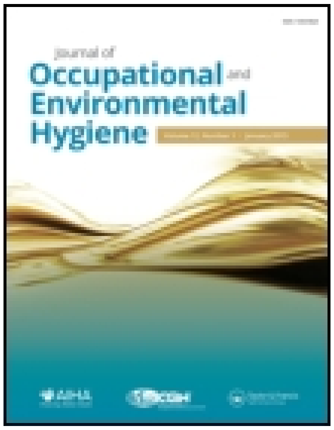

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Occupational Exposures to Emissions from Combustion of Diesel and Alternative Fuels in Underground Mining—A Simulated Pilot Study

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Case Study
Occupational Exposures to Emissions from Combustion of Diesel and Alternative Fuels in Underground Mining—A Simulated Pilot Study

Diesel fuel is commonly used for underground mining equipment, yet diesel engine exhaust is a known human carcinogen. Alternative fuels, including biodiesel, and a natural gas/diesel blend, offer the potential to reduce engine emissions and associated health effects. For this pilot study, exposure monitoring was performed in an underground mine during operation of a load-haul-dump vehicle. Use of low-sulfur diesel, 75% biodiesel/25% diesel blend (B75), and natural gas/diesel blend (GD) fuels were compared. Personal samples were collected for total and respirable diesel particulate matter (tDPM and rDPM, respectively) and total and respirable elemental and organic carbon (tEC, rEC, tOC, rOC, respectively), as well as carbon monoxide (CO), formaldehyde, acetaldehyde, naphthalene, nitric oxide (NO), and nitrogen dioxide (NO_2). Compared to diesel, B75 use was associated with a 33% reduction in rDPM, reductions in rEC, tEC, and naphthalene, increased tDPM, tOC, and NO, and no change in rOC, CO, and NO_2. Compared to diesel, GD was associated with a 66% reduction in rDPM and a reduction in all other exposures except CO. The alternative fuels tested both resulted in reduced rDPM, which is the basis for the current Mine Safety and Health Administration (MSHA) occupational exposure standard. Although additional study is needed with a wider variety of equipment, use of alternative fuels have the promise of reducing exposures from vehicular exhaust in underground mining settings.

INTRODUCTION

There are more than 223,000 actively employed miners across the United States, working at more than 14,000 mines in both surface and underground operations.(1,2) Mines predominantly use diesel-fueled production and support vehicles. Further, exposures to diesel fuel emissions are known to cause adverse health outcomes(3–5) and diesel engine exhaust has been classified by the International Agency for Research on Cancer (IARC) as a Group 1 carcinogen in humans.(6)

To minimize risks to workers, the Mine Safety and Health Administration (MSHA) regulates the amount of diesel engine emissions in underground mines through monitoring of respirable (<1.0 μm with impactor) diesel particulate matter (rDPM) with a permissible exposure limit (PEL)(7) of 160 $\mu g/m^3$ as total (combined inorganic and organic) carbon, using the National Institute for Occupational Safety and Health (NIOSH) analytical Method 5040. However, despite mining ventilation and administrative controls, this underground rDPM exposure standard is frequently exceeded. Further, exposures at concentrations less than the occupational regulatory threshold have been associated with chronic bronchitis, respiratory tract infections, asthma exacerbation, and increased cardiovascular morbidity and mortality.(8–11)

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As an alternative control measure, some underground mine operators have turned to biodiesel/diesel fuel blends, ranging from 20/80% (B20) to 80/20% (B80) to reduce rDPM exposures. In general, biodiesel use appears to decrease total carbon output, but increases in organic carbon, aldehydes, and nitrogen dioxide have been reported.(12–16) One underground mine study showed that at idle and during operation, B20 reduced elemental carbon emissions by 14 and 31%, respectively, and B50 resulted in a reduction of 38 and 45%, respectively.(17) Conversely, other research demonstrated use of biodiesel mixtures increased aldehyde, nitrogen dioxide (NO_2), and organic carbon fraction concentrations.(15,18)

In 2011, an Environmental Protection Agency (EPA)-approved natural gas/diesel (GD) fuel mixture, GDiesel, became commercially available. GD is prepared by combining diesel with natural gas, using a proprietary charged-catalytic reaction. The end product is an ASTM-designated diesel fuel with purportedly reduced tailpipe emissions of DPM and oxides of nitrogen (NOx) compounds.(19,20)

Our pilot-scale study sought to evaluate and compare diesel, B75, and GD exposures from operation of a heavy loader vehicle, commonly called a load-haul-dump (LHD), in an underground mine. Our hypothesis was that use of these alternative fuels would decrease rDPM exposures compared to diesel.

