Comparison of Particulate and Gaseous Emissions for the DPF Retrofitted Tier 2 and SCR-Equipped Tier 4f Engines

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Introduction

For a substantial part of the mining industry, diesel engines are the primary source of power for mobile underground equipment

- The extensive use of diesel-powered equipment in underground mining operations adversely affects exposures of certain occupations to carcinogenic diesel exhaust [Bugarski and Potts, 2018].

- A wide variety of control technologies and strategies are used by the industry to reduce exposures to diesel aerosols and gases [Bugarski et al. 2012]:
  - elimination.
  - substitution.
  - engineering controls.
  - administrative controls.
  - personal protective equipment (PPE).

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Retrofit vs. Repower

- Two leading engineering control strategies available to the underground mining industry to reduce contribution of diesel engines to concentrations of aerosols in the mines are:
  - retrofitting existing power packages with diesel particulate filter (DPF) systems.
  - repowering equipment with advanced power packages.

- These two strategies exploit the benefits of dramatic reductions in the levels of emissions and changes in the physical and chemical properties of aerosols emitted by diesel engines [Herner et. al., 2011; Khalek et al., 2011; Khalek et al. 2015; Ruehl et al., 2015] driven by rapid developments in:
  - engine technologies.
  - exhaust aftertreatment technologies.
  - fuels.

- This study was conducted to compare these two strategies with respect to:
  - their potential to reduce mass concentrations of organic and elemental carbon.
  - their potential to reduce number concentrations of aerosols.
  - effects of those on size distributions of aerosols.
  - effects of those on criteria gases.

- This information should help the efforts to assess the potential benefits for retrofit and repower control strategies in the reduction of miners' exposures.

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Methodology

Methodology: Engines and Exhaust Aftertreatment

- Two electronically controlled turbocharged diesel engines of similar output that meet different emissions standards were evaluated during this study:
  - United States Environmental Protection Agency (U.S. EPA) Tier 2 (Tier 2) engine:
    - 2004 4.3-liter OM 904 LA (family 4MB XL4.25RJA)—rated at 130 kW (174 bhp) @ 2200 rpm and 675 Nm (498 lb-ft) @ 1400 rpm:
      - complies with the Tier 2 emission standards (PM< 0.30 g/kWh / 0.22 g/bhp·hr).
      - approved by the MSHA for use in underground mines in the United States (Approval number: 7E-B098).
      - retrofitted with:
        - » a diesel oxidation catalyst (DOC), Model MinNoDOC from AirFlow Catalyst Systems, Rochester, NY, or
        - » a full-flow DPF system Model Green Trap 1100 from NETT Technologies, Mississauga, ON.

vs.

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Methodology: Engines and Exhaust Aftertreatment (2)

- U.S. EPA Tier 4 final (Tier 4f) engine:
  - 2014 5.1-liter Mercedes Benz Model OM 934 LA (family EMBXL07.7RJA), rated at 129 kW (173 bhp) @ 2200 rpm and 750 Nm (535 lb-ft) @ 1400 rpm:
    - » complies with the Tier 4 final emission standards (PM< 0.02 g/kWh / 0.015 g/bhp·hr).
    - » does not have MSHA approval.
    - » equipped with a cooled exhaust gas recirculation (EGR) system.
    - » fitted with a DOC, diesel exhaust fluid (DEF)-based selective catalyst reduction (SCR) system, and ammonia slip catalyst (ASC).

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Methodology: Fuel

- The engines were fueled with ultralow sulfur diesel (ULSD) obtained from a single batch.

Property	Test Method	Unit	Value
Specific gravity	ASTM D1298	-	0.830
Aromatics content	ASTM D1319	% volume	21.7
Olefins content	ASTM D1319	% volume	3.1
Parafins content	ASTM D1319	% volume	75.2
Cetane number	ASTM D613	-	47.3
Flash point	ASTM D93	K	340
Heat of combustion	ASTM D240	MJ/kg	45.9
Sulfur content	ASTM D5453	ppm	5.6

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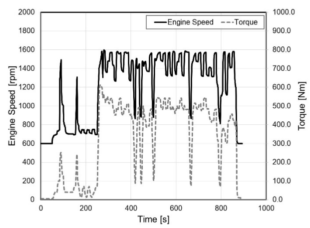
Methodology: Engine Operating Conditions

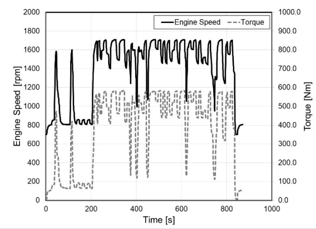
- Both engines were coupled to a 400-kW, water-cooled, eddy-current dynamometer (SAJ, AE400).
- The emissions were assessed for:
  - four steady-state (SS) operating conditions (rated speed 100% load – R100, rated speed 50% load – R50, intermediate speed 100% load – I100, and intermediate speed 50% load – I50).
  - one transient (TR) cycle.

