JOURNAL OF OCCUPATIONAL AND ENVIRONMENTAL HYGIENE
2017, VOL. 14, NO. 7, D102–D109
https://doi.org/10.1080/15459624.2017.1285488

CASE STUDY

Comparison of personal diesel and biodiesel exhaust exposures in an underground mine

Reported By
Eric A. Lutz, Rustin J. Reed, Vivien S.T. Lee, and Jefferey L. Burgess

Mining Safety and Health Program, Environmental and Occupational Health, Division of Community, Environment, and Policy, Mel & Enid Zuckerman College of Public Health, University of Arizona, Tucson, Arizona

ABSTRACT

This study aimed to compare personal exposures to diesel fuel and a biodiesel blend exhaust in an underground mine. Personal exposure monitoring was performed in a non-operational, hard rock underground mine during use of a load-haul-dump vehicle. Eight-hour time-weighted average (TWA_8) exposure concentrations of ultra-low sulfur diesel and 75% biodiesel/25% diesel blend (B75) fuels were compared.

Compared to diesel, use of B75 was associated with relative percent reductions of 22 and 28% in median respirable (r) diesel particulate matter (DPM) and nitrogen dioxide and 25 and 23% increases in median total DPM and nitric oxide TWA_8 exposure concentrations, respectively. Diesel was associated with a slightly greater total geometric mean mass concentration and lower mean surface area concentration.

Although further testing is needed, B75 has the potential to reduce rDPM exposures.

KEYWORDS
Biodiesel; diesel; fuel exhaust; underground mine

Introduction

In the U.S., there are nearly 14,000 mine sites that employ over 210,000 individuals in the workforce.[1,2] Both underground and surface mines predominantly use diesel powered vehicles at their operations to perform tasks such as drilling, mucking, and hauling. Miners are regularly exposed to diesel fuel emissions during their shift, especially in areas where there is limited ventilation. Diesel fuel exhaust has been classified by the International Agency for Research on Cancer (IARC) as a Group 1 carcinogen in humans[3] and its inhalation has been well documented to result in adverse health outcomes.[4–6]

In an effort to control exposures to workers, the Mine Safety and Health Administration (MSHA) created standards for the allowable concentration of respirable (<1.0 µm with impactor) Diesel Particulate Matter (rDPM) in diesel engine emissions in underground mines. The permissible exposure limit (PEL)[7] of 160 µg/m^3 as total (combined inorganic and organic) carbon is monitored through air sampling and processing per the National Institute for Occupational Safety and Health (NIOSH) analytical method 5040. Despite the installation of controls such as mine ventilation, this underground rDPM exposure standard is frequently exceeded. The health consequences associated with exposures at concentrations less than the occupational regulatory threshold are chronic bronchitis, respiratory tract infections, asthma exacerbation, and increased cardiovascular morbidity and mortality.[8–11]

An alternative control measure that has been explored to reduce rDPM exposures to underground mine workers is the use of biodiesel/diesel fuel blends, ranging from 20/80% (B20) to 80/20% (B80). Studies on the biodiesel emission profile report a decrease in total carbon output, but increase in organic carbon, aldehydes, and nitrogen dioxide.[12–16] One study in an underground mine showed a reduction in elemental carbon emissions by 14 and 31% at idle and during operation, respectively, for B20 and a reduction of 38 and 45% for B50, respectively. [17] However, other research demonstrated an increase in aldehyde, nitrogen dioxide (NO_2), and organic carbon fraction concentrations with use of biodiesel mixtures.[15,18]

This research sought to evaluate and compare the profile of diesel and B75 exposures during the operation of a heavy loader vehicle, commonly called a load-haul-dump (LHD), in an underground mine. Our hypothesis was that use of B75 would see a decrease in diesel particulate

CONTACT Eric A. Lutz ealutz@email.arizona.edu Mining Safety and Health Program; Mel and Enid Zuckerman College of Public Health, University of Arizona, 1656 E Mabel St, #113, Tucson, AZ 85724.
Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/uoeh.