METHODS

Fuels and Procedure

As an adjunct to a larger study comparing exposures from diesel and biodiesel blend fuel emissions and health effects, exposures from use of diesel, B75, and GD fuels were compared. The ultra-low sulfur #2 diesel (Arizona Petroleum, Tucson, AZ) was obtained from a regional distributor. 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), obtained from the same regional distributor. The GD fuel #2 was purchased directly from the producer (Advance Refining Concepts, LLC, Reno, NV).

Exposure to vehicle emissions was evaluated at a naturally ventilated portion in the “decline” of the University of Arizona San Xavier Underground Mining Laboratory (SX), a non-operational hard rock mine at which university mine engineering and public health students perform laboratory work (see Figure 1). The decline is a sloping underground opening for rubber-tired vehicle access to the mine. Mucking activities, or the removal of materials during the process of mining, were performed by study participants using the LHD. Prior to each exposure session, the LHD idled in the decline for approximately 45 minutes. To minimize airflow into and out of the decline, its gate (position B) was covered with a canvas tarp, while the metal door (position D) entering the “adit” level was closed at the start of each exposure session. Carbon monoxide (CO) levels in the decline were monitored using real time instrumentation, specifically the 4X Altair gas monitor (MSA Corporation, Cranberry Township, PA), to ensure levels remained below 35 ppm. A university-owned 2005 Wagner B10-203 LHD vehicle (Wagner Equipment Co., Aurora, CO) with an open cab and diesel oxidation catalyst (DOC), but no diesel particulate filter (DPF), was used for the study. The vehicle was operated on a 35-meter all-underground route with a 9.5% grade. The mucking path and pile were sprayed with water to limit dust exposures. The 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, while a separate fuel tank and fuel line were used for GD, so as not to disrupt the larger ongoing study. Fuel tests occurred using the same LHD with no engine or operational changes between fuels.

For the diesel and B75 fuels, two research subjects alternately mucked (110 min) and closely observed (80 min) LHD operation, with a 10-min break in the decline during each 200-min exposure rotation. 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 mucking activities stood at the decline’s “rib,” approximately 3 meters from the mucking pile (position C). For GD, research scientists mucked using the identical procedure, albeit for 100-min total rotations (50 min mucking/50 min observation). 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 assessment day, with seven total days for diesel, eight for B75, and two for GD. For diesel, B75, and GD, 60.9%, 68.1%, and 50%, respectively, of exposure sessions were the first session of the day. There were two days for diesel during which only one exposure session occurred, while there were three for B75. On two occasions, once for diesel and once for B75, exposure assessments were performed within 24 hours of each other. Both GD exposure assessment days occurred one week apart.

Exposure Assessment

Wind speed measurements were taken at the observer’s location (position C) every 70 min during each session using a Kestrel 4500 Weather Meter (Nielsen-Kellerman Company, Boothwyn, PA). Subjects wore a safety vest outfitted with 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). Sampling media were clipped to the front of the vest at shoulder level, within the breathing zone. The 4X gas monitor was clipped to the front of the vest at chest level.

Personal integrated sample collection and analysis was conducted according to the *NIOSH Manual of Analytical Methods* (NMAM). Specifically, respirable ($<1.0\ \mu$m) DPM (rDPM) was sampled using a GS-1 Respirable Cyclone with 37 mm

