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# Isolated zone evaluation of the Tier 4i diesel engine equipped with an SCR system

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ABSTRACT: Implementing the latest engine and exhaust aftertreatment technologies is one of the major strategies used by the mining industry to control exposures of underground miners to gases and aerosols emitted by diesel-powered vehicles. Due to the rapid development of engine and aftertreatment technologies, limited information is available in the literature on their potential impact on concentrations of carbon monoxide (CO), nitric oxide (NO), nitrogen dioxide ($NO_2$), ammonia ($NH_3$), and submicron aerosols in underground mines. This study was conducted to develop a better understanding of how the recently introduced Tier 4i Mercedes Benz OM926 engines equipped with a selective catalyst reduction (SCR) catalyst system might alter concentrations of criteria gases and aerosols in mine air. To provide a reference for the comparison with engines currently used by the industry, the effects of a vehicle powered by the Tier 4i engine were qualitatively compared with the effects of a similar vehicle powered by the comparably rated Tier 3 engine from the same manufacturer, which for testing purposes was equipped with a diesel oxidation catalyst (DOC) or diesel particulate filter (DPF) system. Both engines were fueled with a 50 percent biodiesel blend (B50). Under prevailing test conditions, the Tier 4i engine was found to contribute less than the Tier 3 engine retrofitted with the DOC to concentrations of NO, elemental carbon (EC), organic carbon (OC), total carbon (TC), and total number of aerosols; but more to concentrations of CO, $NO_2$, and $NH_3$. The Tier 4i engine contributed more than the Tier 3 engine equipped with the DPF to concentrations of CO, $NO_2$, EC, TC, and total number concentrations of aerosols, but less to the concentrations of NO and OC; and similarly to $NH_3$ concentrations.

## 1 Introduction

Ever since the U.S. Mine Safety and Health Administration (MSHA) promulgated the rule limiting exposure of underground metal/nonmetal miners to diesel particulate matter (DPM) [30 CFR 57.5060], the mining industry in the U.S. has been extensively searching for viable strategies and technologies capable of reducing the exposure of underground miners to diesel aerosols. Over the past decade, the industry has been pursuing various strategies based on improving ventilation and on implementing contemporary engine technology, emissions-assisted maintenance, retrofit type exhaust aftertreatment systems and alternative fuels [Bugarski et al. 2011]. The latest developments in diesel engine and exhaust aftertreatment technologies have resulted in a new generation of nonroad engines that meet stringent emissions standards for particulates and criteria gases [69 Fed. Reg. 38957 2004].

As of 2011, newly introduced engines with output in the range typically used to power heavy-duty equipment in underground metal and nonmetal mines in the U.S. (between 130 kW and 560 kW) would be required to meet U. S. Environmental Protection Agency (USEPA) Tier 4i nonroad emissions standards [69 Fed. Reg. 38957 2004]. By 2014, the same class of engines will have to comply with the USEPA Tier 4 nonroad emissions standards. The Tier 4i nonroad engines are expected to meet a particulate matter (PM) emission standard that is half of that established for Tier 2 and Tier 3 engines (see Table 1). The PM standard for Tier 4 nonroad engines is one-tenth of the corresponding Tier 2 and Tier 3 standards. In addition, the standard for emissions of nitrogen oxides ($NO_X$) for Tier 4 nonroad engines is approximately 10 times lower than the standards for Tier 3 and Tier 4i nonroad engines.

It is important to note that the USEPA emissions standards are written in terms of cumulative emissions of nitrogen oxides ($NO_X=NO+NO_2$). These standards do not impose emission limits for the individual constituents of $NO_X$, NO, and $NO_2$, which are used as the criteria gases for regulating the exposure of underground miners to airborne contaminants [30 CFR 57.5001].

In order to meet the USEPA emission standards, the majority of manufacturers will most likely equip Tier 4i and Tier 4 nonroad engines from this engine class with advanced exhaust aftertreatment technologies such as diesel particulate filter (DPF) and urea-based selective catalyst reduction (SCR) systems.

DPF systems with ceramic and sintered metal filtration elements have been demonstrated to reduce DPM mass emissions in excess of 85 percent [D'Urbano and Mayer 2007, MSHA 2009]. The engines equipped with retrofit-type DPF systems have been found to be effective at reducing total DPM and elemental carbon concentrations in underground miners [NIOSH 2006, Bugarski et al. 2009, Bugarski et al. 2011]. However, the implementation of retrofit-type DPF systems in underground mining applications has been found to be challenging primarily due to DPF regeneration and reliability related issues [Stachulak et al. 2005].