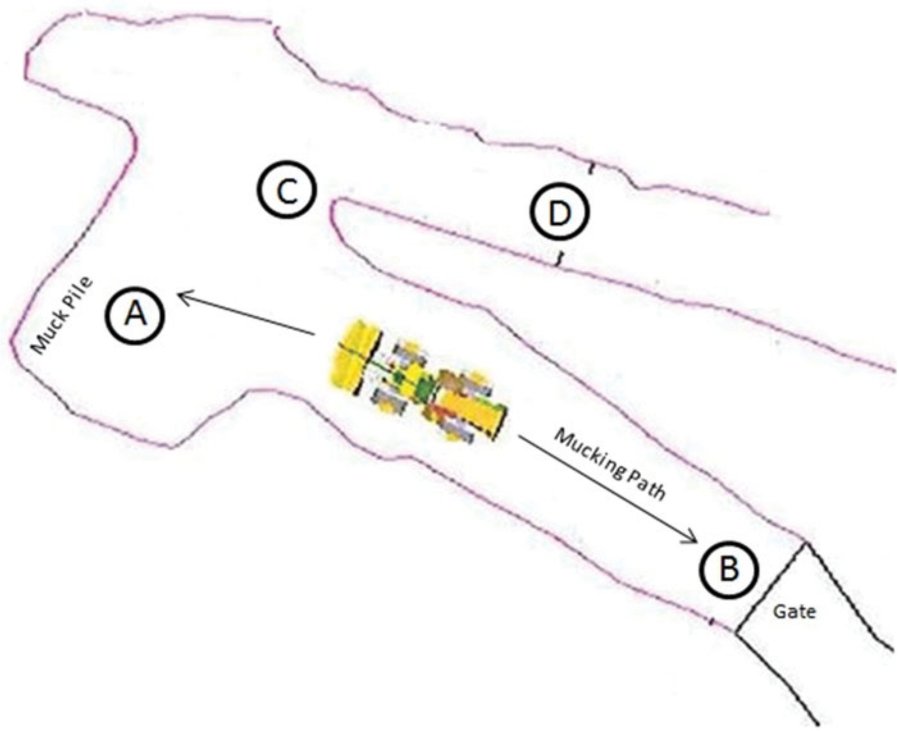

Figure 1. The decline at the University of Arizona San Xavier Underground Mining Laboratory (not to scale). Designations: A – Muck pile, B – Gate, C – Rib, D – Adit entry.

matter (DPM), NO, and naphthalene, and an increase in aldehyde and NO_2 concentrations.

Methods

Fuels and procedure

Both ultra-low sulfur #2 diesel and biodiesel blend were obtained from a regional distributor (Arizona Petroleum, Tucson, AZ). The B75 was prepared by mixing the aforementioned diesel fuel at 25% by volume with a soy methyl ester (SME) biodiesel fuel (ASTM D6751 compliant).

The University of Arizona San Xavier Underground Mining Laboratory (SX) is a non-operational hard rock mine where University mine engineering and public health students perform laboratory work. Exposure to vehicle emissions was evaluated in the "decline", a naturally ventilated portion of the SX with sloping underground opening for rubber-tired vehicle access to the mine (see Figure 1). Mucking activities (the removal of material created during the mining process) were performed by study subjects operating a University-owned 2005 Wagner B10-203 load-haul-dump (LHD) vehicle with open cab and diesel oxidation catalyst (DOC), but no diesel particulate filter (DPF). The vehicle was operated on a 35-m all-underground path with a 9.5% grade. The LHD idled in the decline for approximately 45 min before each exposure assessment. The decline's gate (position B) was covered with a canvas tarp and the metal door (position D) entering the "adit" level was closed at the start of each exposure session to minimize airflow into and out of the decline. The vehicle's fuel tanks were emptied between each fuel type. After changes of fuel, the LHD was operated for approximately one hour with the "new" fuel to ensure all remnants of the previous fuel were removed. The vehicle's fuel tank was used for diesel and B75. All exposure assessments occurred using the same LHD with no engine or operational changes between fuels. The mucking path and pile were sprayed with water during assessments in order to limit dust exposures. To ensure carbon monoxide (CO) levels in the decline remained below 35 ppm, real-time levels were monitored using the 4X Altair gas monitor (MSA Corporation, Cranberry Township, PA).

During each 200-min exposure assessment, two research subjects alternately mucked (110 min) and closely observed (80 min) LHD operation, with a 10-min break in the decline. Mucking activities included filling the LHD bucket at the muck pile (position A), driving to the decline gate (position B), returning to and unloading at the muck pile, driving once again to the decline gate, and then returning to the muck pile for loading. Subjects observing LHD operations stood at the decline "rib", approximately three meters from the muck pile (position C). Generally, after one pair of subjects finished a second pair replaced them, for a total of two exposure sessions (four subjects) per day. Subsequent exposure assessments typically occurred no sooner than one week following the prior day of testing, with seven total days for diesel and eight for B75. For diesel and B75, 58% and 64% of exposure sessions were the first session of the day, respectively. There were four days during which only one diesel exposure session occurred, while there were eight for B75. In nine instances, four times for diesel and five for B75, two days of exposure assessments were performed on subsequent days. A cross-over study design was utilized, with 23 subjects completing first their diesel (early spring) then B75 (late spring) exposure rotations during the first year, and 25 subjects completing their B75 (early spring) exposure rotation first, followed by their diesel (late spring) rotation during the second year.

Exposure assessment

Every 70 min during each session, wind speed measurements were taken using a Kestrel® 4500 Weather Meter (Nielsen-Kellerman Company, Boothwyn, PA) at the observer's location (position C). Universal PCXR 8 (SKC West, Inc., Fullerton, CA) and Escort ELF (Zefon International, Inc., Ocala, FL) air sampling pumps, as well as a 4X Altair gas monitor (MSA Corporation, Cranberry Township, PA), were placed in pockets of or clipped to a safety vest worn by subjects. Sampling media were placed in the subjects' breathing zone, clipped to the vest at shoulder level. The 4X gas monitor was clipped to the front of the vest at chest level. Additionally, assessment of the mean aerodynamic particle size distribution across the range of 500 nm to 10 µm, including a per-size evaluation of airborne particulate concentration, surface area, and mass, was performed during exposure periods using an Aerodynamic Particle Sizer (APS) Spectrometer (TSI, Inc., Shoreview, MN) on a table three feet tall and directly behind the observer at position C.