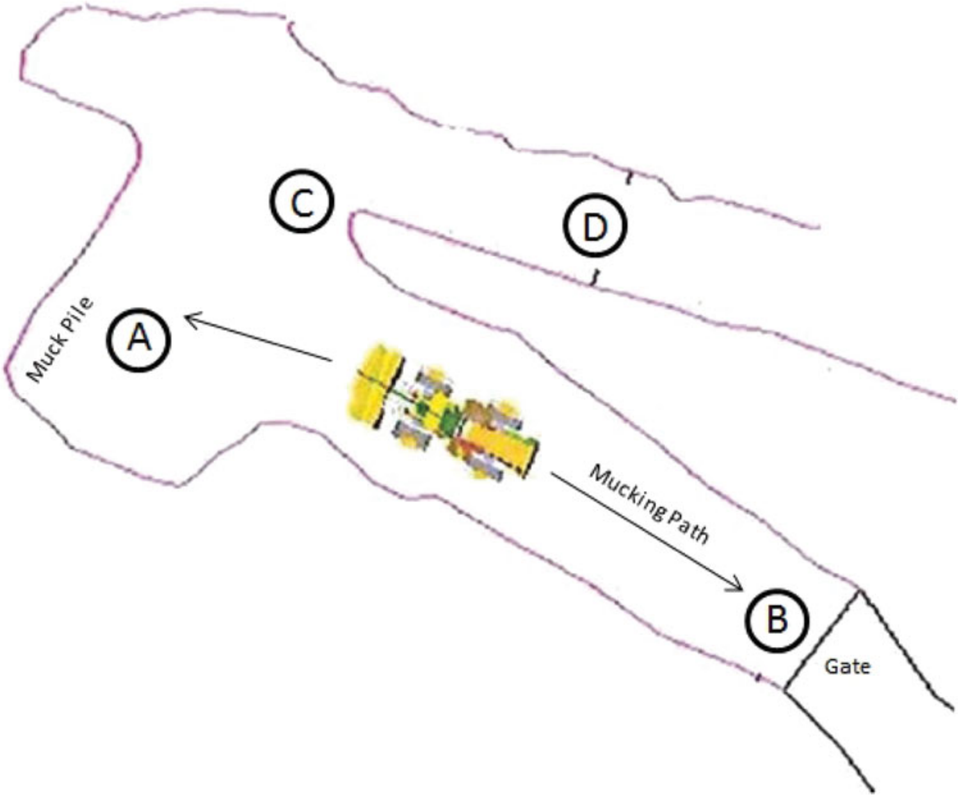

FIGURE 1. Diagram of the San Xavier's decline, with the muck pile (A), gate at decline entry (B), rib (C), and door to adit area (D) labeled (not to scale).

jeweled impactor at a flow rate of 1.7 L/min (NMAM 5040). Total (non-fractionated) DPM (tDPM) was collected using a 37 mm open face quartz fiber filter at a flow rate of 2.0 L/min (NMAM 5040). Nitric oxide (NO) and NO_2 were sampled using a tandem triethanolamine/oxidizer set at 0.025 L/min (NMAM 6014). Formaldehyde and acetaldehyde were sampled using cartridges containing silica gel at a flow rate of 0.1 L/min (NMAM 2016). Finally, sampling trains for naphthalene included a 37-mm Teflon cartridge filter and sorbent tube set, and was calibrated to a flow rate of 2.0 L/min (NMAM 5506). All sampling media originated from the same manufacturer (SKC West, Inc., Fullerton, CA). All pre- and post-sampling confirmation calibration occurred using a Bios Drycal Defender 520 calibrator (Mesa Labs, Inc., Butler, NJ) above ground at the University of Arizona campus. Laboratory analysis was performed by an independent American Industrial Hygiene Association (AIHA)-accredited industrial hygiene laboratory.

Statistical Analysis

All reported laboratory concentrations were time-weighted over an 8-hr exposure period (TWA_8). A total of four acetaldehyde samples, out of 23 collected, resulted in breakthrough during use of diesel fuel; results from both their inclusion and exclusion are provided. Overall, analyte TWA_8 concentrations for the morning exposure rotation tended to be higher than those of the afternoon, though not significantly so. Data were analyzed using STATA 12.0 (StataCorp, College Station, TX). Descriptive statistics assessed measures of central tendency, outliers, and distribution of the data. TWA_8 exposure means were first compared across fuel types using the Kruskal-Wallis rank test with Bonferroni correction. Those analytes with significant differences across all fuel types were further analyzed using the Wilcoxon rank-sum test. An alpha error threshold level of 0.05 was utilized.