SCR systems have recently emerged as an $NO_X$ control technology capable of reducing $NO_X$ emissions by more than 75 percent from engines operated over heavy-duty cycles [Majewski and Khair 2006, Ardanese et al. 2009, Herner et al. 2009]. High reductions in $NO_X$ emissions in SCR systems are achieved with the help of a reducing agent. The reducing agent currently used in mobile SCR applications in the U.S., known as diesel exhaust fluid (DEF), consists of 32.5 percent high purity urea and 67.6 percent deionized water.

Advanced exhaust aftertreatment systems based on DPF and SCR systems have been extensively evaluated under laboratory conditions [D'Urbano and Mayer 2007, Biswas et al. 2008, Ardanese et al. 2009, Herner et al. 2009]. However, limited information is available in the literature on the potential impact of engines equipped with those systems on concentrations of MSHA-criteria gases and aerosols in underground mines. Specifically, the absence of information on the effects of those engines on physical and chemical properties of diesel aerosols and on concentrations of $NO_2$ emitted in mine air is the most evident. This is particularly true for SCR systems that have only recently been retrofitted to North American mobile underground mining vehicles [Rubeli 2010].

The goal of the study described in this manuscript was to assess the effects of a vehicle powered by the Tier 4i Mercedes Benz OM926 engine equipped with a DEF-based SCR system on the concentrations of criteria gases (CO, NO, $NO_2$, and $NH_3$) and on the concentrations of aerosols in underground mines. Additional effort was made to assess the effects of the potential failure of the system to inject DEF. In order to assess those effects, the engine was tested with a fully functional SCR system and with a partially functional system where a fault was induced to prevent the injection of DEF. In order to provide the industry with clear information on current trends, the effects of a vehicle powered by a Tier 4i engine were qualitatively compared with the effects of a similar vehicle powered by a Tier 3 engine equipped with a muffler/diesel oxidation catalyst (DOC) and with a retrofit-type DPF system. The engines were fueled with a 50 percent blend (B50) of fatty acid methyl ester (FAME) biodiesel and petroleum sourced ultralow sulfur diesel (ULSD) from a single batch. FAME biodiesel fuels play an important role in the efforts of the host mine, and in 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.

## 2 Methodology

### 2.1 Vehicles, engines, exhaust aftertreatment systems, and fuel

The testing took place in the underground mining operation at the Newmont USA Ltd. Leeville Mine. Two Sandvik EJC30SX 30-ton haulage trucks used in this study as test vehicles (UHT059 and UHT051) were on temporary loan from the production crew. The gaseous and aerosol emissions of the UHT059 powered by the Mercedes Benz OM 926 LA Tier 4i nonroad engine equipped with a DEF-based SCR system were qualitatively compared with the emissions of the similar vehicle, UHT051 powered by the Mercedes Benz OM 926 LA Tier 3 nonroad engine and tested with the DOC and with the retrofit-type catalyzed passive DPF system. In order to assess the effect of the DEF injection on emissions, two tests were conducted with UTH059. The Tier 4i engine was tested with the fully functional SCR system (FF SCR) as well as with the SCR system with a fault induced to prevent the injection of DEF (PF SCR).

The important features that differentiate the Tier 4i from the Tier 3 engines are higher maximum injection pressure (2500 bar vs. 2000 bar), absence of an exhaust gas recirculation (EGR) system, and presence of the SCR system.

Table 1. The USEPA nonroad emissions standards for diesel engines with output between 130 kW and 560 kW [69 Fed. Reg. 38957 2004].

| U.S. EPA Emissions Standards [g/kWh] | Nitrogen Oxides ($NO_X$) | Non-methane Hydrocarbons (NMHC) | $NO_X$ + NMHC | Carbon Monoxide (CO) | Particulate Matter (PM) |
|---|---|---|---|---|---|
| Tier 3 | - | - | 4.00 | 3.50 | 0.20 |
| Tier 4i | 3.50 | 0.40 | - | 3.50 | 0.10 |
| Tier 4 | 0.40 | 0.19 | - | 3.50 | 0.02 |

The catalyzed passive DPF system used on the Tier 3 engine was retrofitted to UHT051 several months before the study. This system was made by NETT Technologies Inc. (Mississauga, ON) using 0.38 m × 0.38 m (15” × 15”) cordierite substrate with a cell density of 15.5 cells/cm² (100 cells/in²). The substrate was coated with 1.77 g/dm³ (50 g/ft³) of catalyst prepared with a mix of platinum and base metals. For the purposes of assessing emissions for the Tier 3 engine when equipped with the DOC, the DPF system was temporarily replaced with the DOC. The DOC accumulated a substantial (but not documented) number of hours in operation prior to testing.