Personal integrated sample collection and analysis was performed in accordance to NIOSH manual of analytical methods (NMAM). Specifically, a GS-1 Respirable Cyclone with 37 mm jeweled impactor and flow rate of 1.7 L/min (NMAM 5040)[19] were used in respirable (<1.0 µm) DPM (rDPM) sampling (Limit of detection [LOD]: 0.3 µg, Limit of quantification [LOQ]: 8 µg). A 37-mm open face quartz fiber filter with flow rate of 2.0 L/min (NMAM 5040)[19] was utilized to sample total (non-fractionated) DPM (tDPM [LOD: 0.3 µg, LOQ: 8 µg]). A tandem triethanolamine/oxidizer with flow rate 0.025 L/min (NMAM 6014)[20] was used to collect nitric oxide (NO [LOD: unspecified, LOQ: 0.6 µg]) and NO_2 (LOD: 1 µg, LOQ: 1 µg) samples. Sorbent tubes containing silica gel and a flow rate of 0.1 L/min (NMAM 2016)[21] were used in formaldehyde (LOD: 0.07 µg, LOQ: 0.1 µg) and acetaldehyde (LOD: 0.07 µg, LOQ: 0.1 µg) sample collection. Finally, a 37-mm teflon filter cartridge and sorbent tube set at a flow rate of 2.0 L/min (NMAM 5506)[22] were used to sample naphthalene (LOD: unspecified, LOQ: 8 µg). At the project's onset, a profile of 18 polycyclic aromatic hydrocarbons was sampled. However, after several exposure assessments, naphthalene was the only compound with concentrations above the LOD. Sampling media were produced by the same manufacturer (SKC West, Inc., Fullerton, CA). A Bios Drycal Defender 520 calibrator (Mesa Labs, Inc., Butler, NJ) was used for pre- and post-sampling confirmation calibration at the University's Medical Research Laboratory. An independent AIHA-accredited industrial hygiene laboratory performed laboratory analysis.

Statistical analysis

In order to compare exposure concentrations to their associated Occupational Safety and Health Administration PEL and American Conference of Governmental Industrial Hygienists TLV concentrations and to each other, each individual sample's reported laboratory concentration was time-weighted (see Equation (1)) over an 8-hr exposure period (TWA_8):

$$\frac{(C \times T)}{480 \text{ minutes}} \tag{1}$$

where C = Contaminant concentration in mg/m3 or ppm, and T = Sampling duration in minutes.

Outlier testing was performed for each analyte and fuel group by identifying those observations falling outside the lower and upper fences (150% of the interquartile range) and visual inspection of box plots. For D, three rEC, four tEC, three NO, two NO_2, four formaldehyde, and four acetaldehyde outlying exposure concentrations were identified. Only one tEC outlying exposure concentration was identified for BD. Statistical analyses were performed with and without these outliers. In the present study, only the results containing all data are presented because of no changes in overall conclusions. The results containing these outliers have been included. Four out of 43 acetaldehyde samples (9%) resulted in breakthrough while sampling diesel fuel exhaust. While our analysis excluded the breakthrough samples, data containing and excluding the breakthrough samples are reported. When comparing the morning to the afternoon, the morning exposure rotation analyte TWA_8 concentrations tended to be higher than those of the afternoon, although not significantly so. All data analysis was performed using STATA 12.0 (StataCorp, College Station, TX). Descriptive statistics assessed measures of central tendency, outliers, and distribution of the data. The Wilcoxon rank-sum test was used to analyze TWA_8 concentrations for significant differences in sample distribution. An alpha error threshold level of 0.05 was utilized.

Table 1. Analyte TWA_8 exposure concentrations by fuel type.

	Diesel			B75		
Analyte	n	Median	Range	n	Median	Range
rDPM (ug/m3)	49	336.4	129.3–711.9	49	270.4[a]	68.7– 643.8
rEC (ug/m3)	49	125.1	42.4–360.1	49	52.8[c]	15.4–186.8
rOC (ug/m3)	49	205.2	61–353.6	49	176	21–571.5
tDPM (ug/m3)	48	608.2	36.3–1099.6	49	783.8[b]	250–1530
tEC (ug/m3)	48	134.6	56.6–412.5	49	61.3[c]	12.5–280.3
tOC (ug/m3)	48	459.5	197.4–733.1	49	640.6[c]	237.5–1445
Acetaldehyde (ppm)	39	0.030	0.009–0.055	47	0.031	0.008–0.055
Acetaldehyde-all (ppm)	43	0.035	0.009–0.174	47	0.031	0.008–0.055
Formaldehyde (ppm)	43	0.094	0.0192–0.5317	47	0.099	0.028–0.161
Naphthalene (ppm)	49	0.0003	0.0001–0.0031	49	0.0004	0.0001–0.001
Nitrogen Dioxide (ppm)	49	1.58	0.46–7.28	47	1.19[a]	0.39–6.77
Nitric Oxide (ppm)	46	10	3.56–23.08	47	12.63[a]	1.63–25.93
Carbon Monoxide (ppm)	46	12.46	1.44–24.29	49	11.15	0.42–23.78

[a]$p < 0.05$; [b]$p < 0.01$; [c]$p < 0.001$. Acetaldehyde with breakthrough samples included is indicated by "Acetaldehyde-all." Abbreviations: Diesel (D), Biodiesel (B75), Respirable DPM (rDPM), respirable elemental carbon (rEC), respirable organic carbon (rOC), total DPM (tDPM), total elemental carbon (tEC), total organic carbon (tOC). The Wilcoxon rank-sum test was used to compare data for statistical differences from B75 to D.