Engine Operating Conditions	Tier 2			Tier 4f		
	Engine Speed rpm	Torque Nm (lb-ft)	Power kW (hp)	Engine Speed rpm	Torque Nm (lb-ft)	Power kW (hp)
R100	2200	515 (380)	119 (159)	2200	542 (400)	125 (168)
R50	2200	258 (190)	59 (80)	2200	271 (200)	63 (84)
I100	1400	637 (470)	93 (125)	1400	719 (530)	105 (141)
I50	1400	319 (235)	47 (63)	1400	359 (265)	53 (71)

Tier 2



Tier 4f



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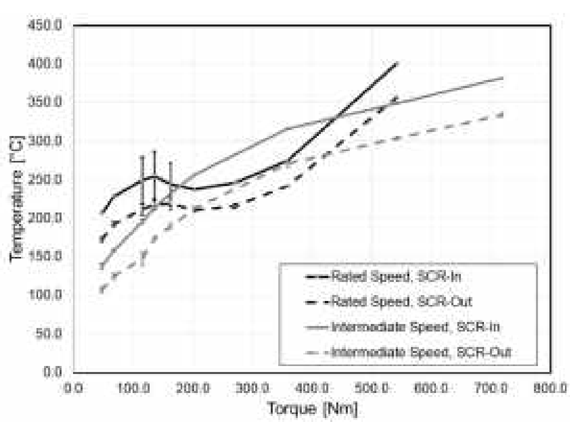
Methodology: Temperature Ramps

- Additional testing was done on the Tier 4f engine in order to assess the effects of exhaust temperature on CO, NO, and NO_2 emissions before (SCR-In) and after (SCR-Out) the DOC/SCR/ASC system.



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Methodology: Carbon Analysis

- Aerosol samples were obtained from the exhaust diluted in a two-stage partial dilution system (Dekati, Tampere, Finland, Model FPS-4000):
  - DR=30.
- Triplicate filter samples for the carbon analysis were collected on tandem 37-mm quartz fiber filters (QFFs, Pall Corporation, Exton, PA, 2500QAT-UP) enclosed in five-piece cassettes (SKC, Eighty Four, PA, 225-3050LF and 225-304).
  - QFFs were pre-baked in a muffle furnace at 800 °C for 4 hours.
- The carbon analysis was performed at National Institute for Occupational Safety and Health (NIOSH) Pittsburgh Mining Research Division (PMRD) using the thermal optical transmittance-evolve gas analysis (TOT-EGA) method, NIOSH Method 5040 [NIOSH 2016].
  - Instrument: Organic Carbon/Elemental Carbon (OC/EC) Aerosol Analyzer from Sunset Laboratory Inc. (Portland, OR).
- The results of the analysis performed on the secondary QFFs were used as a dynamic blank correction for the primary QFFs.

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Methodology: Number Concentrations and Size Distributions of Aerosols

- Number concentration and size distribution measurements were performed in exhaust diluted in the two-stage partial dilution system (Dekati, Tampere, Finland, Model FPS-4000):
  - DR=30.
- A fast mobility particle sizer spectrometer (FMPS Model 3091, TSI, Minneapolis, MN) was used to measure, at 1 Hz frequency, the number of concentrations and size distributions of nonvolatile and volatile aerosols with an electrical mobility diameter (D_{em}) between 5.6 nm to 560 nm.
- In order to enhance the clarity of the figures, the aerosol size distributions were fitted with log-normal curves using DistFit software from Chimera Technologies (Forest Lake, MN).

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Methodology: Concentrations of CO, NO, and NO_2

- The concentrations of CO, NO, and NO_2 in undiluted exhaust were measured in 20-second intervals using a Fourier transform infrared (FTIR) spectrometer (Gasmet, Vantaa, Finland, DX4000).