Both engines used in this study were fueled by a B50 blend supplied by the Thomas Petroleum (Carlin, NV). The neat FAME biodiesel fuel (B100) was supplied by the Renewable Energy Group (REG) (Ames IA, REG9000-10). The petroleum-based ULSD was supplied by Thomas Petroleum (Carlin, NV).

## 2.2 Isolated zone

The effects of test engines on the concentration of criteria gases and aerosols in mine air were assessed under simulated production conditions using an isolated zone methodology [NIOSH 2006]. The isolated zone (Figure 1) was established in the development drift located off the Carlin ramp.

During all of the tests, the vehicle/engine was operated within the 600-foot-long section of the main drift by a single experienced operator. The vehicle/engine was operated over a series of repetitions of a duty cycle developed specifically for this study. The cycle was designed to simulate the operation of the haulage truck in a typical production scenario. The cycle consisted of approximately a 400-second sequence of events (for tests with the Tier 4i engine) and approximately a 300-second sequence of events (for the test with the Tier 3 engine) shown on the examples recorded during the Tier 4i / FF SCR and Tier 3 / DPF tests. The analysis of the time-weighted averages for engine speed and torque data acquired from the engine control units (ECU) of the test engines showed good test-to-test repeatability for the tests involving each specific vehicle/engine.

Despite very similar specifications for the vehicles and engines, as well as an effort on the part of the operator to replicate the cycles, the duty cycles for the Tier 4i and Tier 3 engines were found to be measurably different. Although on average the duty cycles for the tests involving the Tier 4i engine and those for the Tier 3 engine were characterized by relatively similar average torque outputs, the real-time traces of torque and engine speed showed that the engines completed work in a somewhat different fashion. Additionally, the corresponding average engine speed was about 200 rpm lower for the Tier 4i than for the Tier 3 engine. The differences in the duty cycles of the tested engines allowed only for qualitative comparison of the effects for the Tier 4i and the Tier 3 engines.

During the Tier 4i tests, the exhaust temperature ranged between 354 °C (669 °F) and 418 °C (784 °F) with a time-weighted average of 387°C (729 °F). During the Tier 3 tests, the exhaust temperature ranged between 311 °C (592 °F) and 415 °C (779 °F) with a time-weighted average of 371°C (700 °F). It is important to note that the exhaust temperatures were in a range that benefited the performance of the catalysts used in the exhaust aftertreatment devices. On average, the exhaust temperatures were approximately 16 °C (29 °F) higher during tests involving the Tier 4i engine than during tests involving the Tier 3 engine.

## 2.3 Measurement, sampling, and analysis

Two ambient measurement and sampling stations were established in the isolated zone: (1) the background sampling station (BSS) and (2) the main sampling station (MSS) (Figure 1). The objective was to assess the net contribution of the test vehicles to concentrations of the criteria gases and aerosols by subtracting the results of the measurement performed at the BSS from the results of measurements performed at the MSS.

The BSS was established at the upstream end of the isolated zone (see Figure 1) approximately 20 m (66 ft) upstream of the upstream vehicle turning point. At the BSS, an infrared (IR) analyzer (Vaisala, Carboncap GM70IR) was used to measure continuously background concentrations of $CO_2$; an electrochemical cells-based multi-gas monitor (Industrial Scientific, iTX) was used at the same location to continuously measure background concentrations of CO, NO, and $NO_2$; and a condensation particle counter (CPC) (TSI, CPC 3776) was used to continuously measure number concentrations of submicrometer aerosols in the background air. Concurrently, number concentrations of submicron aerosols in background air were measured using a fast mobility particle spectrometer (FMPS) (TSI, FMPS 3091).

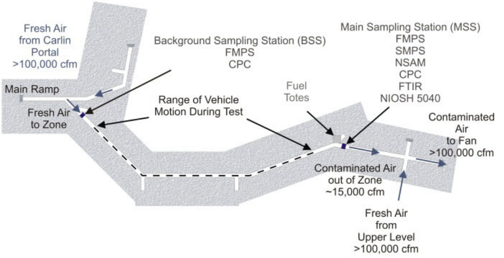


Figure 1. Layout of isolated zone.