RESULTS

Our pilot study comparing exposures to emissions from use of diesel, B75, and GD in an underground mine identified significant differences across the three fuels for all analytes tested except for CO (Kruskal-Wallis, $p < 0.001$; Tables I and II and Figure 2). For pairwise comparisons, B75 rDPM exposures were lower than with diesel exposures ($p = 0.009$). Overall, mean B75 results were mixed, as emissions were significantly higher than diesel for tDPM and total organic carbon (tOC), significantly lower for rDPM, total elemental carbon (tEC), respirable organic carbon (rOC), and naphthalene, and not significantly different for rEC, NO,, NO_2, formaldehyde, and acetaldehyde. Mean GD rDPM exposures were significantly lower than with diesel ($p < 0.001$) and B75 ($p = 0.003$) exposures and significantly lower than both diesel

TABLE I. Analyte TWA$_8$ Concentrations by Fuel Type

Fuel Type	Diesel n = 23	Biodiesel n = 22	GDiesel n = 12
rDPM (μg/m^3)			
Mean (±SD)	**308.7 (±133.7)**[A]	**207.2 (±111.3)**[B]	**104.9 (±23.3)**
Median	284.4	193.3	100.6
95% CI	250.9–366.5	157.8–256.6	90.1–119.7
Range	130.6–586.25	68.7–476.7	79.4–152.3
tDPM (μg/m^3)			
Mean (±SD)	**539.4 (±209)**[A]	**752.9 (±242.7)**[A]	**245.8 (±39.2)**
Median	568.8	780	232.3
95% CI	449–629.7	645.3–860.5	220.9–270.7
Range	36.3–907.5	330–1232.5	195.3–305
Carbon Monoxide (ppm)			
Fuel Type	Diesel n = 23	Biodiesel n = 21	GDiesel n = 8
Mean (±SD)	7.5 (±0.6)	7.8 (±0.7)	7.4 (±0.7)
Median	7.4	7.3	7.3
95% CI	6.2–8.8	6.3–9.2	5.8–8.9
Range	1.4–13.7	0.4–13.9	5.2–10.1
Nitric Oxide (ppm)			
Fuel Type	Diesel n = 23	Biodiesel n = 21	GDiesel n = 12
Mean (±SD)	10.9 (±4.2)[A]	12.3 (±4.6)[A]	**4.9 (±2.9)**
Median	10.3	14.1	4.2
95% CI	9.1–12.7	10.2–14.4	3–6.7
Range	4.9–23	4.6–20.4	1.8–12.5
Nitrogen Dioxide (ppm)			
Mean (±SD)	1.33 (±0.66)[A]	1.29 (±0.57)[A]	**0.56 (±0.2)**
Median	1.36	1.2	0.54
95% CI	1.05–1.62	1.03–1.55	0.43–0.68
Range	0.46–2.72	0.39–2.92	0.23–1
Formaldehyde (ppm)			
Fuel Type	Diesel n = 21	Biodiesel n = 20	GDiesel n = 11
Mean (±SD)	0.14 (±0.13)[A]	0.08 (±0.02)[A]	**0.03 (±0.01)**
Median	0.09	0.09	0.03
95% CI	0.08–0.19	0.08–0.1	0.02–0.04
Range	0.02–0.53	0.05–0.12	0.01–0.05
Acetaldehyde (ppm)			
Fuel Type	Diesel n = 18	Biodiesel n = 20	GDiesel n = 11
Mean (±SD)	0.03 (±0.021)[A]	0.03 (±0.008)[B]	**0.01 (±0.004)**
Median	0.03	0.03	0.01
95% CI	0.02–0.04	0.03–0.03	0.01–0.01
Range	0.0085–0.107	0.012–0.046	0.002–0.016
Naphthalene (ppm)			
Fuel Type	Diesel n = 23	Biodiesel n = 22	GDiesel n = 11
Mean (±SD)	**0.0013 (±0.00072)**[A]	**0.0006 (±0.00027)**[A]	**0.0001 (±0.00003)**
Median	0.0012	0.0006	0.0001
95% CI	0.00104–0.00166	0.00053–0.00076	0.00012–0.00016
Range	0.0005–0.0031	0.0003–0.001	0.00009–0.00018

Note: Bold indicates $p < 0.05$ compared to both other fuel types.