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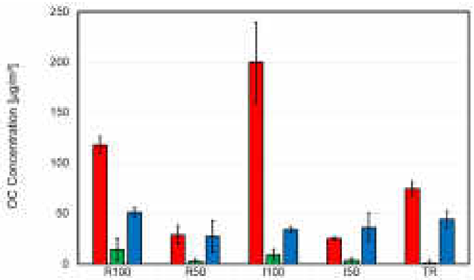
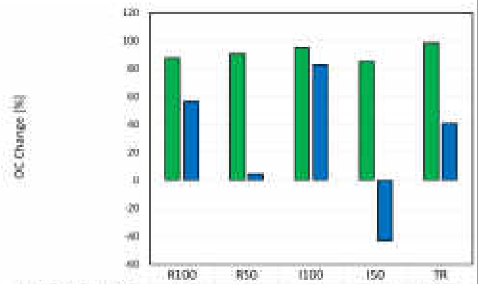
Results and Discussion

Results: Effects on Mass Concentrations of OC

- Depending on the engine operating conditions, the Tier 2 engine emitted between **85.3** and **98.7 percent less** OC when retrofitted with the DPF rather than with the DOC.
- The Tier 4f engine emitted between **4.8** and **82.8 percent less** OC than the Tier 2 engine equipped with the DOC for all but I50 engine operating conditions.
- For I50 engine operating conditions, the Tier 4f engine emitted **43.2 percent more** than the Tier 2 engine equipped with the DOC.



Mode	R100	R50	I100	I50	TR
Tier 2 DOC	117.8	28.8	199.9	25.3	74.9
Tier 2 DPF	14.6	2.7	9.3	3.7	1.0
Tier 4f	51.2	27.4	34.3	36.3	44.4



Mode	R100	R50	I100	I50	TR
Tier 2 DPF vs. DOC	87.6	90.6	95.4	85.3	98.7
Tier 4f vs. Tier 2 DOC	56.5	4.8	82.8	-43.2	40.8

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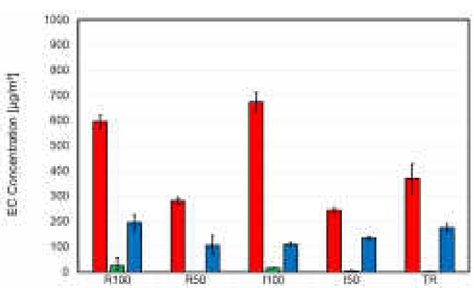
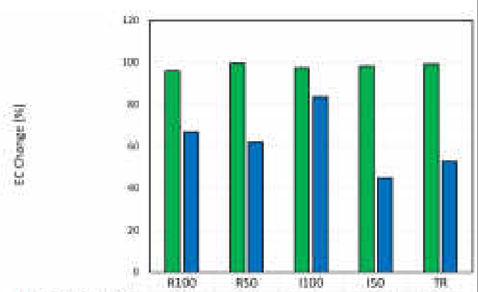
Results: Effects on Mass Concentrations of EC

- Depending on the engine operating conditions:
  - the Tier 2 engine emitted between **97.5** and **99.8 percent less** EC when retrofitted with the DPF than with the DOC.
  - the Tier 4f engine emitted **44.9** and **83.7 percent less** EC than the Tier 2 engine equipped with the DOC.



Mode	R100	R50	I100	I50	TR
Tier 2 DOC	595.4	282.3	674.7	244.5	371.2
Tier 2 DPF	24.8	0.7	16.8	4.4	3.0
Tier 4f	197.1	107.3	110.2	134.6	175.4



Mode	R100	R50	I100	I50	TR
Tier 2 DPF vs. DOC	95.8	99.8	97.5	98.2	99.2
Tier 4f vs. Tier 2 DOC	66.9	62.0	83.7	44.9	52.7

