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Aerosols and Criteria Gases in an Underground Mine That Uses FAME Biodiesel Blends

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Abstract

The contribution of heavy-duty haulage trucks to the concentrations of aerosols and criteria gases in underground mine air and the physical properties of those aerosols were assessed for three fuel blends made with fatty acid methyl esters biodiesel and petroleum-based ultra-low-sulfur diesel (ULSD). The contributions of blends with 20, 50, and 57% of biodiesel as well as neat ULSD were assessed using a 30-ton truck operated over a simulated production cycle in an isolated zone of an operating underground metal mine. When fueled with the B20 (blend of biodiesel with ULSD with 20% of biodiesel content), B50 (blend of biodiesel with ULSD with 50% of biodiesel content), and B57 (blend of biodiesel with ULSD with 57% of biodiesel content) blends in place of ULSD, the truck's contribution to mass concentrations of elemental and total carbon was reduced by 20, 50, and 61%, respectively. Size distribution measurements showed that the aerosols produced by the engine fueled with these blends were characterized by smaller median electrical mobility diameter and lower peak concentrations than the aerosols produced by the same engine fueled with ULSD. The use of the blends resulted in number concentrations of aerosols that were 13–29% lower than those when ULSD was used. Depending on the content of biodiesel in the blends, the average reductions in the surface area concentrations of aerosol which could be deposited in the alveolar region of the lung (as measured by a nanoparticle surface area monitor) ranged between 6 and 37%. The use of blends also resulted in slight but measurable reductions in CO emissions, as well as an increase in NO_X emissions. All of the above changes in concentrations and physical properties were found to be correlated with the proportion of biodiesel in the blends.

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SUPPLEMENTARY DATA

Supplementary data can be found at http://annhyg.oxfordjournals.org/.

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Keywords

alternative fuels; diesel aerosols; FAME biodiesel; nitrogen oxides; number concentrations; size distributions; underground mining

INTRODUCTION

Changing the fuel supply from petroleum diesel to neat or blended biodiesel is considered by a number of underground metal and nonmetal mine operators in the USA to be a viable method for controlling diesel particulate matter (DPM) emissions (Tomko *et al.*, 2010) and complying with current US Mine Safety and Health Administration (MSHA) regulations that limit the exposure of underground metal/nonmetal mines to DPM (30 CFR 57.5060). Currently, underground mines in the USA using biodiesel fuels are exclusively using fatty acid methyl ester (FAME) biodiesels, which are made from various vegetable oils and animal fats through the process of transesterifcation (Graboski and McCormick, 1998).

The effects of FAME biodiesel and FAME biodiesel blends with petroleum diesel on regulated and non-regulated emissions from heavy-duty diesel engines have been previously extensive evaluated in the laboratory (Tsolakis, 2006; Mueller *et al.*, 2009; Tsai *et al.*, 2010; Hajbabaei *et al.*, 2012) and in on-road environments (Durbin *et al.*, 2007; Walkowicz *et al.*, 2009). Very few studies were conducted in occupational settings to examine impact of those fuels on quality of air and risks associated with exposure of workers to aerosols and gases emitted by in-use diesel-powered vehicles (National Institute for Occupational Safety and Health [NIOSH], 2006a,b; Bugarski *et al.*, 2010; Traviss *et al.*, 2010).

When compared to low-sulfur and ultra-low-sulfur petroleum diesels (LSD and ULSD), FAME biodiesels reduce emissions of total DPM and nonvolatile fractions of DPM (Williams *et al.*, 2006; Yuan *et al.*, 2007; Sappok and Wong, 2008; Bugarski *et al.*, 2010) and, under certain engine operating conditions, can increase the particle-bound volatile organic fraction of DPM (Purcell *et al.*, 1996; Stackpole, 2009; Bugarski *et al.*, 2010).

In-use studies have shown the potential of neat soy methyl ester (SME) FAME (McDonald *et al.*, 1997; Bugarski *et al.*, 2010) and SME biodiesel blends (NIOSH, 2006a,b; Bugarski *et al.*, 2010) to reduce the exposures of underground miners to elemental carbon (EC), total carbon (TC), and total DPM. The relatively low particulate mass emissions of FAME biodiesel fuels have been attributed to certain properties of these fuels such as the presence of fuel-bound oxygen, increased Cetane number, and increased flame temperature (less soot-radiative heat transfer) (Schönborn *et al.*, 2009). Substantial increases in emissions of the organic carbon (OC) fractions of DPM were observed when the engine was fueled with SME FAME fuels and operated at light-load conditions (McDonald *et al.*, 1995; Schönborn *et al.*, 2009; Bugarski *et al.*, 2010). At these conditions, during the late stages of the expansion stroke when temperatures in the cylinder drop below the boiling point of the fuel, the unburned fuel condenses into nucleation mode particles primarily composed of OC (Schönborn *et al.*, 2009).

Several researchers have studied the impact of rapeseed methyl ester (RME) (Tsolakis, 2006) and SME (Jung *et al.*, 2006; Chung *et al.*, 2008; Bugarski *et al.*, 2010) FAME fuels on the size distribution of aerosols emitted by diesel engines. Relative to ULSD, FAME fuels produced smaller particles (Jung *et al.*, 2006; Tsolakis, 2006; Bugarski *et al.*, 2010). Increases in the concentration of nucleation mode aerosols and reductions in the concentration of accumulation mode aerosols relative to LSD (Jung *et al.*, 2006) and ULSD (Chung *et al.*, 2008; Zhu *et al.*, 2010) were also reported. However, this increase in nucleation particles was not observed for the conditions in an underground mine environment (Bugarski *et al.*, 2010).

A number of studies found a relatively modest increase in emissions of nitrogen oxides (NO_X = NO + NO_2) associated with the use of biodiesel in place of ULSD (Monyem and Van Gerpen, 2001; Tsolakis, 2006; Durbin *et al.*, 2007; Kawano *et al.*, 2007; Verbeek *et al.*, 2009; Hajbabaei *et al.*, 2012; Hoekman and Robbins, 2012). The differences in chemical composition (e.g. oxygen content) and physical properties (e.g. bulk modulus of compressibility, Cetane number) between biodiesel and petroleum-based fuels were found to affect a number of complex coupled mechanisms controlling combustion behavior of those fuels (Kawano *et al.*, 2007; Mueller *et al.*, 2009; Schönborn *et al.*, 2009; Bittle *et al.*, 2010; Hoekman and Robbins, 2012). FAME biodiesel was shown to reduce CO and hydrocarbon (HC) emissions (Monyem and Van Gerpen, 2001; Yuan *et al.*, 2007; Cheung *et al.*, 2009). These reductions in CO and HC emissions were explained primarily by the presence of fuel-bound oxygen in the biodiesel (Schönborn *et al.*, 2009).