Triplicates of background DPM samples for EC, OC, and TC analysis were collected on DPM cassettes (SKC, Eighty Four, PA) using a standard compliance sampling train and procedure [30 CFR 57.5060].

The MSS was established at the downstream end of the isolated zone (see Figure 1). The MSS was located approximately 30 m (98 ft) downstream of the downstream vehicle turning point. A portable Fourier Transform Infrared (FTIR) analyzer (Gasmet, DX4000-SYS) was used to measure the concentrations of CO, $CO_2$, NO, $NO_2$, $NH_3$ and several other gases in the air at the MSS. A CPC (TSI, CPC 3776) was used to measure number concentrations of aerosols at the MS. Due to high aerosol concentrations, it was necessary to use a rotating disk diluter (Matter Engineering, MD19-2E) to reduce aerosol concentrations at the inlet to the CPC below $3\times10^5$ particles/cm³. The number concentrations of the submicrometer aerosols were measured using an FMPS (TSI, FMPS 3091) and a scanning mobility particle size (SMPS) spectrometer (TSI, SMPS 3936). DPM samples for the carbon analysis were collected in triplicate at the MSS using a methodology identical to the one used to collect background DPM samples for the carbon analysis.

At the BSS, all sampling and measurements were performed from a single point centrally located in the drift. At the MSS, in order to minimize the effects of thermal stratification, the measurements were performed using sampling ports located on a metal structure that was rotated in the vertical plane around a centrally located point in the drift. A geared motor was used to revolve the structure on a 1-meter-long arm at a radial speed of 1 rpm.

A carbon analysis was performed by the NIOSH laboratory using the thermal optical transmittance-evolve gas analysis (TOT-EGA) known as NIOSH Method 5040 [NIOSH 1999].

In addition to ambient measurements, concentrations of CO, $CO_2$, NO, and $NO_2$ were measured in the exhaust upstream and downstream of the exhaust aftertreatment systems using a SEMTECH DS mobile emissions analyzer (Sensors Inc., Saline, MI). This portable emissions measurement analyzer system uses a non-dispersive infrared (NDIR) analyzer to measure CO and $CO_2$ concentrations and a non-dispersive ultraviolet (NDUV) analyzer to measure NO and $NO_2$ concentrations [Sensors 2011].

# 3 Results

## 3.1 Background Gas and Aerosol Concentrations

The analysis of the results of the total aerosol number concentration measurements performed with CPCs at the BSS and the MSS showed that the contribution of background aerosol to the total aerosol concentrations was minor. In a few instances, occasional traffic at the Carlin ramp resulted in elevated background aerosol concentrations. For two tests involving the Tier 4i engine, and for the Tier 3/DPF test, the background concentrations contributed less than one percent to the total concentrations measured at the MS. In the case of the Tier 3 / DOC test, the background concentrations contributed an average of two percent of the total concentrations at the MSS.

The TOT-EGA analysis of DPM samples collected at the BSS and MSS confirmed that the contribution of background air to the total EC, OC, and TC concentrations at the MSS was minor.

## 3.2 Concentrations of $CO_2$

The results of the continuous measurement of $CO_2$ concentrations emitted by test engines (NDIR) as well as $CO_2$ concentrations in mine air at the MSS (FTIR) were used to assess test-to-test variability in the engine performance and test-to-test variability in the ventilation rates. The analysis of data showed that the differences in the average $CO_2$ concentrations in the exhaust and in mine air were minor for tests involving the same vehicle/engine. However, the $CO_2$ concentrations were measurably higher for tests involving the Tier 4i engine than for tests involving the Tier 3 engine (Figure 2). Higher $CO_2$ concentrations indicated that the fuel consumption of the Tier 4i engine was higher than that of the Tier 3 engine.

The averages of $CO_2$ concentrations in the exhaust of the Tier 4i engine measured by the NDIR downstream of the SCR system and in the exhaust of the Tier 3 engine downstream of the DOC and DPF, and the average $CO_2$ concentrations in mine air at the MSS measured by the FTIR, were used to calculate the average dilution rates (DR) for the tests (Table 2). Calculated DRs were used to calculate DR normalization factors (Table 2). These factors were used to normalize all measured aerosol and gas concentrations to the average ventilation conditions observed during the Tier4i / FF SCR test.