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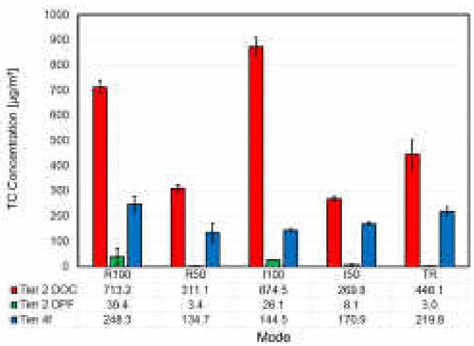
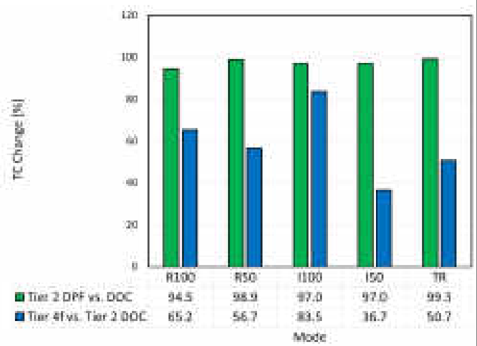
Results: Effects on Mass Concentrations of TC

- Depending on the engine operating conditions:
  - the Tier 2 engine emitted between **97.0** and **99.3 percent less** TC when retrofitted with the DPF than with the DOC.
  - the Tier 4f engine emitted **36.7** and **83.5 percent less** TC than the Tier 2 engine equipped with the DOC.





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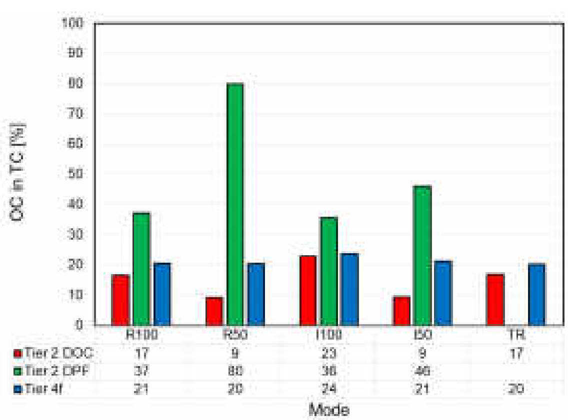
Results: Fractionation of Carbon Emissions

- Depending on the engine operating conditions OC made :
  - between **9** and **23** percent of TC in the exhaust of the Tier 2 engine operated with the DOC.
  - between **36** and **80** percent of TC in the exhaust of the Tier 2 engine operated with the DPF.
  - between **15** and **24** percent of TC for the Tier 4f engine.



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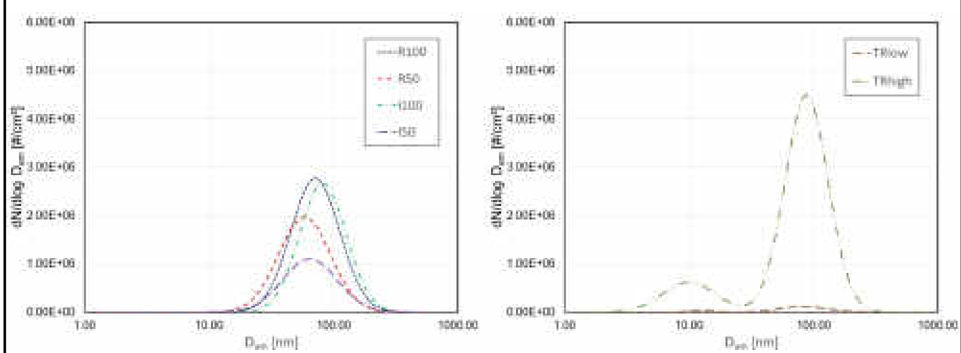
Results: Size Distributions of Aerosols Emitted by the Tier 2 Engine Retrofitted with the DOC

- When operated at SS engine operating conditions, the Tier 2 engine retrofitted with the DOC emitted aerosols distributed in single accumulation modes:
  - Count median diameter (CMD) of the accumulation mode – between **59** and **83 nm**.
- When operated at TR engine operating conditions, the Tier 2 engine retrofitted with the DOC emitted aerosols distributed predominantly in single accumulation modes:
  - CMD of the accumulation mode – **83** and **88 nm**.