Additionally, RME and SME FAME biofuels have been found to reduce total monocyclic aromatic hydrocarbons (MAHs), polycyclic aromatic hydrocarbons (PAHs), and benzo(a)pyrene equivalent emissions (Correa and Arbilla, 2006; Yuan *et al.*, 2007; Verbeek *et al.*, 2009). The biodiesel fuels were reported to have both favorable (Ratcliff *et al.*, 2010; Traviss *et al.*, 2010) and adverse (Cheung *et al.*, 2009; Liu *et al.*, 2009; Karavalakis *et al.*, 2010) effects on carbonyl emissions. The impact of FAME on the emissions of individual MAHs and PAHs is not clear, however. Lower emissions of unburned HCs are generally attributed to a higher ignition quality of FAME fuels (Schönborn *et al.*, 2009).

Limited information is available on the effects of FAME emissions on health (McCormick, 2007; Swanson *et al.*, 2007). Aerosols generated by engines operated on biodiesel are not necessarily less toxic than those generated by the same engine operated on ULSD (Liu *et al.*, 2009; Verbeek *et al.*, 2009). In one study, B100 (neat FAME biodiesel fuel) RME FAME was found to produce a significant increase in cytotoxicity and mutagenicity/genotoxicity and a reduction in oxidative stress potential (Verbeek *et al.*, 2009). Liu *et al.* (2009) showed that an engine without a diesel oxidation catalytic converter (DOC) produced emissions with higher acute toxicity and cytotoxicity when fueled with 10% RME FAME biodiesel blend rather than ULSD fuel. A study by Yanamala *et al.* (2013) showed elevated magnitude of phagocytic immune cell responses, higher lung permeability, higher pulmonary cytotoxicity, and elevated inflammatory response when the mice were exposed to B100 aerosols rather than to ULSD aerosols.

The potential increase in OC emissions due to the use of biodiesel is commonly counteracted by DOCs. Those were shown to be effective in controlling the emissions of organic compounds emitted by the mining engines operated on FAME blends (Bagley *et al.*, 1998; Stackpole, 2009). Jalava *et al.* (2010) showed that DOC decreased oxidative potential of diesel particulate samples generated by nonroad diesel engine operated with RME fuel. However, the effects of DOCs on OC emissions depend upon the catalyst formulation, fuel formulation, and the engine operating conditions. Some DOCs were shown to be effective in reducing the number and mass concentrations of aerosol emitted by engines fueled with SME FAME fuel (Bugarski *et al.*, 2010). For these reasons, the use of a DOC is an excellent control strategy for reducing OC exposures at light-load conditions, when higher concentrations of OC are emitted. The drawback of using a DOC to control OC emissions is the potential for an increase in NO_2 emissions, particularly at high-load conditions (Bagley *et al.*, 1998; Stackpole, 2009; Bugarski *et al.*, 2010).

The effects of FAME biodiesel fuels on diesel engine emissions are not consistent over the range of possible applications. These effects have been found to vary widely with FAME type, usage conditions, and engine type and age (Durbin *et al.*, 2007; Bugarski *et al.*, 2010). Some engine technologies are more responsive to the biodiesel blends than others (Durbin *et al.*, 2007). In addition, engine operating conditions play a major role in defining the characteristics of the emissions when using FAME fuels as a control strategy (Bugarski *et al.*, 2010).

The primary objective of the study described in this manuscript was to investigate the effects that three fuel blends produced from FAME biodiesel and petroleum-based ULSD have on the physical properties and overall concentrations of aerosols exhausted in a production-like setting in the underground mine. Additional efforts were made to assess the effects of tested fuels on the in-use gaseous emissions. The experimental part of the study was designed to compromise between the genuineness of *in situ* measurements of contributions of the vehicle to concentrations of submicron aerosols and the repeatability and accuracy of the emission measurements obtained under research laboratory conditions. The intention was to complement already available knowledge gained on FAME biodiesel through numerous emissions laboratory studies with information needed to advance the efforts on reducing workers exposure to diesel pollutants. In order to accomplish this, the effects of FAME biodiesel were studied on the results of testing performed with a haulage truck (powered by a late model heavy-duty diesel engine) that was operated over a simulated heavy-duty transient production cycle in an isolated section of a working underground mine. The effects of the blends were then compared with the corresponding effects of ULSD fuel. The results of this study should help the industry to understand benefits and limitations of biodiesel as strategy used to curtail exposure of underground miners to diesel aerosols and gases.

MATERIAL AND METHODS

Vehicle and fuels

The testing took place in the Newmont USA Ltd Leeville underground mining operation close to Carlin, NV, USA. At the time of the study, the host mine was using 50% FAME biodiesel blend to fuel its entire fleet of diesel-powered underground heavy- and light-duty

engines. The test vehicle used in this study, a 30-ton haulage truck, was powered by a 6-cylinder liquid-cooled, turbocharged, and electronically controlled EPA Tier 3 nonroad engine. The engine was equipped with a DOC and a closed crankcase ventilation system.

The biodiesel fuels evaluated in this study were blended using B100 supplied by the Renewable Energy Group (REG9000-10; Ames, IA, USA) and petroleum-based ULSD supplied by Thomas Petroleum (Carlin, NV, USA). The primary source of the oils for the biodiesel was soy. Blends with 20% (B20), 50% (B50), and 57% (B57) of biodiesel content were evaluated. Supplementary Table S1 in Supplementary Material, available at *Annals of Occupational Hygiene* online, summarizes the results of a fuel property analysis performed on these test fuels by Bentley Tribology Services (Minden, NV, USA).

Isolated zone and vehicle duty cycle

The contribution of the test engine to the concentration of aerosols and criteria gases in the mine air was assessed under simulated production conditions using an isolated zone methodology (NIOSH, 2006a,b). The test zone (Fig. 1) was established in a development drift situated ~1500 m above sea level. The zone was selected, so that the contribution from other diesel-powered vehicles concurrently operated in the mine was absent or minimized in intensity and duration. The only source of aerosols and gasses was the tested vehicle.

For all tests, a single, experienced worker operated the truck within a 200-m-long section of the main drift (Fig. 1). During all of the tests, the truck bed was loaded with ~30 tons of ore. The vehicle was operated over a series of repetitions of a 300-s duty cycle which was developed specifically for this study (Supplementary Figure S1, available at *Annals of Occupational Hygiene* online).

Measurement, sampling, and analysis

Due to the complex physical and chemical nature of DPM, as well as the changing nature of the aerosol or of the environment, the measurement and characterization methodology plays important role in linking DPM to health (Russell and Brunekreef, 2009; Bugarski *et al.*, 2012; Cauda *et al.*, 2012; Giechaskiel *et al.*, 2014). In this study, several metrics were used to characterize primary and secondary submicron aerosols in the underground environment directly resulting from the contributions of a diesel-powered vehicle, including potentially some of those that were non-exhaust related. The traditionally used measurements of mass concentrations of total DPM and EC were complemented with measurements of number and surface concentrations and size distribution. A large number of studies have shown that size, number, and surface area are aerosol attributes essential for assessing risk associated with exposure to nanometer and ultrafine aerosols (Donaldson *et al.*, 2005; Cauda *et al.*, 2012).

