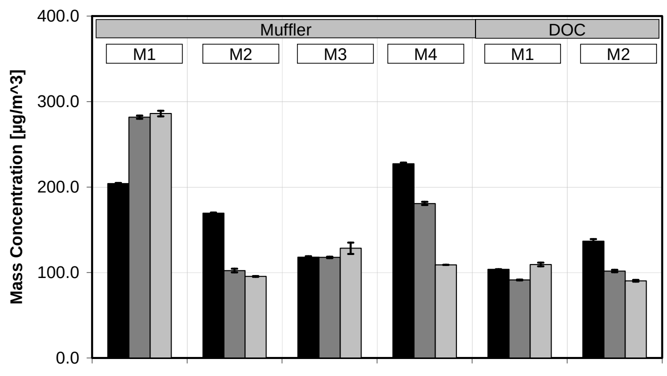
Average Aerosol Mass Concentrations [μg/m³]

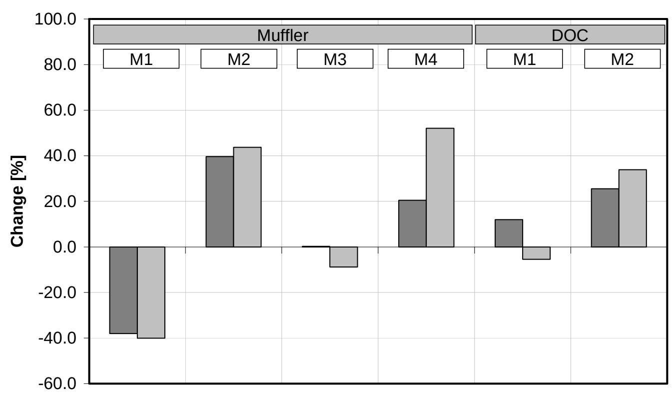


	M1	M2	M3	M4	M1	M2
ULSD	204.2	169.6	118.0	227.2	103.8	136.7
B50	281.8	102.4	117.8	180.8	91.4	101.8
B100	286.0	95.5	128.4	109.0	109.5	90.4

Exhaust/Mode

- Biodiesel fuels increased total mass concentrations of aerosols for M1 (muffler) and M3, but
- total number concentrations of aerosols decreased for M2 (muffler and DOC) and M4.

Effects of Fuel on Aerosol Mass Concentrations [%]

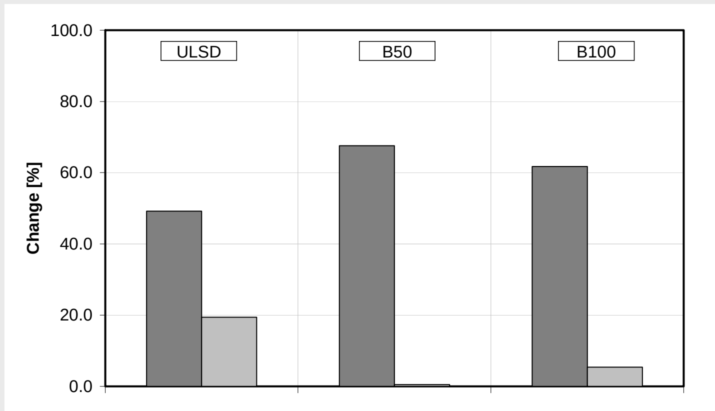


	M1	M2	M3	M4	M1	M2
B50	-38.0	39.6	0.2	20.4	12.0	25.5
B100	-40.1	43.7	-8.8	52.0	-5.5	33.9

Exhaust / Mode

- For M1 and M3, increase in total mass concentrations was augmented with increase in fraction of biodiesel in the fuels.
- For M2 (muffler and DOC) and M4, reduction in total mass concentrations was augmented with increase in fraction of biodiesel in the fuels.