Results

We found there to be significant differences between the exhaust profiles of diesel (D) and biodiesel (B75), in both particulate and gas composition (Table 1). TWA_8 median values for rDPM, rEC, and tEC were statistically significantly lower in B75 than in D ($p < 0.05$, $p < 0.001$, and $p < 0.001$, respectively), while concentrations of tDPM and tOC were higher in B75 than in D ($p < 0.01$ and $p < 0.001$, respectively). The concentration of rOC was higher in D than in B75, but this difference was not significant. In analyzing the gas composition of the exhaust, we found there to be fewer significant differences, with B75 having a slightly higher concentration of formaldehyde and naphthalene. D exhaust contained a higher median concentration of acetaldehyde and carbon monoxide, but neither was a significant increase from that of B75. The concentration of nitrogen dioxide was significantly lower in B75 at 1.19 ppm ($p < 0.05$) compared to D, which had a median concentration of 1.58 ppm. However, the concentration of nitric oxide was higher in B75 (12.63 ppm) than in D (10.00 ppm, $p < 0.05$).

APS-derived, size-differentiated, mean, aerosol, particulate mass (dM/dlogDp) and surface area (dS/dlogDp) data collected during diesel and B75 fuel tests are summarized in Figures 2 and 3, respectively. The peak geometric mean particle mass across the size range of 50 0 nm to 10 μm for both diesel and B75 occurred at 10.37 μm, with diesel having a slightly higher total mean mass concentration than B75 at 46.608 μg/cm^3 vs. 41.471 μg/cm^3. The geometric mean particle surface area followed the expected bimodal distribution, with the first peak of 0.777 μm and 0.542 μm for diesel and B75, respectively, and the second peak for diesel at 9.647 μm and B75 at 5.048 μm. However, unlike with the mean particle mass measures, total mean geometric mean surface area was higher for B75 at 53,317.37 nm^2/cm^3 than diesel at 47,253.23 nm^2/cm^3. Further as depicted in Figures 2 and3, B75 was observed to have higher concentration values for both geometric mean particle mass and surface area at lower size fractions, decreasing below diesel concentration values for the same measures above aerodynamic diameters of approximately 6.732 μm. The total mean aerodynamic diameter (dN/dlogDp) particle count was 4,918.92 particles for diesel and 9,688.33 particles for B75.

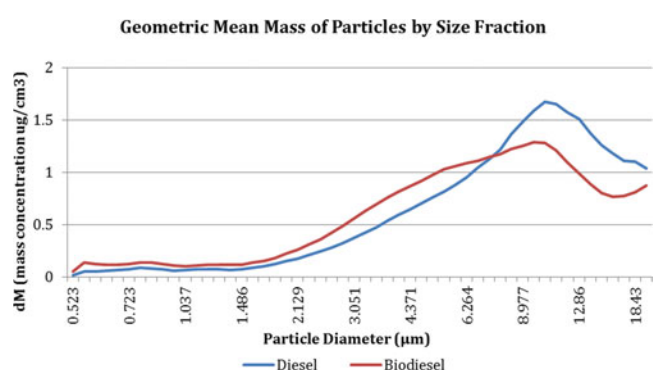

Figure 2. Size distribution of geometric mean mass of particles by fuel type.

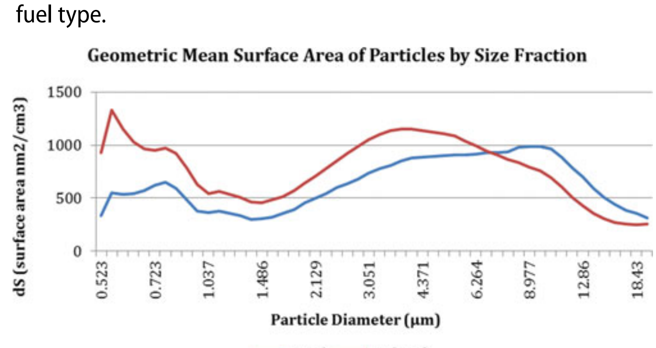

Figure 3. Size distribution of geometric mean surface area of particles by fuel type.

Discussion

Our study demonstrates that reductions in median rDPM can be achieved with a 75/25 biodiesel blend. Use of B75 would likely increase compliance with the MSHA federal standard (30 CFR 57.5060), as the regulation specifically targets rDPM exposures. However, use of B75 should be carefully considered as many components of vehicle exhaust contribute to adverse health effects and our particle mass and surface area measures indicate greater concentrations of B75 to diesel in the inhalable size fractions less than 6.7 µm. Likewise, we observed increases in certain analyte TWA_8 exposure concentrations associated with B75.