[A] Compared to GDiesel distribution, indicates $p < 0.01$.

[B] Compared to GDiesel distribution, indicates $p < 0.001$.

TABLE II. Organic and Elemental Carbon TWA_8 Concentrations for rDPM and tDPM

Fuel Type	Diesel n = 23	Biodiesel n = 22	GDiesel n = 12
		rOC (μg/m3)	
Mean (±SD)	159.4 (64.4)^A	157.5 (121.7)^A	53.5 (14.5)
Median	163.3	120.1	49.7
95% CI	131.5–187.2	103.5–211.5	44.3–62.7
Range	61–290.3	30–571.5	36.7–78.8
		rEC (μg/m3)	
Mean (±SD)	**147.3 (78.3)**^{A}	**98.6 (53.1)**^{A}	**51.8 (11.6)**
Median	119	86.4	51.1
95% CI	113.5–181.2	75–122.1	44.4–59.2
Range	68.8–360.1	36.4–186.3	37.5–73.5
		tOC (μg/m3)	
Mean (±SD)	**394.6 (127.6)**^{A}	**633 (233.7)**^{A}	**187.6 (31.2)**
Median	427.1	609.6	181.4
95% CI	339.4–449.8	529.4–736.6	167.8–207.5
Range	197.4–643.8	257.7–1045	143.1–236.4
		tEC (μg/m3)	
Mean (±SD)	**162.5 (81)**^{A}	**114.9 (66.8)**^{A}	**58.1 (11.5)**
Median	138	96.9	58.3
95% CI	127.4–197.5	85.2–144.5	50.8–65.5
Range	74.7–412.5	47.9–272	37.2–74.3

Note: Bold indicates $p < 0.05$ compared to both other fuel types.
[A] Compared to GDiesel distribution, indicates $p < 0.001$.

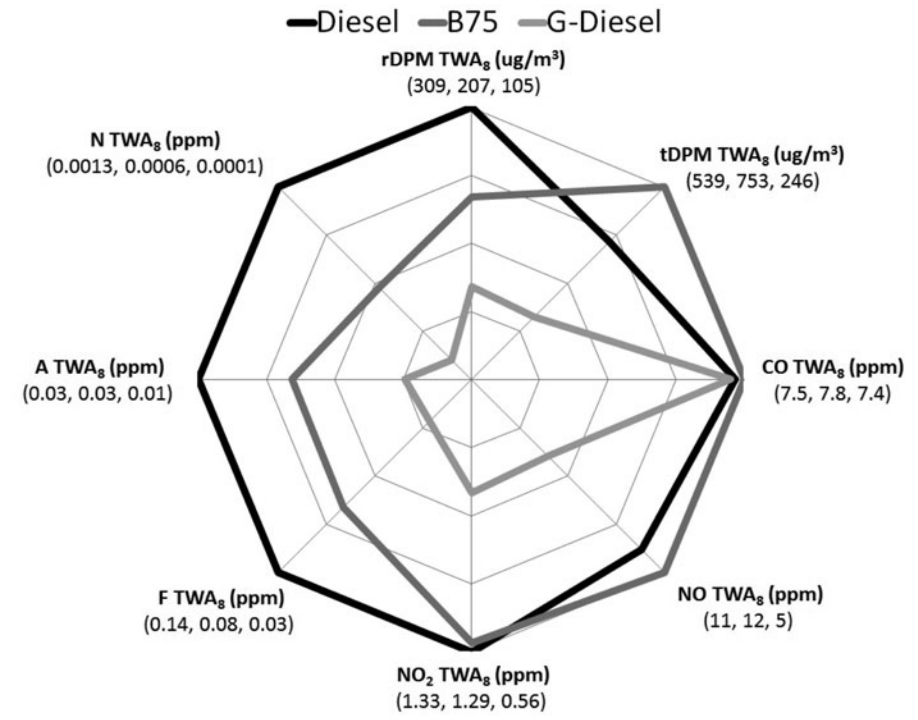

FIGURE 2. Mean TWA_8 concentrations for each fuel type by analyte. Ordered diesel, B75, and GDiesel, mean TWA_8 concentration values are included in parentheses. Axes all begin at a respective concentration of zero. Naphthalene (N), Formaldehyde (F), and Acetaldehyde (A) have been abbreviated.

and B75 for all other analytes except CO. While the inclusion of acetaldehyde breakthrough samples in our analysis resulted in a higher mean TWA_8 exposure concentration (0.04 [$\pm$0.042] ppm) for diesel fuel, its ranked sum remained similar to that of biodiesel.