Effects of DOC on Aerosol Mass Concentrations [%]



	ULSD	B50	B100
M1	49.2	67.6	61.7
M2	19.4	0.5	5.4

- DOC reduced total mass concentrations for M1 and M2.
- Reductions in total mass concentrations were substantially higher for M1 then for M2, probably due to substantially higher organic fraction emitted for M1 then for M2.

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Effects of Fuels on Total Mass Concentrations TEOM

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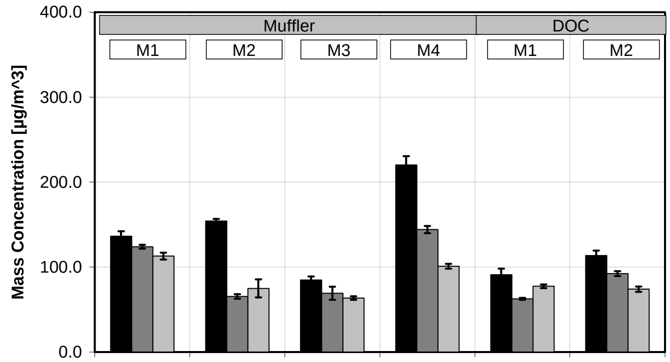
Average Mass Concentrations
TEOM



	M1	M2	M3	M4	M1	M2
ULSD	136.2	154.1	84.7	220.2	90.9	113.5
B50	123.9	65.3	69.3	144.2	62.5	92.3
B100	112.9	74.8	63.6	101.0	77.4	74.0

Exhaust/Mode

- Biodiesel fuels reduced total mass concentrations of aerosols for all modes

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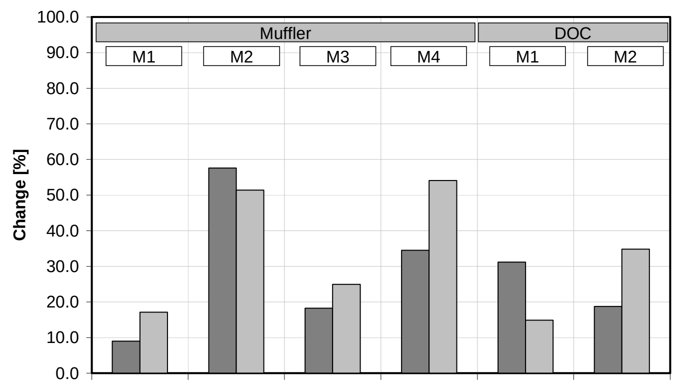
Effects of Fuels on Average Mass Concentrations [%]
TEOM



	M1	M2	M3	M4	M1	M2
B50	9.0	57.6	18.3	34.5	31.2	18.7
B100	17.1	51.4	25.0	54.1	14.9	34.8

Exhaust/Mode

- For M1 (muffler), M2 (DOC), M3, and M4, reductions in total mass concentrations were augmented with increase in biodiesel fraction.
- For M1 (DOC) and M2 (muffler), reduction in total mass concentrations were diminished with increase in biodiesel fraction.

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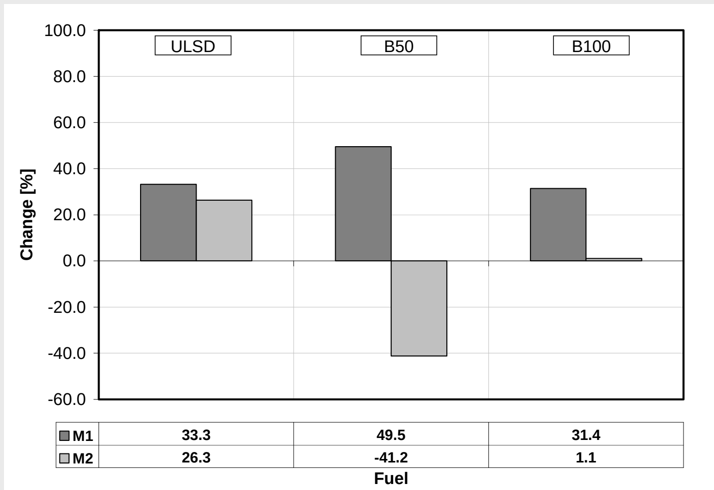
Effects of DOC on Average Mass Concentrations [%] TEOM