Relevant literature (see Table 2) has produced mixed results when comparing particulate exposures and DPM between or among diesel and biodiesel blends, with some finding no difference,[12,17] others showing significant reductions,[13,14,16,23–26] or a small increase.[27] Consistent with other studies,[15,17,24,27,28] our work demonstrated increasing tOC and decreasing tEC concentrations associated with B75 use. Previous studies used a range of biodiesel blends, engine configurations, pollution control devices (or lack thereof), and loading procedures—all of which may influence vehicle emissions.

Comparable to prior research,[12,17,18,27] our study did not show a significant difference in CO exposures between D and B75. However, we did observe significant differences in NOx concentrations—unlike previous work.[12,17,18,27] Similarly, inconsistent, other studies have demonstrated a reduction in CO Biodiesel emission concentrations compared to diesel fuel.[15,27] Likewise, prior studies observing increased aldehyde concentrations with biodiesel use,[12,18] compared to the lack of difference we observed. Unlike our study, however, the engines used in these studies[12,18] did not utilize a DOC. Dissimilar to some studies,[12,25,26] we found increasing naphthalene concentrations with use of B75—although these results were not statistically significant.

For B75, our study showed a greater aerosolized particle peak count, geometric mass and geometric surface area concentration, particularly at lower size fractions, compared to diesel. While the mean mass concentration for B75 was less than that of diesel across all sizes, B75 size mass concentrations exceeded diesel's at all sizes less than approximately 6.732 µm. Several previous studies[15,17,25,29–31] have shown that some biodiesel blends under specific loading conditions also demonstrate greater particle concentrations at smaller fractions, compared to diesel. Others,[25,31,32] however, have found that greater loads and/or moderate biodiesel blends, such as B10 or B20, can produce lower particle concentrations than diesel fuel. This may partially explain our observation of higher particle concentration for B75.

The type of equipment, load, and pollution control equipment, including catalytic converters and particle traps, have been observed as factors that influence diesel emissions.[15,17,18,26,27,33] Because it is frequently used in underground mine settings, and can be associated with high exposures to diesel exhaust,[17,33] we selected the LHD vehicle for our study. Pollution control devices present on the LHD included a DOC, but no DPF. Other studies used neither DOC nor DPF,[12,18,26] only a DOC,[15] or combination of pollution control configurations.[17,27,33] Some evidence suggests that DOCs may have little effect on NOx exposures,[34] but may reduce biodiesel's CO and hydrocarbon emissions. Our LHD is representative of the types of equipment commonly found in current use, despite it not representing the newest or most advanced vehicles available.

Limitations

One limitation of our study is that the data were generated using a single vehicle with a DOC. Operational underground mining settings typically include multiple pieces of heavy equipment operating simultaneously, each outfitted with one or more pollution control attachments. Expansion of the study to include additional vehicles and pollution control configurations is needed to determine whether our results are representative of other types of equipment.

Unlike an operational underground mine, our study was conducted in a naturally ventilated area with the aid of inexperienced LHD operators. In addition, the specific job tasks performed by our participants may not necessarily depict what is typical of the mining industry. Because airflow measurements were not taken at the decline gate and adit entry, we cannot estimate the impact of natural ventilation on observed exposures. Any significant variation in air changes per hour among fuel types exposure sessions could potentially influence our results.

Breakthrough in our acetaldehyde samples all occurred during use of diesel fuel. This likely results in an underestimate in the overall diesel exposure concentrations. Finally, the lower exposure measures do not guarantee the health effects would be any less severe than those related to diesel exhaust exposure. The comparison of health effects from use of diesel and B75 will be reported as part of the larger study.

Differences in fuel chemical composition, vehicle engine conditions (i.e., temperature of combustion, concentration of oxygen present, etc.), and emission source controls (i.e., DOCs, DPFs, etc.) are all contributors to

Table 2. Summary of literature evaluating biodiesel and other diesel controls.