Two ambient measurement and sampling stations were established in the isolated zone: (i) the background sampling station (BSS) at the upstream end of the zone and (ii) the main sampling station (MSS) at the downstream end of the zone (Fig. 1). The BSS was located at the upstream end of the isolated zone ~20 m beyond the upstream vehicle direction changing point. The MSS was established at the downstream end of the isolated zone ~30 m beyond the downstream vehicle direction changing point. The net contribution of the test vehicle to

concentrations of aerosols and criteria gases was determined by subtracting the results of measurements performed at the BSS from the results of measurements performed at the MSS.

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

At the BSS, triplicates of background DPM samples for EC, OC, and TC analysis were collected on DPM cassettes (SKC, Eighty Four, PA, USA) using standard MSHA compliance sampling procedures as well as standard MSHA compliance sampling train components (30 CFR 57.5060). Concurrently, number concentrations and size distributions of submicron aerosols in background air were measured using a fast mobility particle spectrometer (FMPS) (FMPS 3091; TSI) (Johnson *et al.*, 2004).

An infrared analyzer (Carboncap GM70IR; Vaisala) was used to continuously measure background concentrations of CO_2; an electrochemical cell-based multi-gas monitor (iTX; Industrial Scientific) was used at the same location to continuously measure background concentrations of CO, NO, and NO_2. The ventilation flow rate at the BSS was calculated from the results of periodic measurements of air velocity across the opening using a mechanical vane anemometer (Davis Instruments, A2/4”) and a traverse method. A continuous ventilation flow rate was also estimated from the results of an air velocity measurement obtained at a single point (centrally located in a cross section of the drift and ~20 m downstream of the BSS) using an electronic vane anemometer that was recording throughout each test (Alnor RVA501; TSI).

DPM samples for carbon analysis were collected in triplicate at the MSS using a methodology identical to the one used to collect background DPM samples for carbon analysis. The number concentrations and size distributions of the submicrometer aerosols were measured using an FMPS (FMPS 3091; TSI) and a scanning mobility particle size (SMPS) spectrometer (SMPS 3936; TSI) (Wang and Flagan, 1990). Concurrently, a nanoparticle surface area monitor (NSAM) (NSAM 3550; TSI) was used to measure the surface area of aerosols which could be deposited in the alveolar region of the lungs (Fissan *et al.*, 2007; Asbach *et al.*, 2009). The concentrations of CO_2 and CO, NO, and NO_2 and ventilation flow rate at the MSS were determined using the same methodology and instrumentation used at the BSS.

Carbon analysis on DPM samples collected at the BSS and the MSS was performed using the thermal optical transmittance-evolve gas analysis (TOT-EGA) known as NIOSH Method 5040 (Birch and Cary, 1996; NIOSH, 1999).

In addition, concentrations of CO, CO_2, NO, and NO_2 were measured in the exhaust upstream and downstream of the DOC using a SEMTECH DS mobile emissions analyzer from Sensors Inc., Saline, MI, USA. The data acquisition system of the SEMTECH DS was

used to record pertinent parameters available from the engine control unit of the tested engine.

Ventilation and ambient parameters

Fresh air (from the Carlin Portal and main ramp) was pulled through the isolated zone by a fan located in an exhaust shaft downstream of the test area (Fig. 1). The same fan was pulling additional quantities of air from the upper level of the mine. These two flows merged downwind from the tested section. In order to prevent contamination of dilution air by other diesel-powered vehicles, the main ramp was closed to all traffic during the tests. The average ventilation flow rates were between 3.02 and 3.54 m^3 s^{-1}. CO_2 concentration measurements taken in the vehicle exhaust (downstream of the DOC) and in mine air (at the MSS) were used to normalize all measured aerosol and gas concentrations to the average ventilation conditions observed during the ULSD test.

The time-weighted averages for barometric pressure and ambient temperature measured on the vehicle were 83.9 ± 2.6 kPa and 27.4 ± 3.9°C. The corresponding time-weighted average ambient temperature at MSS was 20.9 ± 1.3°C.

RESULTS AND DISCUSSION

Background aerosol concentrations

The results of total aerosol number concentration measurements performed with condensation particle counters at the BSS and the MSS were used to assess the contribution of background air to the total aerosol concentrations. For all test cases, the background concentrations contributed <1% to the total time-weighted average number concentrations measured at the MSS. Since the TOT-EGA analysis for 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 negligible, the contribution from the background aerosols was not considered in the analysis.

EC, OC, and TC concentrations

The results of the TOT-EGA analysis performed on the time-integrated DPM samples collected at the MSS are shown in Fig. 2a. Those results were used to calculate changes in the concentrations from the baseline (ULSD) case (Fig. 2b). The positive and negative error bars shown on top of the average values in Fig. 2 represent the single standard deviations from the mean. The EC and TC concentrations at the MSS were substantially lower for B20, B50, and B57 blends than for ULSD (Fig. 2). 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 certain (Fig. 2). This can potentially be explained by the higher uncertainty of the OC results.

Total number concentrations of aerosols

The total aerosol number concentrations were measured with the FMPS (one measurement per second from the rotating platform) and the SMPS (one measurement per 120 s from a fixed location in the center of the drift). As shown for the ULSD and B57 tests in Fig. 3, the

combination of the effects of continuously changing engine operating conditions, the movement of the vehicle within the zone, and a number of processes controlling the formation and transformation of diesel aerosols in mine air resulted in transient and cyclic traces. The data clearly show the 300-s vehicle duty cycle. Although quantitative comparison of the FMPS and SMPS results is not possible due to differences in the measurement principles, a general agreement is still apparent (Fig. 3). The higher peak concentration values and larger value ranges that are shown in the FMPS data are explained by the increased measurement frequency and the radial movement of the FMPS sampling inlet throughout the tunnel opening.

The results of continuous measurements were used to calculate the contributions to the average total number concentrations of aerosols (Fig. 4). The error bars represent 1 SD from the respective means. According to the FMPS results, the biodiesel blends (when compared with ULSD) produced 13–29% lower number concentrations of aerosols in the air at the MSS. The SMPS measurements showed that in B20 and B57 cases number concentrations were 12 and 5%, respectively, lower than in ULSD case. In the case of B50, the concentrations were 6% higher than those for ULSD. The results did not exhibit a clear linear relationship between FAME biodiesel content in the fuels and a change in total number concentrations.

Size distribution of aerosols

The effects of the fuel type used on the aerosol size distributions were therefore examined using measurements made at selected instances throughout these cycles. 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, USA). For reasons of brevity, only the results of FMPS measurements were used in further discussion. Five of those distributions were examined for each of the tests. The example of size distributions measured for selected instances of the ULSD and B57 tests are shown in Supplementary Figure S2 in the Supplementary Material, available at *Annals of Occupational Hygiene* online.