	ULSD	B50	B100
M1	33.3	49.5	31.4
M2	26.3	-41.2	1.1

- In majority of the cases DOC reduced total mass concentrations for M1 and M2.
- Reductions in total mass concentrations were higher for M1 then for M2

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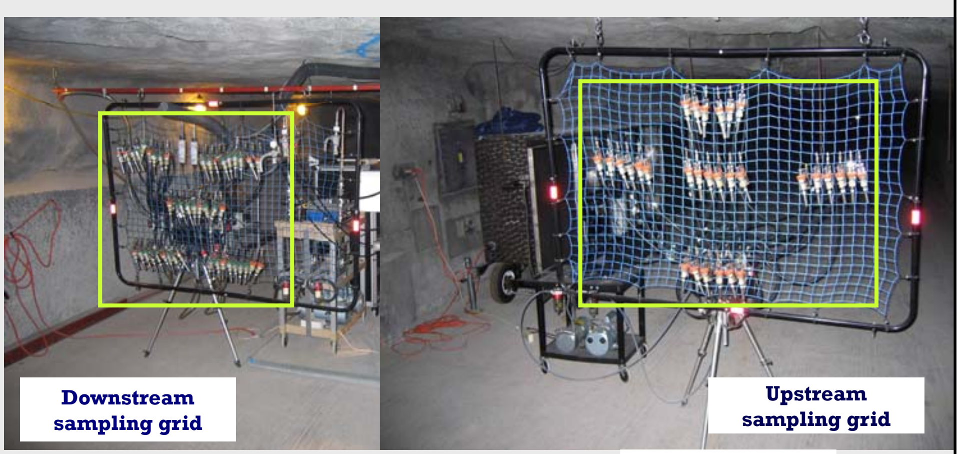
Effects of Fuels and DOC on Integrated Elemental, Organic, and Total Carbon Concentrations Determined by Performing NIOSH 5040 on Primary Filters



Upstream Concentrations below LOQ

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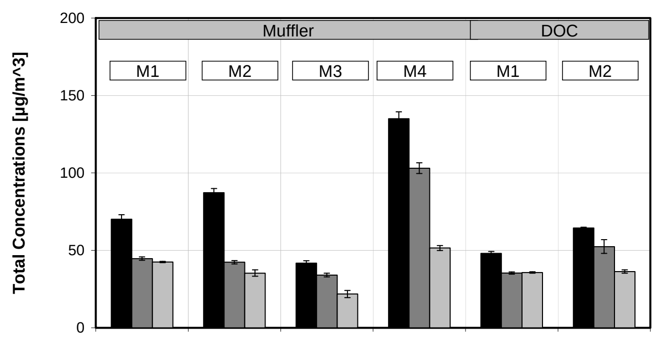
Average Elemental Carbon (EC) Concentrations [μg/m³]



ULSD	70.2	87.2	41.8	135.0	48.0	64.5
B50	44.7	42.4	34.1	103.0	35.4	52.4
B100	42.5	35.3	21.8	51.5	35.7	36.3

Exhaust / Mode

- Biodiesel fuels reduced concentrations of EC for all modes.