Ref. #	Setting	Engine(s)/Equipment	Pollution Control(s)	Operating Conditions	Comparison	Control(s)	Results
12	Laboratory	Turbocharged EURO 2 IVECO 8360.46R heavy duty diesel engine	None	Steady-state European 13 mode cycle, ECE R49	Diesel oil	B20 methyl ester (from rapeseed oil)	Formaldehyde: Increase; Decrease in CO, PAH's; PM: Increase; NOx: No change
13	Laboratory	2003 model year Detroit Diesel Corporation (DDC) Series 60 diesel engine	None	Heavy-duty transient Federal Test Procedure (FTP) cycle	Petrodiesel	Commercial grade B100 (methyl soyate)	PM: Decrease; NOx: Increase; CO: Decrease
14	Field	Instrumented research tractor	None	No-load engine speed set to 2200 rpm during tillage and drill operations	Diesel	B20, B50, B100 (soybean-based)	NOx: Decrease for B20 during tillage and drill; Increases for B50, B100; CO: Decrease for B20, B50, B100 during tillage and drill
15	Laboratory	Isuzu C240 diesel engine	Muffler; Muffler and DOC	Engine operated over four steady-state modes	ULSD	B50, B100 (soy methyl ester)	EC: Decrease for B50, B100; OC: Increases for B50, B100
16	Laboratory	Turbocharged diesel engine (FAW-WDEW 4CK, China)	None	ISO 8178 Type C18-mode steady state cycle with 8 modes	Neat fossil diesel fuel	B100 (from soybean oil)	Formaldehyde: Increase
17	Field	Caterpillar CAT 3306 DITA engine	DPF, DOC	Repeatable load/dump cycles in isolated zone	#1 diesel/#2 diesel mix	B20, B50 (#2 diesel, neat biodiesel)	EC: Decrease; PM: Decrease; CO: No change; Decrease with B20, increase with B50 for NO, NO_2
18	Laboratory	Diesel generator (QC495)	None	Idling, 10%, 33%, 50%, and 55% loads	Premium diesel	B10, B30, B50, B75, B100 (palm fatty acid methyl ester)	Increase in Formaldehyde, NOx; CO: Increase at low loads, decrease at high loads
23	Field	Large front-end loader (2001 John Deere model 624H), small front-end loader (1994 JCB model 409), skid steer (2001 New Holland model LS190)	None	Daily operations in a naturally ventilated building	Petroleum diesel	B20 (soy-based)	PM: Decrease
24	Field	Large front-end loader (2001 John Deere model 624H), small front-end loader (1994 JCB model 409), skid steer (2001 New Holland model LS190)	None	Daily operations in a naturally-ventilated building	Petroleum diesel	B20 (soy-based)	Decrease in EC, OC, respirable PM
25	Laboratory	Non-catalytic diesel engine generator (NM260L, Mitsubishi)	None	Idling, 5 kW, 7 kW, 10 kW	Premium diesel	B10, B20, B50, B100 (soybean oil)	Decrease in PM, EC, OC, TC at 5 kW, 7 kW; Increase for all at 10 kW
26	Laboratory	583 cc engine (Yanmar Corporation, Japan)	None	0 kW, 1.5 kW, 3 kW	Fossil diesel	B10, B20, B30, B50 (waste-edible-oil)	OC: Increase for B50 at 0 kW, 1.5 kW; Decrease in PM, TC, EC, PAH's; OC: Decrease except for B50 @ 0 kW, 1.5 kW
27	Laboratory	Four light heavy-duty diesel vehicles	DOC (2), None (2)	FTP at LA4 driving schedule	10% aromatic diesel fuel (California reformulated diesel)	B100, B20	PM: Increase with one vehicle, no change with three; CO: Increase with same vehicle, decrease with three; NOx: Increase with non-DOC; TC: Increase; OC: Increase except B20 with one vehicle; EC: Decrease except B100 in one and B20 in two vehicles.

(*Continued on next page*)

Table 2. Continued

Ref. #	Setting	Engine(s)/Equipment	Pollution Control(s)	Operating Conditions	Comparison	Control(s)	Results
28	Laboratory	1993 diesel-powered John Deere tractor, 7700 model	None	Idle and 2100 RPM/126 HP	ULSD	B25, B50, B75, B100 (soybean oil); B50T, B100T (beef tallow)	OC: Increase except B25, B50T; EC: Decrease; PAHs: Decrease
29	Laboratory	Medium duty transportation engine (Mahindra, India, MDI-3000)	None	Varying speed at constant engine load, varying load at constant engine speed	Mineral diesel	B20, B100	PM: Increase at low load, decrease at high load for B20; Increase for B100
30	Laboratory	Diesel engine tractor (Fendt 306 LSA)	None	Heavy-duty 13-mode test cycle (ECE R49)	Common fossil diesel fuel	Rape-seed oil methyl ester	PM: Increase in smaller size fractions, decrease at larger size fraction
31	Laboratory	Isuzu diesel engine (4HF1)	None	Low and high load	ULSD	B100 (waste cooking oil)	OC: Decrease; EC: Increase at high load, decrease at low load
32	Laboratory	1983 Caterpillar 3304 PCNA	With and without DOC	Light-duty and heavy-duty transient speed/load test cycles	Low sulfur number 2 diesel	B100 (soy methyl ester)	TPM: Decrease, decrease at larger size fractions, increase at some smaller size fractions; PAHs: Decrease
33	Field	Deutz BF6M1013 FC engine, Deutz BF6M1013EC engine, Caterpillar CAT 3306 DITA engine	Various DPFs and DOCs	Normal operation in production zone	N/A	Various DPFs and DOCs	Difference observations for CO, NO, NO_2 based on engine type and pollution configuration
34	Laboratory	John Deere 4276T turbo-charged DI diesel engine	None	20% and full load	Number 2 diesel	Un-oxidized and oxidized B20 (soybean oil)	CO: Decrease; HC: Decrease; NOx: Increase