The majority of aerosols generated by the engine for each of the tested fuels were distributed in single accumulation mode. For each of the evaluated fuels, the distributions were characterized by almost identical geometric mean electrical mobility diameters ($_{EM}D_{50}$) of accumulation mode and peak concentrations dependent on the stage of vehicle/engine duty cycle. Depending on the fuel, $_{EM}D_{50}$ of accumulation modes were between 70 and 92 nm.

The effects of fuels on $_{EM}D_{50}$ of aerosols are illustrated on the example shown in Fig. 5. In general, the size distributions of aerosols observed for the biodiesel blends were found to be characterized by smaller $_{EM}D_{50}$ and lower peak concentrations than the corresponding size distributions observed for ULSD. For B50, B20, and ULSD, the $_{EM}D_{50}$ of aerosols decreased with the amount of biodiesel in the blends. The same trend was not apparent for the blend with highest biodiesel content. The $_{EM}D_{50}$ for B57 was slightly larger than the one for B50.

Surface area concentrations measured by NSAM

The surface area concentrations (SAC) of aerosols which could be deposited in the alveolar region of the lungs were measured by NSAM at the MSS. Similar to the other measured parameters, the SAC measured by NSAM were also transient and cyclic in nature.

The effects of fuel formulations on SAC were examined on the averages calculated for each of the tests (Fig. 6). The error bars represent the standard deviation from the means. The results showed that the use of biodiesel blends produced measurable reductions in average SAC in the air at the MSS. Depending on the content of biodiesel in the blends, the average reductions ranged between 6 and 37%. However, a direct correlation between biodiesel content and changes in average SAC was not evident in the results of those measurements.

Tailpipe concentrations of CO, NO, and NO_2

The results of measurements acquired in the vehicle exhaust stream both upstream and downstream of the DOC were used to assess the effects of the DOC on CO, NO_X, NO, and NO_2 (Fig. 7). Minor reductions in CO emissions and major reductions in NO_2 concentrations indicated that, at the time of the tests, the catalyst in this vintage DOC was most likely completely deactivated. Reductions in NO_2 concentrations were, therefore, probably a result of reaction of that gas with soot deposited on the walls of the DOC.

The results of continuous measurements of CO, NO_X, NO, and NO_2 concentrations in the exhaust of the test engine downstream of the practically deactivated DOC showed that, in general, when compared to measurements made with ULSD, the biodiesel fuels reduced CO emissions and increased NO and NO_2 emissions (Fig. 8). The data for CO and NO_2 emissions in Fig. 8 demonstrate a direct correlation with biodiesel content in the blends. The relation between biodiesel content and the effects on NO emissions is not clear.

CONCLUSIONS

The effects of three fuel blends produced from FAME biodiesel and petroleum-based ULSD on aerosols and criteria gases emitted by heavy-duty diesel haulage truck equipped with a most likely deactivated DOC in underground mine air were assessed in the simulated production conditions. The use of FAME biodiesel blends in place of ULSD resulted in substantial reductions in the contribution of a truck to EC and TC mass concentrations in an underground mine environment. Those reductions were found to be correlated with changes to biodiesel content in the blends. Size distribution measurement showed that the aerosols produced by the engine fueled with those biodiesel blends were characterized by smaller $_{EM}D_{50}$ and lower peak number concentrations than the aerosols produced by the same engine fueled with ULSD. The changes in number concentrations and the SAC of aerosols that could be deposited in the alveolar region of the lungs (as measured by NSAM) were found to be relatively moderate compared to the changes in EC and TC mass concentrations. Therefore, the reductions in EC and TC mass concentrations can be primarily attributed to the changes in the size of the generated aerosols. The results emphasize necessity for use of several metrics to assess the effects of control technologies and strategies on submicron aerosols in the occupational settings.

The use of FAME blends, when compared to ULSD, also resulted in slight but measurable reductions in CO emissions and a slight increase in NO_X emissions. Both of those were found to be directly related to the content of biodiesel in the blends. The fraction of NO_2 in NO_X increased slightly with biodiesel content.

In general, the results of this study corroborate with the results of a study previously conducted by the authors in an experimental mine using a naturally aspirated mechanically controlled engine operated over steady-state conditions (Bugarski *et al.*, 2010). This study confirmed that fueling diesel-powered vehicles with neat or blended FAME biodiesel is a viable strategy for reducing DPM mass emissions. However, substantial changes in physical and chemical properties of aerosols emitted by diesel engines fueled with FAME fuels warrant further investigations on the effectiveness of this strategy in reducing health risk associated with exposure to those aerosols.