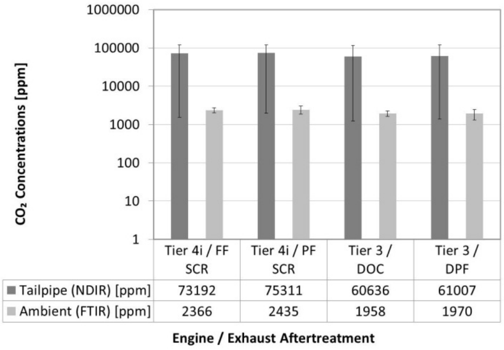


Figure 2. Average $CO_2$ concentrations in the exhaust systems of tested engines (NDIR) and in air at the MSS (FTIR).

## 3.3 Concentrations of CO, NO, $NO_2$, and $NH_3$

The CO, NO, and $NO_2$ concentrations were measured in the exhaust of tested vehicles upstream and downstream of the aftertreatment devices using a SEMTECH DS (NDIR and NDUV). The CO, NO, and $NO_2$ concentrations in mine air at the MSS were measured concurrently using an FTIR analyzer. Continuous data were used to calculate time weighted average concentrations (Figure 3, Figure 4, and Figure 5). The positive error bars shown on top of the average values represent the difference between the maximum observed value and the calculated average. The negative error bars represent the difference between the calculated average and the minimum observed values.

Table 2. Average dilution rate (DR) and DR normalization factors.

| Test | DR | DR Normalization Factors |
|---|---|---|
| Tier 4i / FF SCR | 30.7 | 1.00 |
| Tier 4i / PF SCR | 31.3 | 1.02 |
| Tier 3 / DOC | 24.5 | 0.78 |
| Tier 3 / DPF | 20.7 | 0.82 |

The analysis of the average engine-out CO concentrations showed that the Tier 4i emitted substantially more CO than the Tier 3 engine (Figure 3). This information can be partially attributed to the intermittent high peak concentrations reaching up to 40000 ppm. Despite approximately a 45 percent reduction in CO concentrations by a catalyst in the SCR, the average SCR-out CO emissions for the Tier 4i engine were still higher than the average DOC-out CO emissions for the Tier 3 engine. It is important to note that the tested DOC provided very modest reductions in CO emitted by the Tier 3 engine. These results indicate that the catalyst in the DOC was probably almost completely deactivated at the time of the study. On the contrary, the catalyzed DPF system was found to be very effective at reducing CO concentrations emitted by the Tier 3 engine. On average, those reductions were found to be approximately 82 percent. The results of CO exhaust measurements were corroborated by the results of ambient measurements performed with an FTIR. The DEF injection was found to have adverse effects on CO concentrations in air at the MSS (Figure 3b).

The comparison of the results of NO concentration measurements in the exhaust (Figure 4a) showed that the engine-out NO emissions were substantially higher for the Tier 4i than for the Tier 3 engine. However, the SCR system was found to be very effective at reducing NO emissions over the test cycle. The average efficiency for the SCR system over the observed cycle was calculated to be approximately 90 percent. The DOC and DPF had minor effects on the concentrations of NO emitted by the Tier 3 engine (Figure 4a). Of all the test cases, the Tier 4i / FF SCR emitted by far the lowest concentrations of NO (Figure 4a).

According to results of the FTIR measurements, the SCR system rendered the concentrations of NO in ambient air at the MSS to almost undetectable levels (Figure 4b). The concentrations of NO in mine air were found to be much higher when the Tier 3 engine powered vehicle was equipped with the DOC or DPF than when the Tier 4i engine powered vehicle with the FF SCR was tested. The highest concentrations of NO in the air at the MSS were observed when the Tier 4i engine was operated without DEF injection (Figure 4b).

The engine-out $NO_2$ concentrations were found to be substantially higher for the Tier 4i than for the Tier 3 engine (Figure 5a). For the Tier 4i engine, the average SCR-out $NO_2$ concentrations were 36 percent lower than the average engine-out $NO_2$ concentrations. However, in a number of the instances, the peak SCR-out $NO_2$ concentrations were several times higher than the peak engine-out $NO_2$ concentrations. On average, the SCR-out $NO_2$ concentrations for the Tier 4i engine were measurably higher than the DOC-out and DPF-out $NO_2$ concentrations for the Tier 3 engine (Figure 5a). Evidently, under prevailing conditions, the FF SCR system was much more efficient at removing NO than $NO_2$ from the exhaust of the Tier 4i engine (Figure 6). For the Tier 3 engine, the average DOC-out $NO_2$ concentrations were 52 percent lower than the average engine-out $NO_2$ concentrations. These results corroborate the hypothesis on deactivation of the catalyst in the tested DOC discussed in the paragraph on the results of CO measurements. The average DPF-out $NO_2$ concentrations were 73 percent lower than the average $NO_2$ concentrations emitted by the Tier 3 engine.