Note. **Bold** text indicates a statistically significant result. Parameters included here represent those reported by the respective authors as closely as possible. Biodiesel fuels are designated as the percent of biodiesel (B%) mixed with the comparison diesel fuel. CO: Carbon monoxide, DOC: Diesel oxidative catalyst, DPF: Diesel particulate filter, EC: Elemental carbon, HC: Hydrocarbons, NO: Nitric oxide, NO_2: Nitrogen dioxide, NOx: Oxides of nitrogen, OC: Organic carbon, PAH: Polycyclic aromatic hydrocarbons, PM: Particulate matter, TC: Total carbon, TPM: Total particulate matter, ULSD: Ultra-low sulfur diesel.

the resulting differences in the level of exhaust components. For example, impurities in the fuel and higher engine temperatures could affect the concentration of DPM in the exhaust. Furthermore, variation in NOx concentrations could be a result of higher combustion temperatures, as well as interaction with the LHD's DOC. Higher engine temperatures and increased oxygen content may lead to conditions that increase the formation of short hydrocarbons, such as formaldehyde and acetaldehyde.

Although the current study was limited to the underground mining setting, our results suggest that use of B75 could potentially decrease exposures to harmful emissions from the use of diesel engine-powered vehicles. Both occupational and general population exposures could be impacted.

Conclusion

We observed significant reduction in rDPM using B75. Despite this, our study was limited to a single engine configuration and vehicle with limited pollution controls, and further investigation with additional vehicles and more pollution controls is needed. Our study suggests that use of biodiesel blends can significantly reduce some harmful emissions from diesel equipment.

References

[1] **U.S. Department of Labor:** "Industries at a Glance: Mining (except Oil and Gas): NCAIS 212." Available at http://www.bls.gov/iag/tgs/iag212.htm accessed May 1, 2014.

[2] **U.S. Department of Labor:** "Mining Safety and Health At a Glance." Available at http://www.msha.gov/MSHAINFO/FactSheets/MSHAFCT10.asp (accessed May 1, 2014).

[3] **World Health Organization:** "IARC: Diesel Engine Exhaust Carcinogenic." Lyon, France: International Agency for Research on Cancer, June 2012.

[4] **Sydbom, A., A. Blomberg, S. Parnia, N. Stenfors, T. Sandstrom, and S. E. Dahlen:** Health effects of diesel exhaust emissions. *Eur. Respir. J. 17*(4):733–746 (2001).

[5] **Attfield, M.D., P.L. Schleiff, J. H. Lubin, et al.:** The diesel exhaust in miners study: a cohort mortality study with emphasis on lung cancer. *Jnci-J. Nat. Cancer Instit. 104*(11):869–883 (2012).

[6] **Silverman, D. T., C. M. Samanic, J. H. Lubin, et al.:** The diesel exhaust in miners study: a nested case-control study of lung cancer and diesel exhaust. *J. Nat. Cancer Instit. 104*(11):855–868 (2012).

[7] "Limit on Exposure to Diesel Particulate Matter." *Code of Federal Regulations Title 30*, Part 57.5060, 2010. pp. 370–372.

[8] **Pope, C. A., R. T. Burnett, M. J. Thun, et al.:** Lung cancer, cardiopulmonary mortality, and long-term exposure

to fine particulate air pollution. *Jama-J. Am. Med. Assoc. 287*(9):1132–1141 (2002).

[9] **Kagawa, J.:** Health effects of diesel exhaust emissions - a mixture of air pollutants of worldwide concern. *Toxicology 181*:349–353 (2002).

[10] **Kato, A., A. Nagai, and J. Kagawa:** Morphological changes in rat lung after long-term exposure to diesel emissions. *Inhal. Toxicol. 12*(6):469–490 (2000).

[11] **Harrod, K.S., R. J. Jaramillo, C. L. Rosenberger, et al.:** Increased susceptibility to RSV infection by exposure to inhaled diesel engine emissions. *Am. J. Respir. Cell Molec. Biol. 28*(4):451–463 (2003).

[12] **Turrio-Baldassarri, L., C. L. Battistelli, L. Conti, et al.:** Emission comparison of urban bus engine fueled with diesel oil and 'biodiesel' blend. *Sci. Total Environ. 327*(1–3):147–162 (2004).

[13] **Knothe, G., C. A. Sharp, and T. W. Ryan:** Exhaust emissions of biodiesel, petrodiesel, neat methyl esters, and alkanes in a new technology engine. *Energy Fuels 20*(1):403–408 (2006).

[14] **Li, Y., and N. McLaughlin:** Fuel Efficiency and Exhaust Emissions for Biodiesel Blends in an Agricultural Tractor. Presented at the Canadian Society for Engineering in Agricultural, Food, and Biological Systems, Winnipeg, Manitoba, Canada, June 26–29, 2005.

[15] **Bugarski, A. D., E. G. Cauda, S. J. Janisko, J. A. Hummer, and L. D. Patts:** Aerosols emitted in underground mine air by diesel engine fueled with biodiesel. *J. Air & Waste Manage. Assoc. 60*(2):237–244 (2010).

[16] **He, C., Y. S. Ge, J. W. Tan, et al.:** Comparison of carbonyl compounds emissions from diesel engine fueled with biodiesel and diesel. *Atmosph. Environ. 43*(24):3657–3661 (2009).