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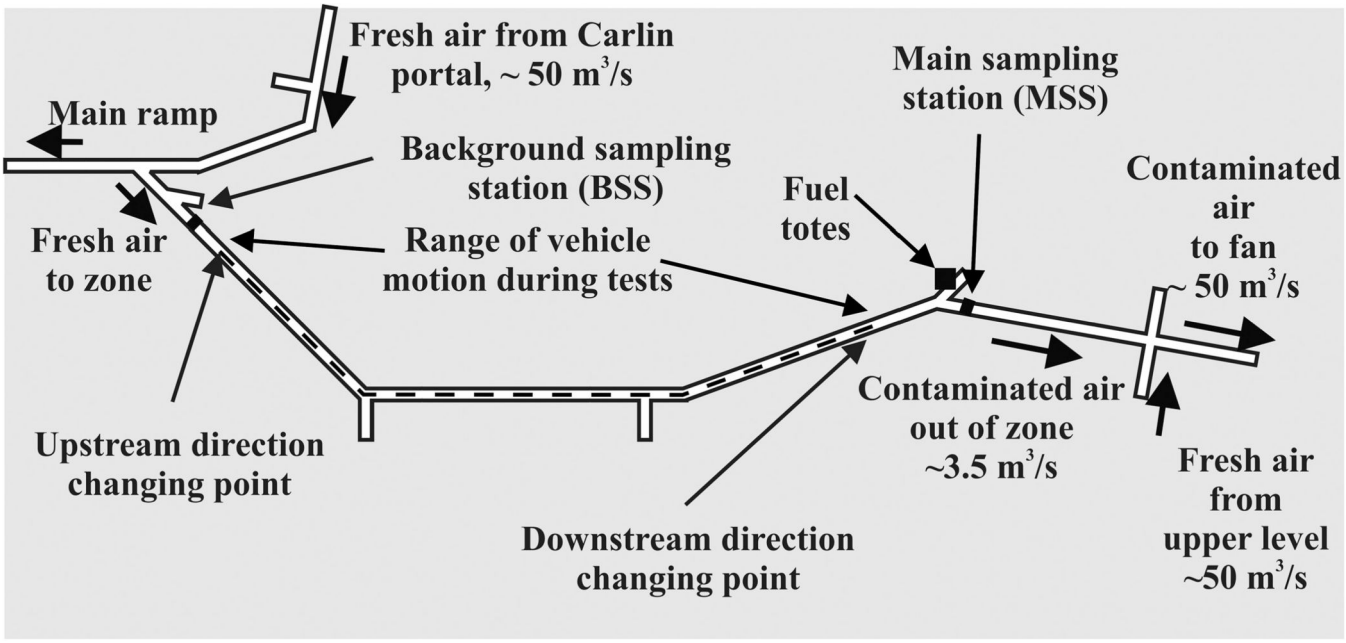
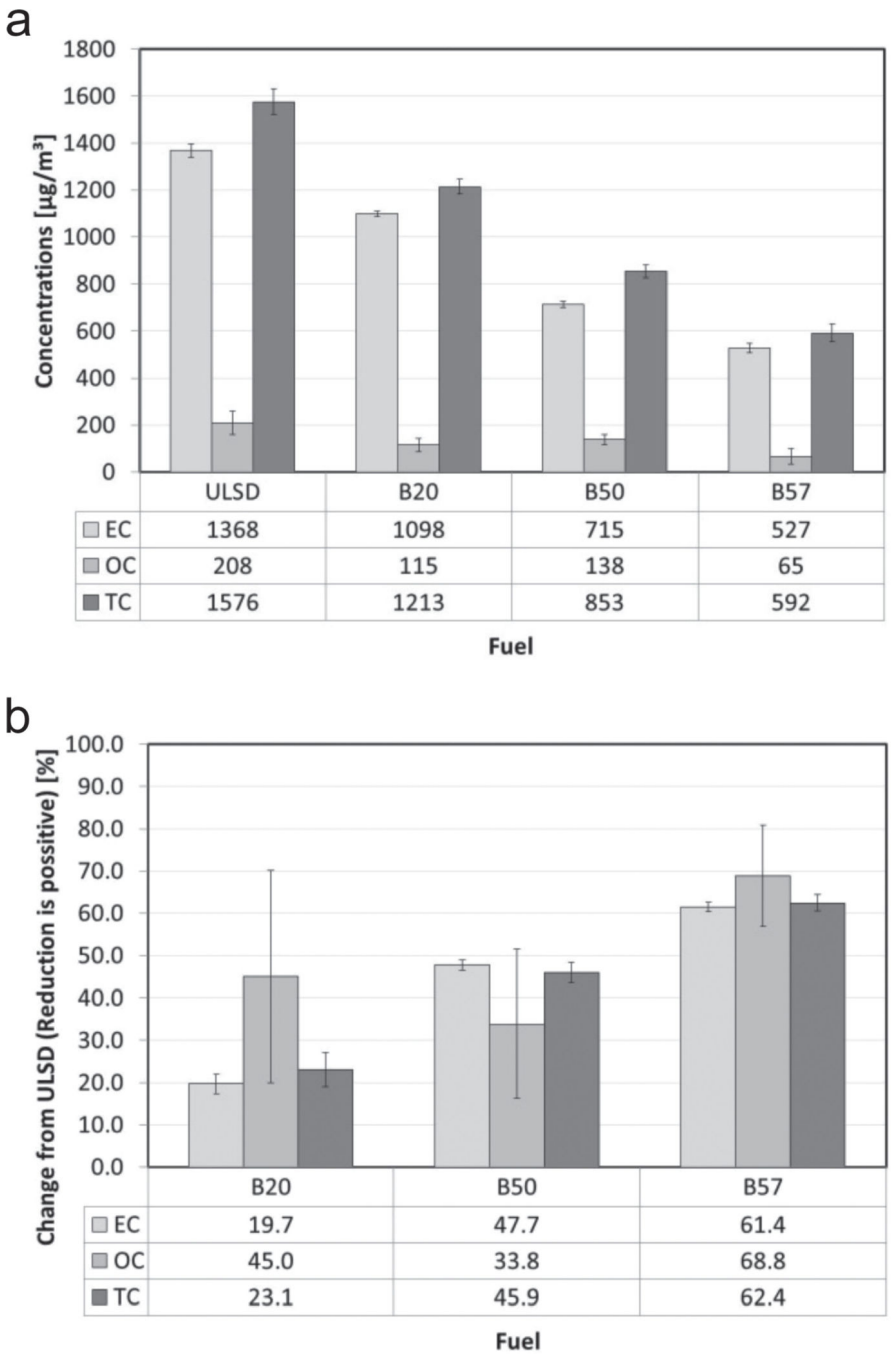
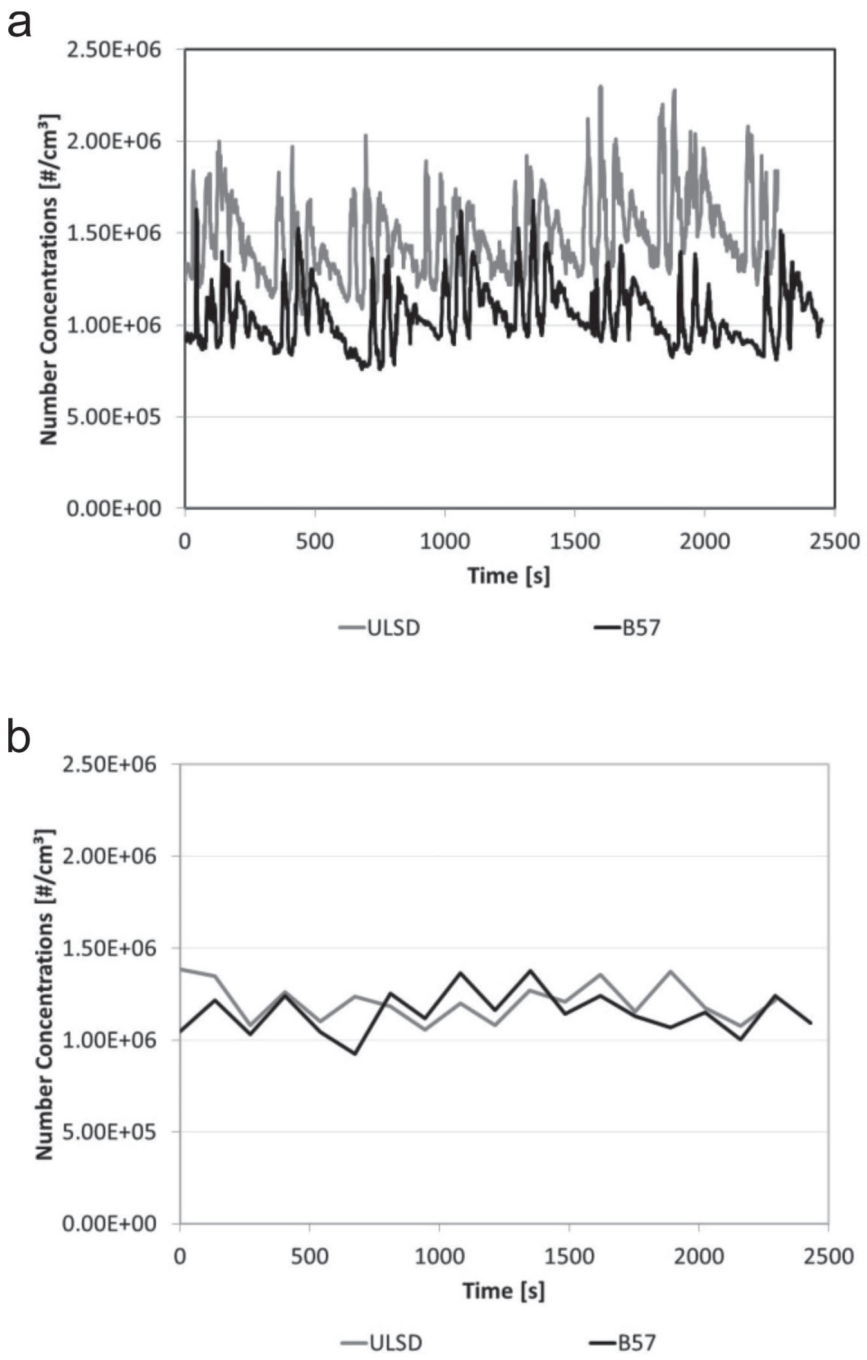