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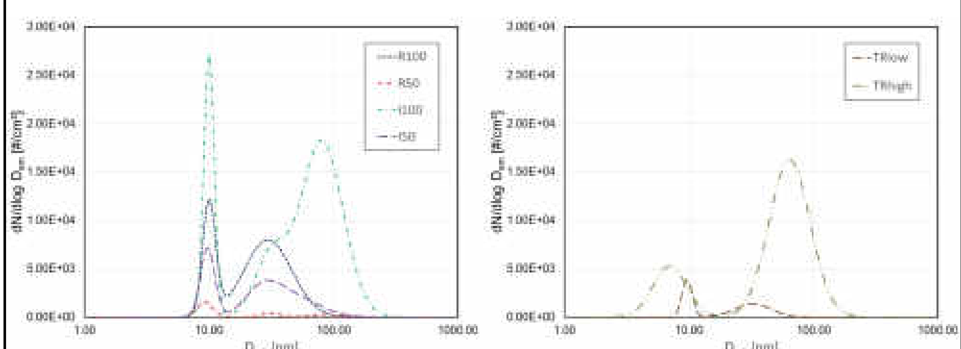
Results: Size Distributions of Aerosols in the Exhaust of the Tier 2 Engine Retrofitted with the DPF

- When operated at SS engine operating conditions, aerosols emitted by the Tier 2 engine retrofitted with the DPF were distributed between two or three modes:
  - CMD of the nucleation mode – between **9** and **10 nm**.
  - CMD of the first accumulation mode – between **27** and **31 nm**.
  - CMD of the second accumulation mode (when apparent) – between **46** and **86 nm**.
- When operated at TR engine operating conditions, the distributions of aerosols emitted by the Tier 2 engine retrofitted with the DPF were also multi modal:
  - CMD of the nucleation mode – **7** and **10 nm**.
  - CMD of the accumulation mode – **32** and **64 nm**.



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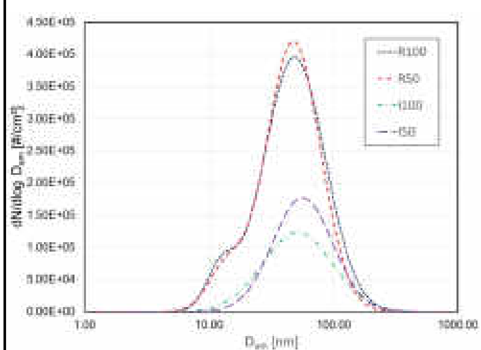
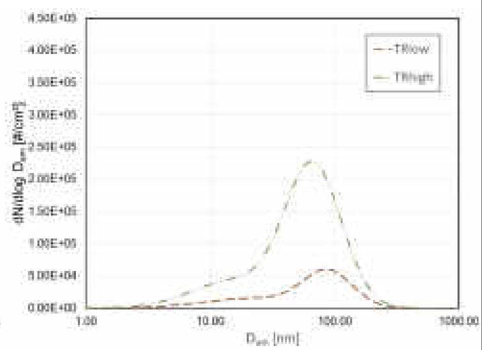
Results: Size Distributions of Aerosols Emitted by the Tier 4f Engine

- When operated at SS engine operating conditions, the Tier 4f engine emitted aerosols distributed predominantly in single accumulation mode:
  - Count median diameter (CMD) of the accumulation mode – between **48** and **57 nm**.
- When operated at TR engine operating conditions, the Tier 4f engine emitted aerosols distributed predominantly in single accumulation mode:
  - CMD of the accumulation mode – **88** and **67 nm.**





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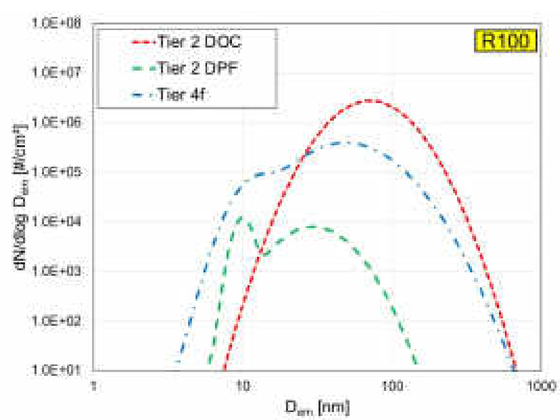
Results: Peak Concentrations of Aerosols

- Peak concentrations of aerosols for all SS engine operating conditions:
  - Tier 2 Engine Retrofitted with the DOC: between **$1.10e^6$** and **$2.77e^6$ #/cm³**.
  - Tier 2 Engine Retrofitted with the DPF: between **$7.12e^3$** and **$2.73e^4$ #/cm³**.
  - Tier 4f Engine: between **$1.77e^5$** and **$4.20e^5$ #/cm³**.