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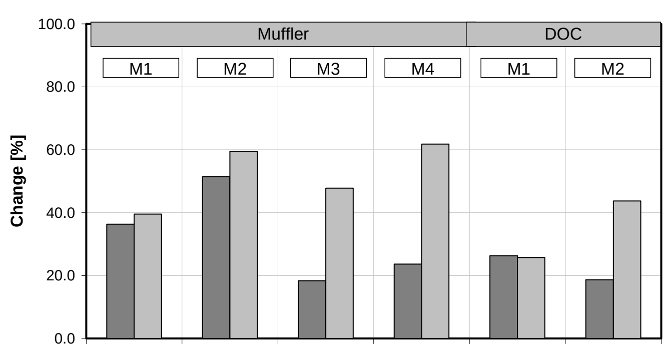
Effects of Fuels on Elemental Carbon (EC) Concentrations [%]



B50	36.4	51.4	18.3	23.6	26.3	18.7
B100	39.5	59.5	47.8	61.8	25.7	43.7

Mode

- In general, reductions in EC was augmented with increase in fraction of biodiesel in the fuels (the exception was M1, DOC).

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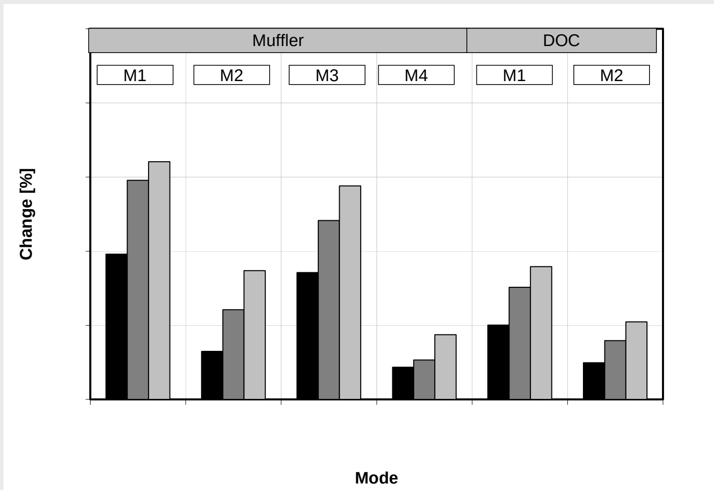
Organic vs. Total Carbon (OC vs. TC) [%]
Primary Filter Analysis



- Fraction of OC in TC increased with increase in biodiesel fraction in the fuels for all modes and both exhaust configurations.

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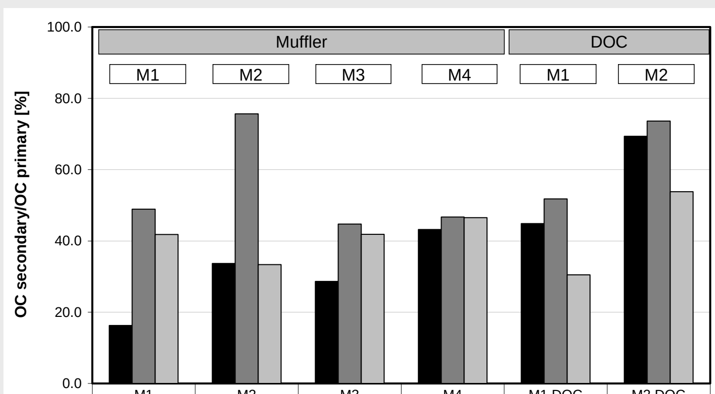
OC artifacts



	M1	M2	M3	M4	M1 DOC	M2 DOC
ULSD	16.31	33.71	28.62	43.22	44.89	69.35
B50	48.91	75.66	44.76	46.72	51.79	73.65
B100	41.80	33.33	41.86	46.55	30.45	53.81

Mode

- Significant OC on the secondary filter
- Particulate phase or gaseous phase organics?
- Quartz fiber media gas phase adsorption or primary filter solid phase desorption?