1.
Layout of isolated zone (not in scale).



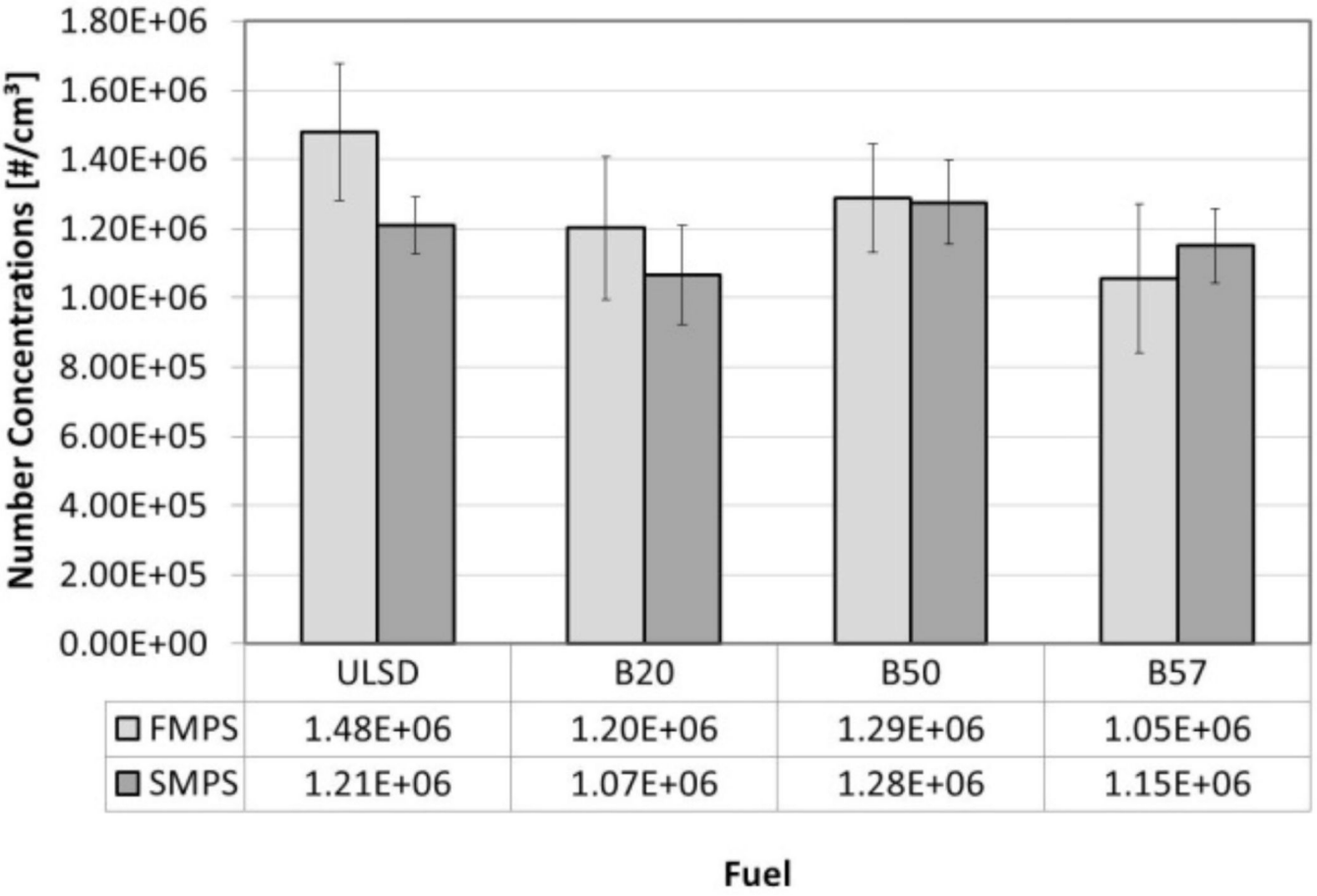
2.

EC, OC, and TC: (a) concentrations at the MSS and (b) changes in concentrations with respect to ULSD case.



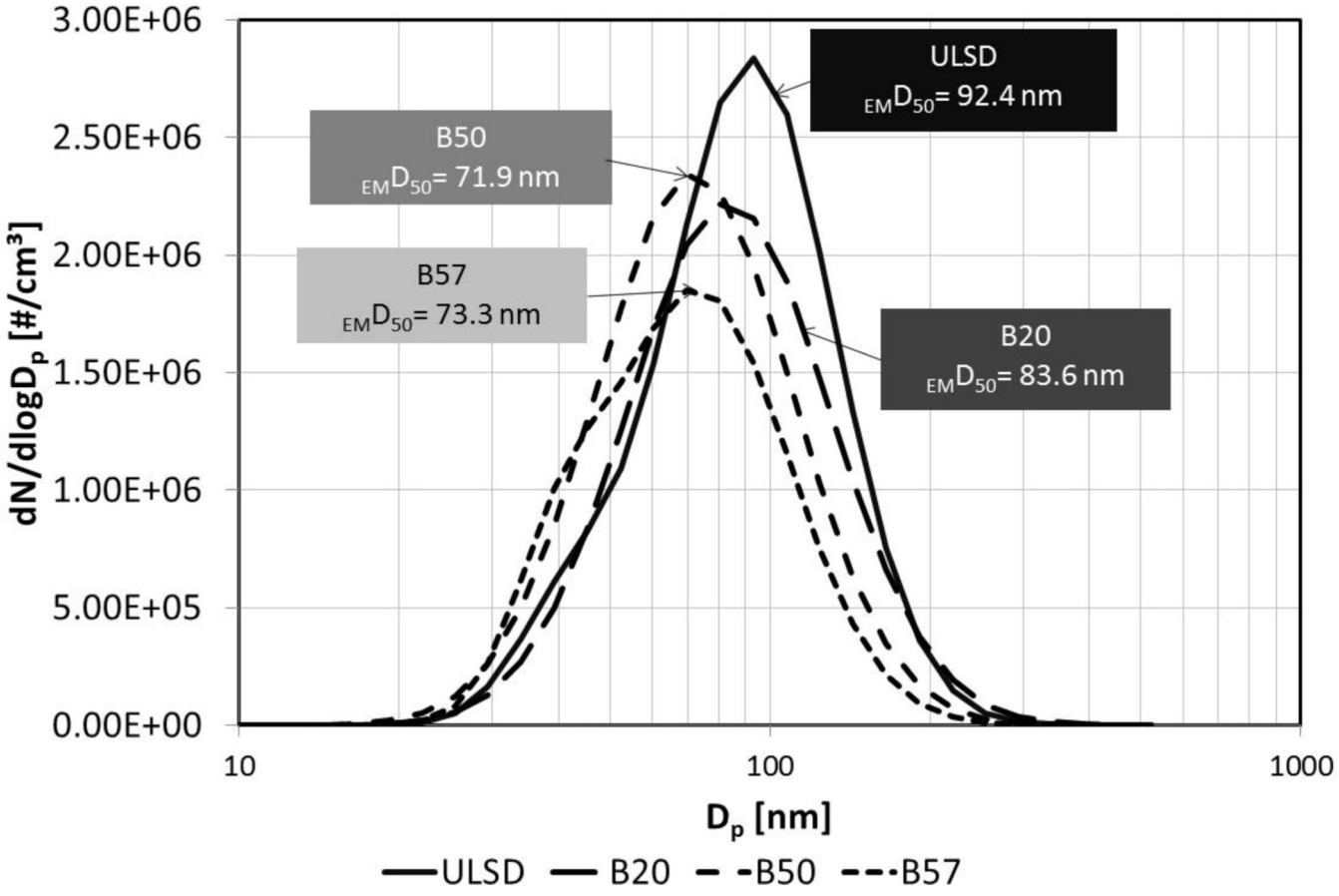
3.