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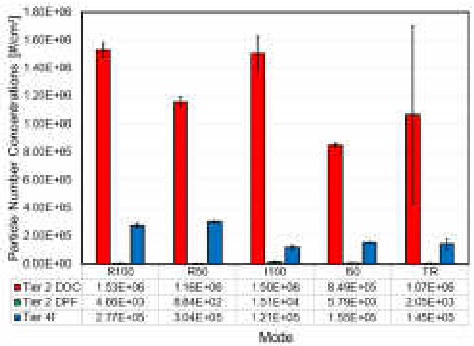
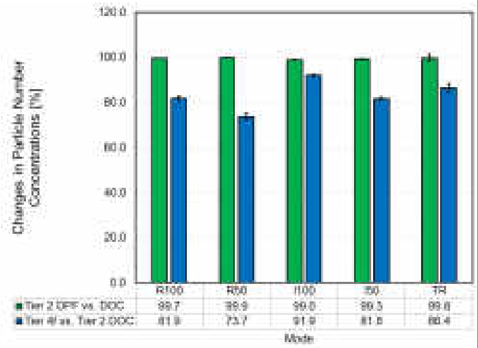
Results: Effects on Average Number Concentrations of Aerosols

- Depending on the engine operating conditions:
  - the Tier 2 engine emitted between **99.0** and **99.9** percent less aerosols by number when retrofitted with the DPF rather than with the DOC.
  - the Tier 4f engine emitted **73.7** and **91.9** percent less aerosols by number than the Tier 2 engine equipped with the DOC.





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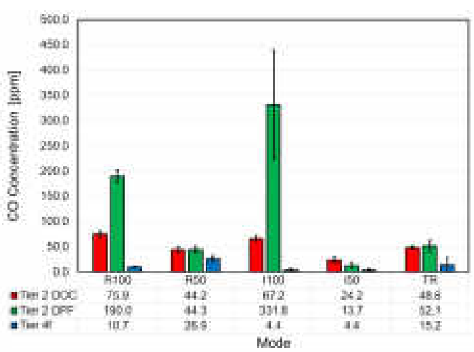
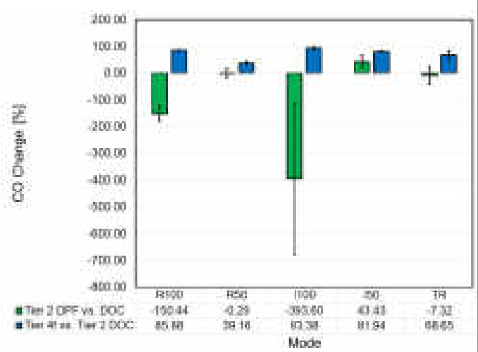
Results: Effects on CO concentrations

- Depending on the engine operating conditions:
  - the Tier 2 engine emitted between **43.4 percent less** and **393.6 percent more CO** when retrofitted with the DPF rather than with the DOC.
  - the Tier 4f engine emitted between **39.2** and **93.4 percent less CO** than the Tier 2 engine equipped with the DOC.





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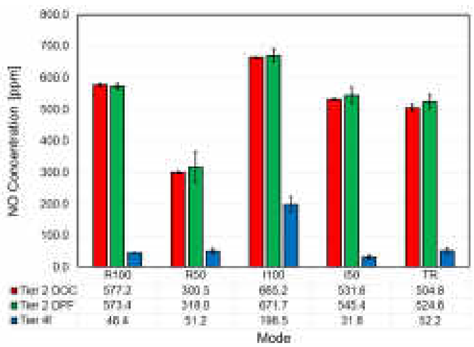
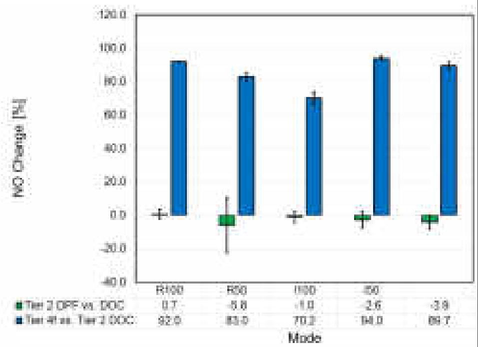
Results: Effects on NO concentrations

- The Tier 2 engine emitted **similar quantities of NO** when retrofitted with the DPF than with the DOC.
- Depending on the engine operating conditions the Tier 4f engine emitted between **70.2** and **94.0 percent less NO** than the Tier 2 engine equipped with the DOC.