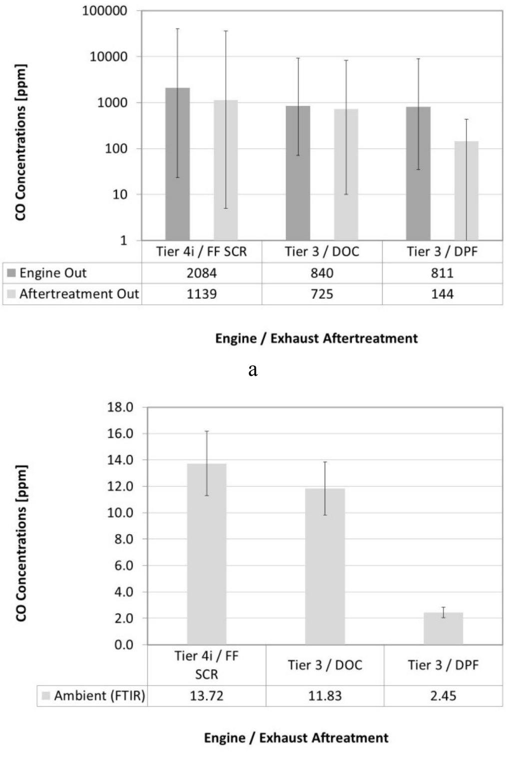
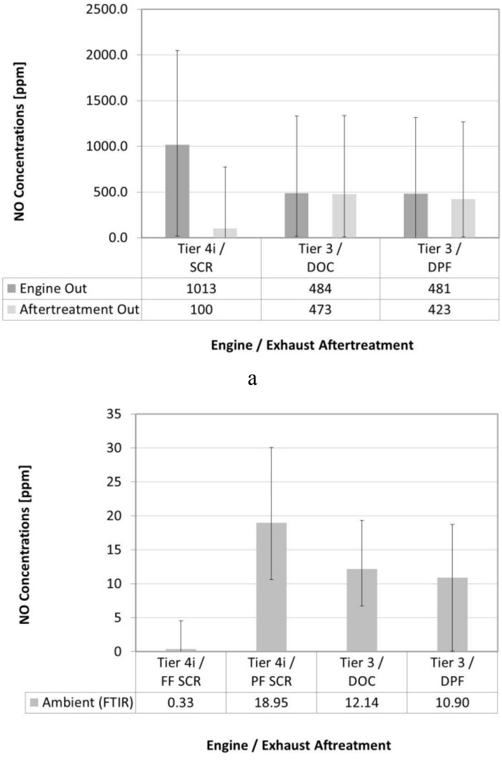


Figure 3. Average CO concentrations: (a) in exhaust and (b) in air at the MSS.

The failure of the system to inject DEF resulted in exceptionally high $NO_2$ concentrations at the MSS (Figure 5b). Apparently, under prevailing test conditions, the pre-catalyst in the SCR system was quite effective at oxidizing NO to $NO_2$ but, in the absence of DEF injection the SCR system, it was not able to efficiently reduce NO and $NO_2$ to N.

The makeup of engine-out $NO_X$ is similar for the Tier 4i and Tier 3 engines (Figure 6). However, for the Tier 4i engine, the average percentage of $NO_2$ in $NO_X$ was substantially higher downstream than upstream of the SCR system (Figure 6). At a number of instances during the Tier 4i / FF SCR test, the majority of $NO_X$ measured downstream of the SCR was made up of $NO_2$ (Figure 6). For the Tier 3 engine, the average percentage of $NO_2$ in $NO_X$ out of the DOC and DPF was lower than the corresponding engine-out percentages of $NO_2$ in $NO_X$ (Figure 6).