Number concentrations of aerosols at the MSS for ULSD and B57 tests: (a) FMPS and (b) SMPS.



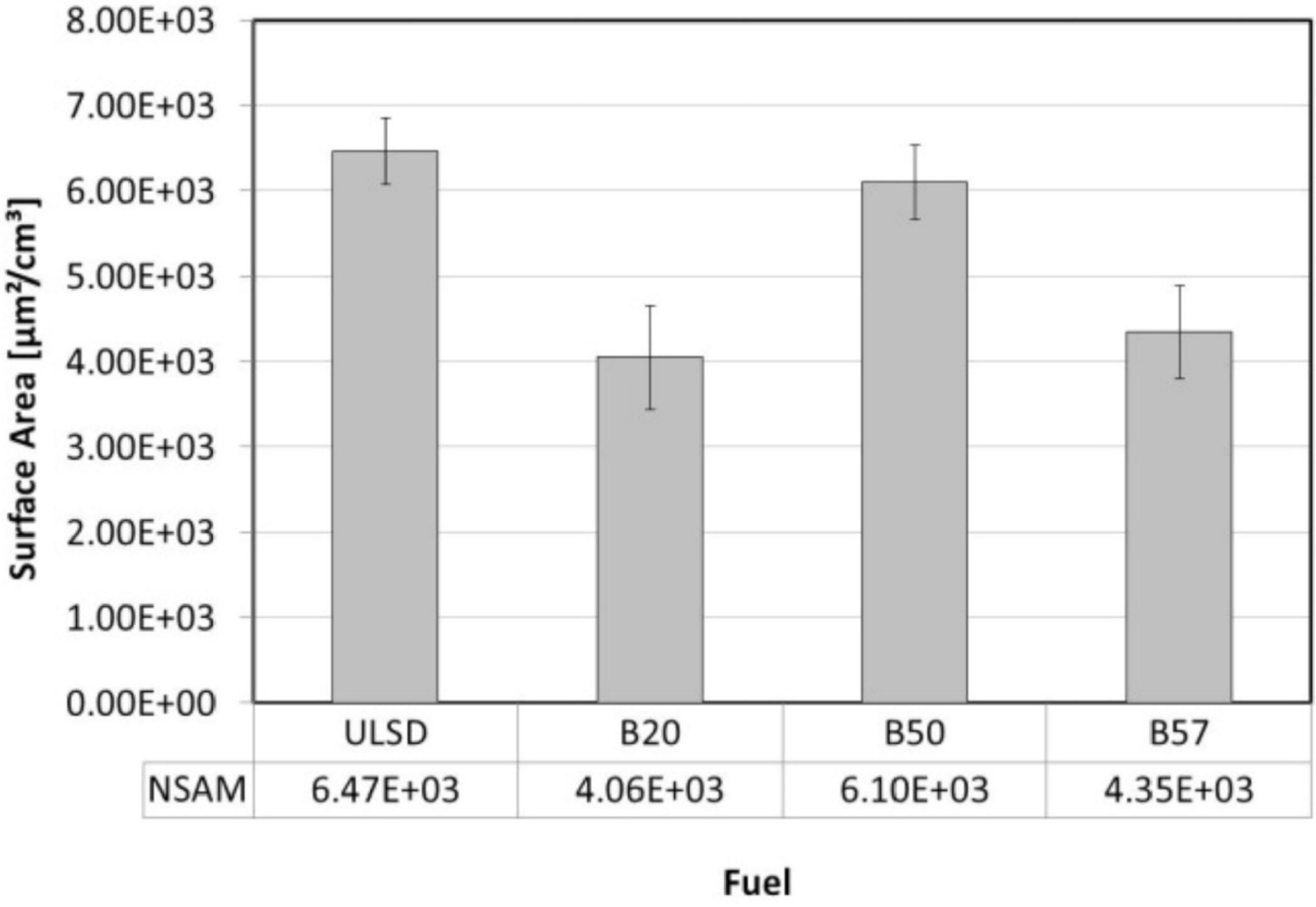
4.

Average number concentrations of aerosols at the MSS for the ULSD and three biodiesel blends.