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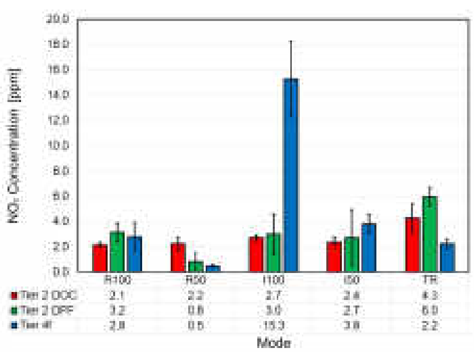
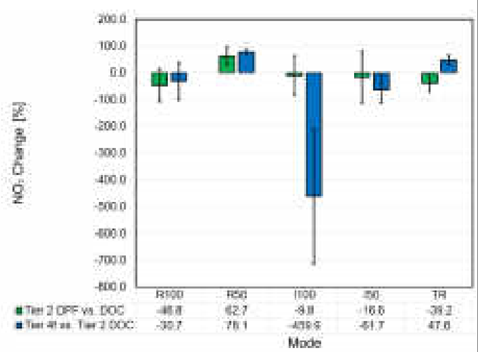
Results: Effects on NO_2 concentrations

- The NO_2 emissions for the Tier 2 engine retrofitted with the DPF and with the DOC were generally low and differences were within measurement error.
- With the exception of I100 engine operating conditions, the NO_2 emissions for the Tier 4f engine and the Tier 2 engine equipped with the DOC were also generally low and differences were within measurement error.





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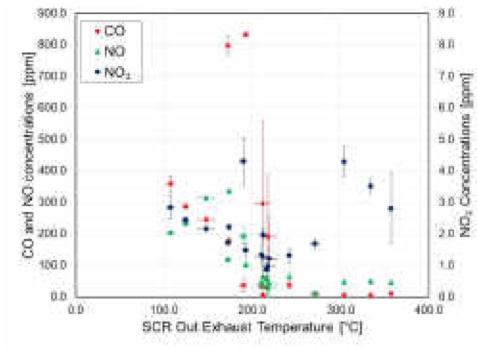
Results: Effects of Exhaust Temperatures on CO, NO, and NO_2 SCR-Out Emissions for Tier 4f Engine

- Due to low catalytic activity and the absence of urea injections, the CO and NO emissions were highest for the engine operating conditions that generated exhaust temperatures below 200 °C (392 °F).
- At temperatures above 200 °C (392 °F), the system was found to effectively convert CO and NO.
- Evidence of limited NO_2 formation was found for an engine operating condition that generated temperatures above 300 °C (572 °F) (I100).



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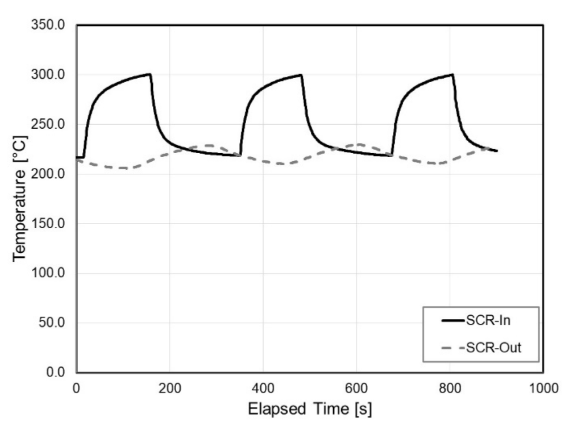
The active exhaust temperature control strategies are used on the Tier 4f engine to support operation of SCR systems

- SCR-In and SCR-Out exhaust temperatures for US EPA Tier 4f engine operated at rated speed and 136 Nm (100 lb-ft).



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Conclusion

Conclusion

- High reductions of OC, EC, and TC mass concentrations and total number concentrations of aerosols were achieved by fitting the Tier 2 engine with the DPF system rather than with the DOC.
- The Tier 4f engine contributed substantially less than the Tier 2 retrofitted with the DOC to the mass concentrations of EC and TC, number concentrations of aerosols, and concentrations of CO and NO.
- Based on the above results, strategy established on repowering existing vehicles currently powered by Tier 2 engines (and Tier 3 engines) with Tier 4 final engines fitted with the DEF-based SCR systems has the potential to reduce the contribution of diesel-powered underground mining vehicles to mass concentrations of submicron aerosols and criteria gases in underground mines.
- The use of DPFs in advanced exhaust aftertreatment systems would be critical to efforts to reduce contributions of advanced engines to aerosol number concentrations.
- Additional work is needed to assess other aspects of implementation of these strategies in underground operations including:
  - technical complexity, space requirements, higher capital and operational costs, fluid requirements, reliability, durability, maintenance, and economics.