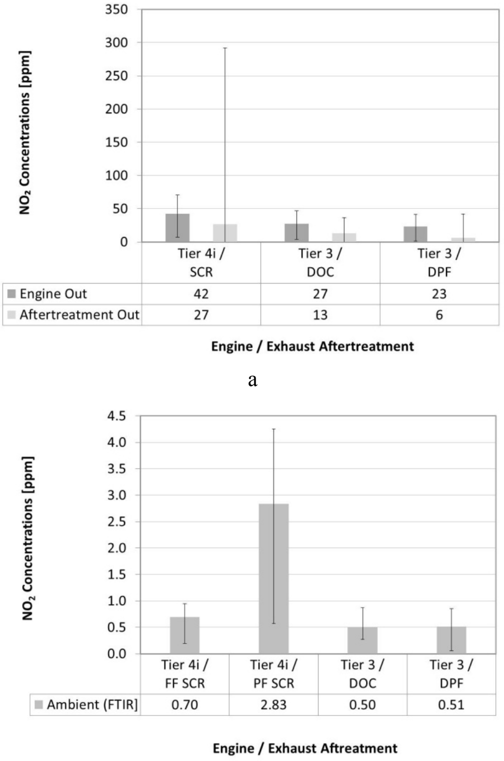


a

b

Figure 4. Average NO concentrations: (a) in exhaust and (b) in air at the MSS.

For all tests, the concentrations of $NH_3$ at the MSS (FTIR) were found to be below 0.8 ppm. The $NH_3$ concentrations during the Tier 4i / FF SCR test were comparable to those during the Tier 3 / DPF test and somewhat higher than those during the Tier 3 / DOC test. On average, the $NH_3$ concentrations were 600 percent higher during the Tier 4i / FF SCR test than during the Tier 4i / PF SCR test.



a

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Figure 5. Average $NO_2$ concentrations: (a) in exhaust and (b) in air at the MSS.

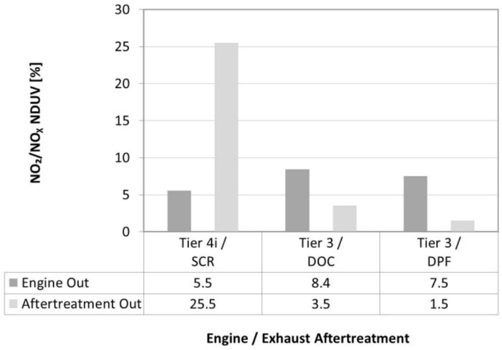
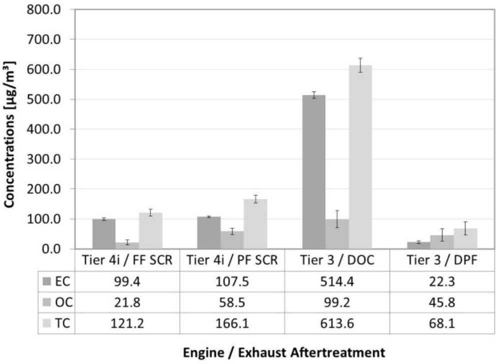


Figure 6. Average percentage of $NO_2$ in $NO_X$.

### 3.4 Concentrations of EC, OC, and TC

The carbon analysis showed that the Tier 4i engine contributed substantially less to the concentrations of EC, OC, and TC than the Tier 3 engine retrofitted by the DOC (Figure 7). However, in general, the Tier 4i engine contributed more than the Tier 3 engine retrofitted with the DPF system to the EC and TC concentrations but less to OC concentrations. The Tier 4i engine with a PF SCR system contributed eight percent more to EC concentrations, 169 percent more to OC concentrations, and 37 percent more to TC concentrations than the same engine with a FF SCR system (Figure 7).



|  | Tier 4i / FF SCR | Tier 4i / PF SCR | Tier 3 / DOC | Tier 3 / DPF |
|---|---|---|---|---|
| EC | 99.4 | 107.5 | 514.4 | 22.3 |
| OC | 21.8 | 58.5 | 99.2 | 45.8 |
| TC | 121.2 | 166.1 | 613.6 | 68.1 |

Figure 7. EC, OC, and TC concentrations at the MSS.

### 3.5 Total Number Concentrations of Aerosols

The results of continuous measurements with the FMPS (one measurement per second from the rotating platform) and the SMPS (one measurement per 120 seconds from a fixed location in the center of the drift) (Figure 8) were used to calculate the average contributions of the tested systems to the total aerosol concentrations (Figure 9). Although direct comparison of the FMPS and SMPS results is not possible due to differences in the methods of measurement, the qualitative agreement of both results is apparent (Figure 8 and Figure 9).