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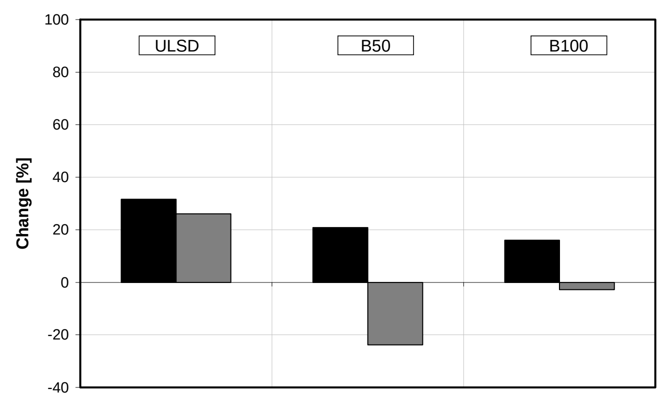
Effects of DOC on EC for M1 & M2



	ULSD	B50	B100
M1	31.6	20.8	16.0
M2	26.1	-23.8	-2.8

Fuel

- DOC was more effective in reducing EC for M1 than for M2.

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Effects of DOC on NO, NO_2, and NO_X

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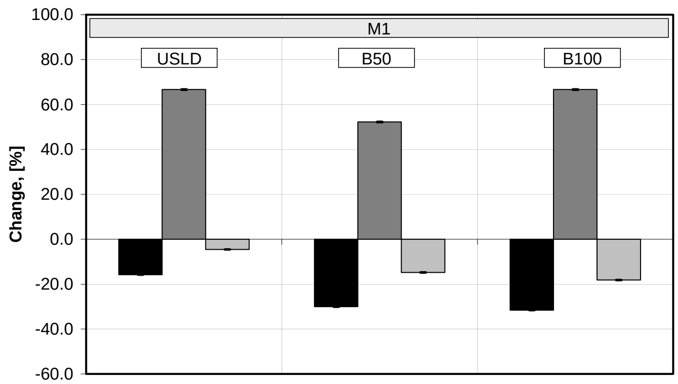
Effects of DOC on NO, NO_2, and NO_X M1



	USLD	B50	B100
NO	-15.8	-30.1	-31.6
NO2	66.7	52.2	66.7
NOx	-4.5	-14.8	-18.2

Fuel

- For M1, DOC increased concentrations of NO and NO_x and reduced concentrations of NO_2.

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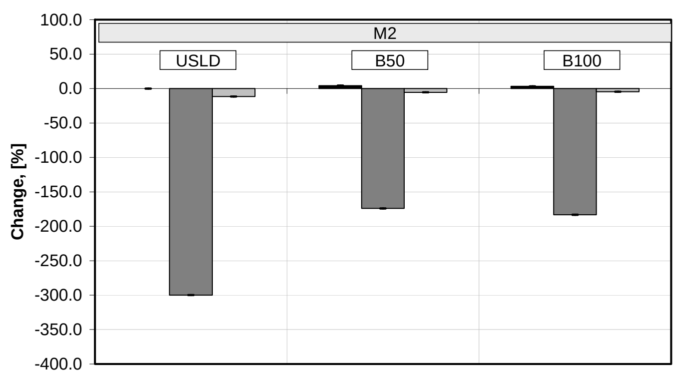
Effects of DOC on NO, NO_2, and NO_X M2



	USLD	B50	B100
NO	0.0	4.3	3.3
NO2	-300.0	-174.1	-183.3
NOx	-11.5	-5.4	-4.6

Fuel

- For M2, DOC increased slightly concentrations of NO_x but increased substantially concentrations of NO_2.

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Conclusions

- Effects of biodiesel fuels on size distribution, number and mass concentrations, and EC concentrations are found to be strongly dependent of engine operating mode.
- Substantial reductions in EC were observed for all engine operating modes and exhaust configurations when biodiesel fuels were used.
- The increase in number and mass concentrations observed for the light-load modes (M1 and M3) can be attributed to increase in semi-volatile organic compounds.
- The advantage of using DOC are particularly evident in the case of light-load mode M1.
- The downside of using the DOC similar to one evaluated in this study would be increase in NO_2 concentrations at high-load modes (M2).

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We would like to acknowledge support from NIOSH Lake Lynn Laboratory personnel for their help and assistance in the experimental phase of this study.

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