[17] **U.S. Department of Health and Human Services:** *The Effectiveness of Selected Technologies in Controlling Diesel Emissions in an Underground Mine - Isolated Zone Study at Stillwater Mining Company's Nye Mine*, by A. Bugarski, G. Schnakenberg, J. Noll, S. Mischler, L. Patts, J. Hummer, S. Vanderslice, M. Crum, and R. Anderson. National Institute for Occupational Safety and Health, January 2004.

[18] **Liu, Y. Y., T. C. Lin, Y. J. Wang, and W. L. Ho:** Carbonyl compounds and toxicity assessments of emissions from a diesel engine running on biodiesels. *J. Air Waste Manage. Assoc. 59*(2):163–171 (2009).

[19] **U.S. Department of Health and Human Services:** Diesel Particulate Matter, 5040. *NIOSH Manual of Analytical Methods (NMAM)*, Fourth Edition. National Institute of Occupational Safety and Health, March 15, 2003.

[20] **U.S. Department of Health and Human Services:** Nitric Oxide and Nitrogen Dioxide, 6014. *NIOSH Manual of Analytical Methods (NMAM)*, Fourth Edition. National Institute of Occupational Safety and Health, August 15, 1994.

[21] **U.S. Department of Health and Human Services:** Formaldehyde, 2016. *NIOSH Manual of Analytical Methods (NMAM)*, Fourth Edition. National Institute of Occupational Safety and Health, March 15, 2003.

[22] **U.S. Department of Health and Human Services:** Polynuclear Aromatic Hydrocarbons by HPLC, 5506. *NIOSH Manual of Analytical Methods (NMAM)*, Fourth Edition.National Institute of Occupational Safety and Health, January 15, 1998.

[23] **Traviss, N., B. A. Thelen, J. K. Ingalls, and M. D. Treadwell:** Biodiesel versus diesel: A pilot study comparing exhaust exposures for employees at a rural municipal facility. *J. Air Waste Manage. Assoc. 60*(9):1026–1033 (2010).

[24] **Traviss, N., B. A. Thelen, J. K. Ingalls, and M. D. Treadwell:** Evaluation of biodiesel's impact on real-world occupational and environmental particulate matter exposures at a municipal facility in Keene, NH. *Air Qual. Atmosph. Health 5*(1):101–114 (2012).

[25] **Tsai, J. H., S. J. Chen, K. L. Huang, et al.:** PM, carbon, and PAH emissions from a diesel generator fuelled with soy-biodiesel blends. *J. Hazard. Mater. 179*(1–3):237–243 (2010).

[26] **Tsai, J. H., S. J. Chen, K. L. Huang, W. J. Lee, W. C. Kuo, and W. Y. Lin:** Characteristics of particulate emissions from a diesel generator fueled with varying blends of biodiesel and fossil diesel. *J. Environ. Sci. Health Part A-Toxic/Hazard. Subst. Environ. Eng. 46*(2):204–213 (2011).

[27] **Durbin, T. D., J. R. Collins, J. M. Norbeck, and M. R. Smith:** Effects of biodiesel, biodiesel blends, and a synthetic diesel on emissions from light heavy-duty diesel vehicles. *Environ. Sci. Technol. 34*(3):349–355 (2000).

[28] **Magara-Gomez, K. T., M. R. Olson, T. Okuda, K. A. Walz, and J. J. Schauer:** Sensitivity of diesel particulate material emissions and composition to blends of petroleum diesel and biodiesel fuel. *Aer. Sci. Technol. 46*(10):1109–1118 (2012).

[29] **Agarwal, A. K., T. Gupta, and A. Kothari:** Particulate emissions from biodiesel vs diesel fuelled compression ignition engine. *Renew. Sustain. Energy Rev. 15*(6):3278–3300 (2011).

[30] **Bunger, J., J. Krahl, K. Baum, et al.:** Cytotoxic and mutagenic effects, particle size and concentration analysis of diesel engine emissions using biodiesel and petrol diesel as fuel. *Arch. Toxicol. 74*(8):490–498 (2000).

[31] **Lu, T., Z. Huang, C. S. Cheung, and J. Ma:** Size distribution of EC, OC and particle-phase PAHs emissions from a diesel engine fueled with three fuels. *Sci. Total Environ. 438*:33–41 (2012).

[32] **Bagley, S. T., L. D. Gratz, J. H. Johnson, and J. F. McDonald:** Effects of an oxidation catalytic converter and a biodiesel fuel on the chemical, mutagenic, and particle size characteristics of emissions from a diesel engine. *Environ. Sci. Technol. 32*(9):1183–1191 (1998).

[33] **U.S. Department of Health and Human Services:** *An Evaluation of the Effects of Diesel Particulate Filter Systems on Air Quality and Personal Exposure of Miners at Stillwater Mine Case Study: Production Zone*, by A.D. Bugarski, J. Noll, G. Schnakenberg, M. Crum, and R. Anderson. National Institute for Occupational Safety and Health, April 2004.

[34] **Monyem, A., and J. H. Van Gerpen:** The effect of biodiesel oxidation on engine performance and emissions. *Biomass Bioener. 20*(4):317–325 (2001).