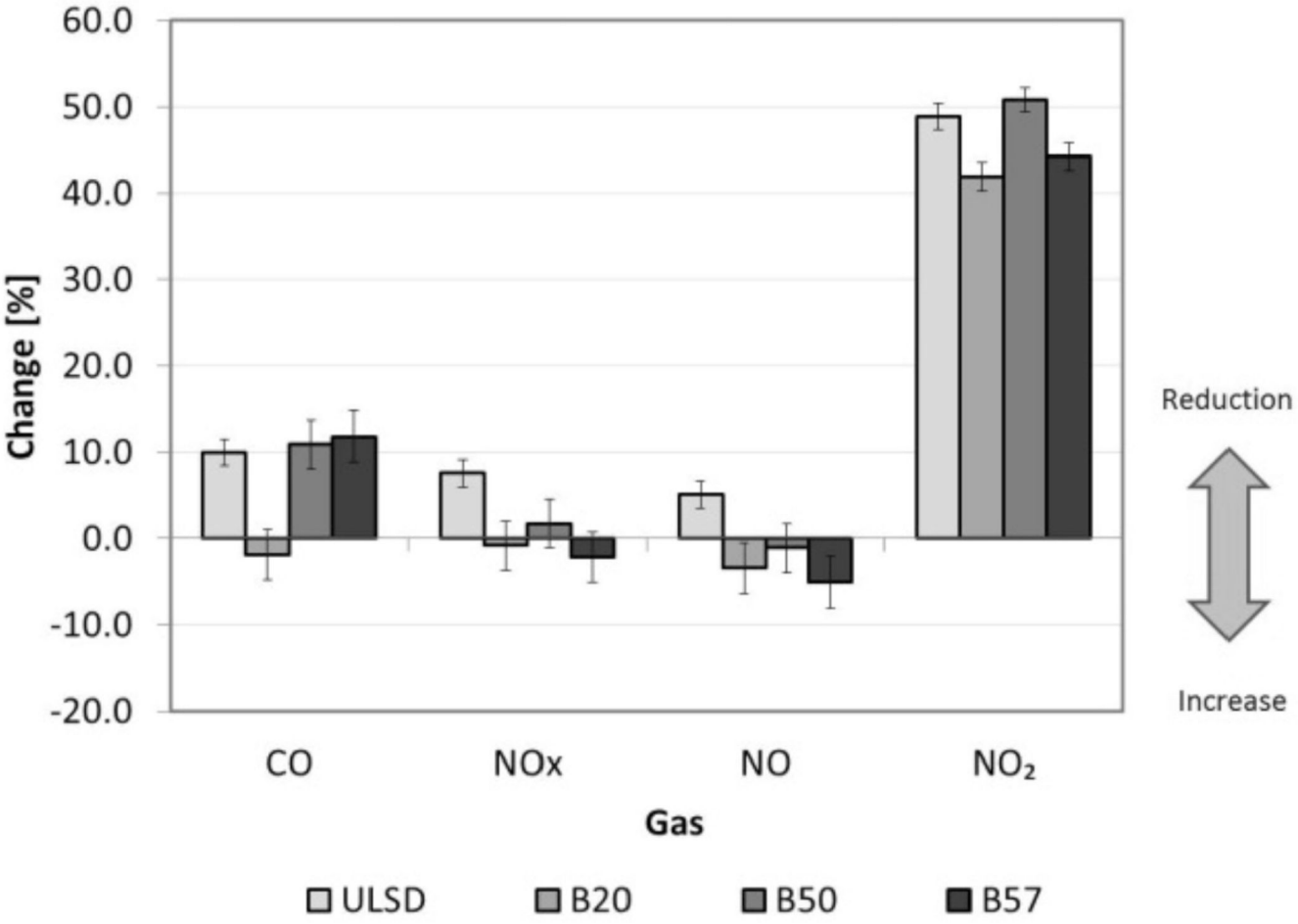
5.

Effects of fuel on electrical mobility median diameter of aerosols measured using FMPS at the MSS.



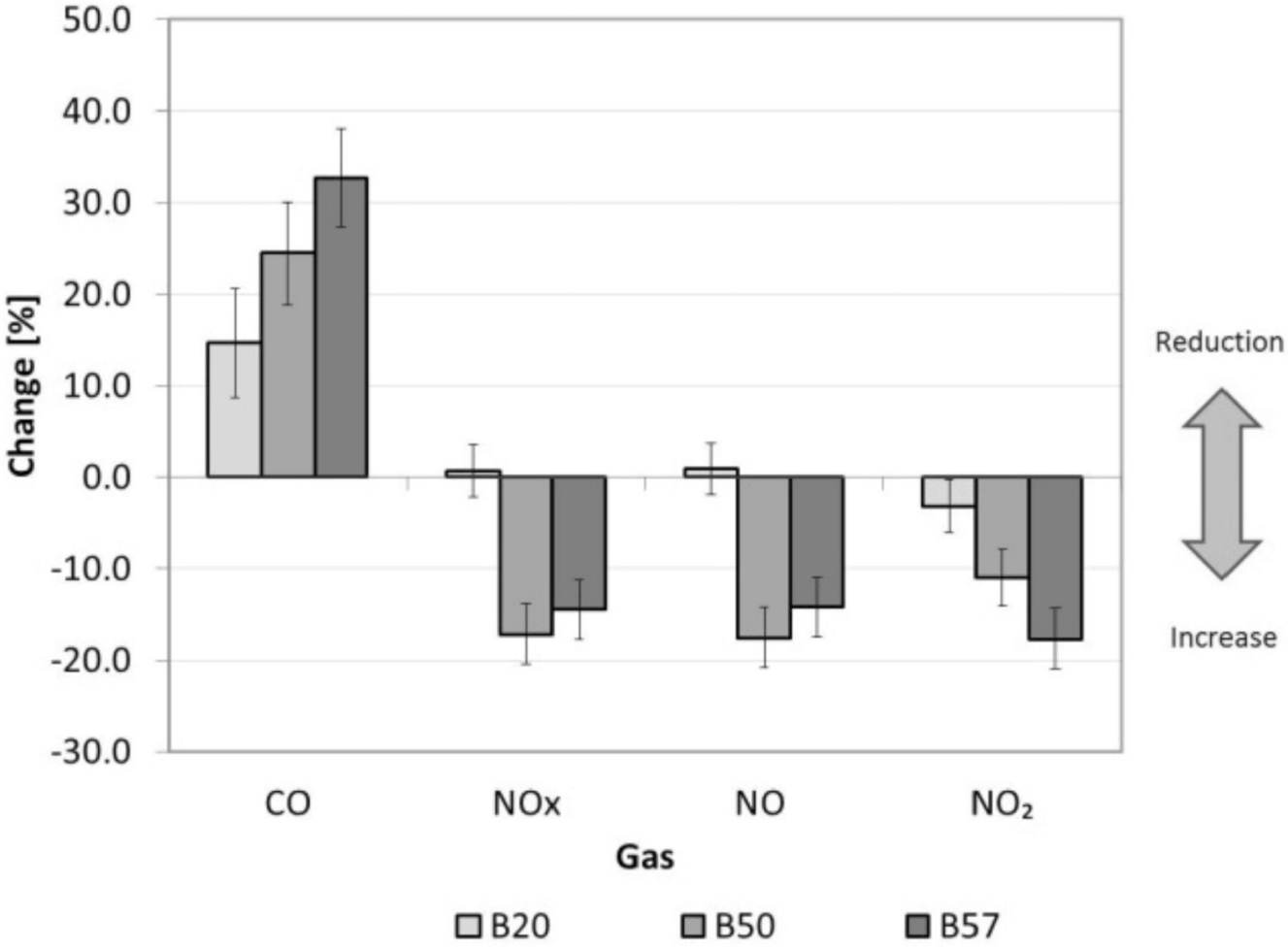
6.

Average surface area concentrations of aerosols deposited in the alveolar region of lungs as measured by NSAM at the MSS.



7.

Effects of the DOC on CO, NO_X, NO, and NO_2 emissions.



8.

Effects of biodiesel fuels when compared to ULSD on CO, NO_X, NO, and NO_2 emissions from deactivated DOC.