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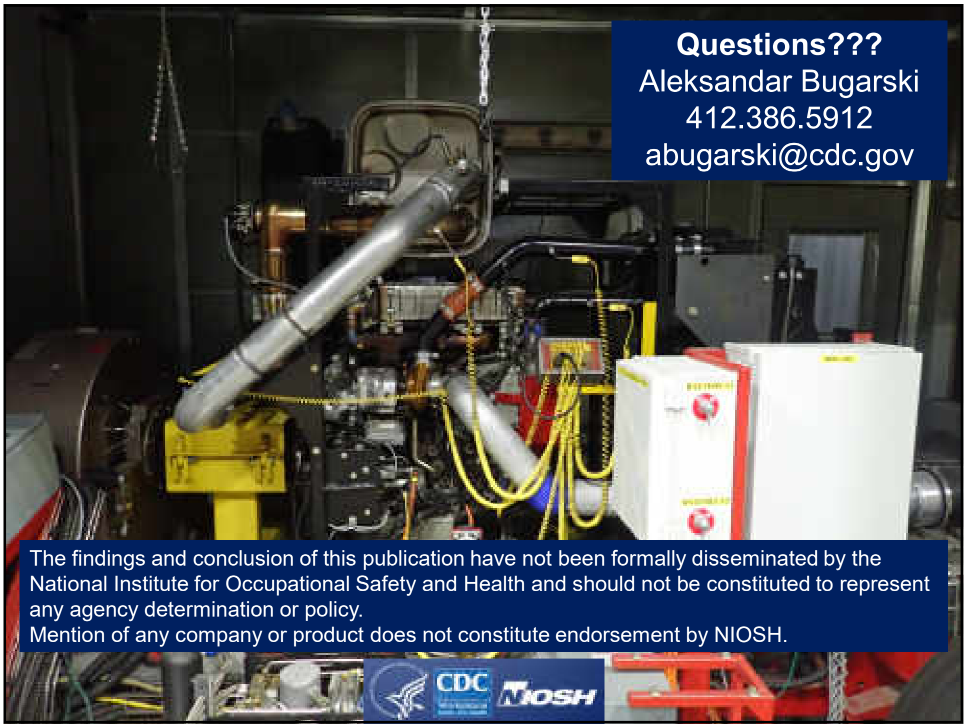

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Abstract

A study was conducted by the National Institute for Occupational Safety and Health (NIOSH) to examine the potential of two diesel emissions control strategies to reduce exposures of mineworkers to diesel aerosols. The results of laboratory evaluations were used to examine emissions of a U.S. EPA Tier 2 compliant engine (Tier 2) retrofitted with a diesel oxidation catalyst (DOC) and diesel particulate filter (DPF) and those of a U.S. EPA Tier 4 final compliant engine (Tier 4f) equipped with a cooled exhaust gas recirculation system and selective catalytic reduction system, but not with a DPF system. The emissions were evaluated for four steady-state engine operating conditions and one transient cycle. The Tier 2 engine emitted 85 percent less OC, 97 percent less EC, and 99 percent less particles by number when retrofitted with the DPF rather than with the DOC. For the majority of test conditions, the tested DPF achieved reductions in the aforementioned emissions without adversely affecting emissions of NO_2 and nanosized aerosols. The Tier 4f engine contributed substantially less than the Tier 2 engine retrofitted with the DOC to the EC and OC mass, aerosol number, and CO and NO concentrations. However, the Tier 4f engine emitted much more OC and EC than the Tier 2 engine retrofitted with the DPF. The Tier 4f engine emitted between 39 and 93 percent less CO and between 70 and 94 percent less NO than the Tier 2 engine operated with the DOC. The implementation of viable exhaust aftertreatment systems and advanced diesel power packages could be instrumental to the underground mining industry to secure a clean, economical, and dependable source of power for mobile equipment.