The aerosol concentrations in mine air were found to be lower for the Tier 4i engine than for the Tier 3 engine equipped with the DOC, but higher than those generated by the Tier 3 engine retrofitted with the DPF system (Figure 8 and Figure 9). The average concentrations generated by the Tier 4i engine were found to be 24.6 percent (FMPS) and 22.6 percent (SMPS) higher for the PF SCR system than for the FF SCR system.

## 4 Summary

Under prevailing test conditions, the Tier 4i engine was found to contribute less than the Tier 3 engine retrofitted with the DOC to the concentrations of NO, EC, OC, TC, and total number concentrations of aerosols; but more to the concentrations of CO, $NO_2$, and $NH_3$. However, the Tier 4i engine contributed more than the Tier 3 engine equipped with the DPF to the concentrations of CO, $NO_2$, EC, TC, and total number concentrations of aerosols, less to the concentrations of NO and OC, and equally to $NH_3$ concentrations. Therefore, in certain applications, the Tier 4i engines with SCR systems might prove to be a viable technology for helping the underground mining industry comply with regulations limiting the exposure of underground metal/nonmetal miners to DPM [30 CFR 57.5060].

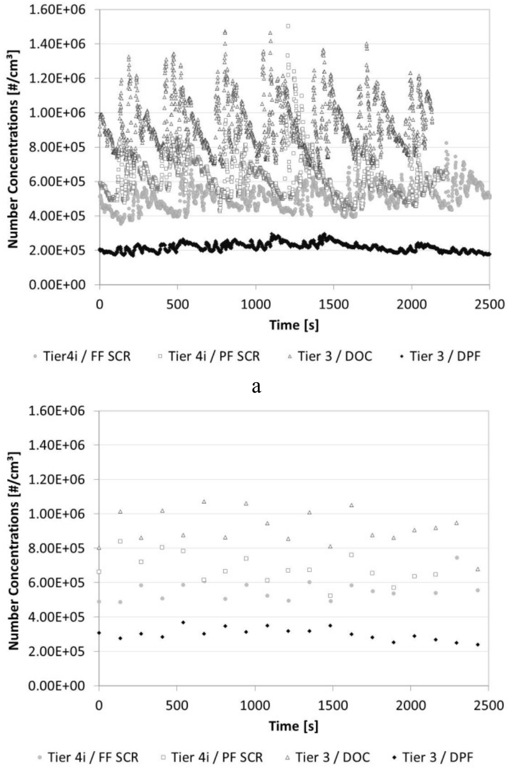


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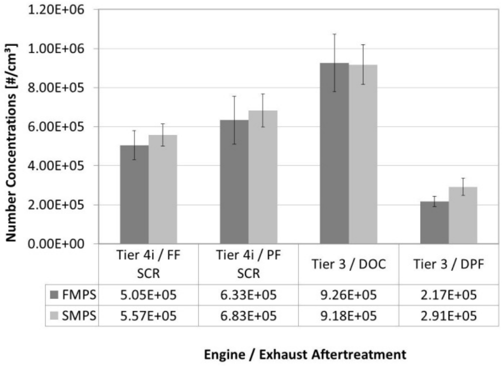
Figure 8. Number concentrations of aerosols at the MSS: (a) FMPS, and (b) SMPS.



|  | Tier 4i / FF SCR | Tier 4i / PF SCR | Tier 3 / DOC | Tier 3 / DPF |
|---|---|---|---|---|
| FMPS | 5.05E+05 | 6.33E+05 | 9.26E+05 | 2.17E+05 |
| SMPS | 5.57E+05 | 6.83E+05 | 9.18E+05 | 2.91E+05 |

Figure 9. Number concentrations of aerosols at the MSS.

It is important to note that the reduction in DPM emissions from this particular Tier 4i engine was achieved internally to the engine and does not depend on the use of DPF system. Implementing the Tier 4i engines with SCR systems would require establishing procedures for managing the supply of DEF. Special precautions should be taken to avoid potential problems associated with the overexposure of underground miners to NO and $NO_2$ due to the failure of these systems to inject DEF. The failure of the system tested in this study to inject DEF resulted in the four fold increase in $NO_2$ concentrations in mine air.

## 5 Acknowledgement

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## 6 Disclaimer

The findings and conclusions of this publication are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

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