Overall, the median TWA_8 exposure concentrations for tDPM ($p = 0.006$), NO ($p = 0.025$), NO_2 ($p = 0.045$), and CO ($p = 0.038$) were higher during the first exposure sessions than those of the second. While there were no differences in average exposures between first and second sessions for D, tDPM ($p = 0.005$), NO ($p = 0.024$), and CO ($p = 0.012$) exposure concentrations were higher during the first B75 sessions, and rDPM ($p = 0.025$), tDPM ($p = 0.016$), and formaldehyde ($p = 0.035$) were higher during the first GD exposure sessions. During one session of a diesel exposure day a wind speed measurement of approximately 2.0 m/s was observed. During one session of a B75 exposure day a wind speed measurement of approximately 1.0 m/s was recorded at the decline rib. It was noted that, in each case, it was particularly windy above ground. There were no other recordable wind speeds measured.

DISCUSSION

Compared to regular diesel fuel, our pilot study demonstrates reduction in rDPM with use of B75 and an even greater decrease with GD. Given that the MSHA standard is based on total carbon rDPM exposures, use of both alternative fuel types would likely increase compliance with this federal standard (30 CFR 57.5060). However, other components of vehicle exhaust contribute to adverse health effects, and the increases in certain analytes associated with B75 use should therefore be considered. GD fuel use resulted in decreased exposures for every analyte measured in our study, with the exception of CO, suggesting that from the perspective of the analytes evaluated, its use would likely reduce adverse health effects as compared with use of diesel and B75 fuels.

Previous studies have shown mixed results comparing particulate exposures and DPM across diesel and biodiesel blends, with some finding no difference,(12,17) others showing significant reductions,(13,14,16,21–24) and one finding a small increase.(25) Our research revealed increasing tOC and decreasing tEC concentrations associated with B75 use, consistent with previously published studies.(15,17,22,25,26) These studies used a variety of biodiesel blends, pollution control devices (or lack thereof), loading procedures, and engine configurations, all of which can influence vehicle emissions.

Our study failed to demonstrate a statistically significant difference in CO and NOx exposure concentrations between diesel and biodiesel fuels consistent with reported results from several prior studies.(12,17,18,25) However, other studies have shown an increase in NO_2 or reductions in CO biodiesel emission concentrations compared to diesel fuel.(15,25) Our findings are also inconsistent with prior studies showing increased aldehyde concentrations with biodiesel use.(12,18) However, neither of the engines used in these studies used a DOC as was done in our study. Further, we found decreasing naphthalene concentrations with use of B75 consistent with other studies.(12,23,24)

Compared to diesel fuel, use of natural gas has been shown to reduce particulate emissions.(27–29) Although there are no other published peer-reviewed studies comparing its use to diesel, reduction in exposures with a GD fuel would seem reasonable given the cleaner burning qualities of natural gas. Our results are also consistent with those described by the manufacturer of GD.(19,20) However, the Nevada Division of Environmental Protection reported that use of GD may cause small increases in CO and total hydrocarbon emissions.(19)

Previous studies have shown that diesel emissions are influenced by a variety of factors including type of equipment, load, and pollution control equipment, including catalytic converters and particle traps.(15,17,18,24,25,30) The LHD vehicle in our study was chosen because it is commonly used in underground mine settings, and is often associated with high exposures to diesel exhaust.(17,30) Pollution control devices present on the LHD included a DOC but no DPF. Other studies used neither DOC nor DPF,(12,18,24) only a DOC,(15) or combination of pollution control configurations.(25,30) Evidence suggests that DOCs can reduce biodiesel's CO and hydrocarbon emissions but have little effect on NOx exposures.(31) Although our LHD does not represent the newest or most advanced LHD available, it is representative of the types of equipment frequently found in current use.

LIMITATIONS

The limitations of our pilot study include use of a single vehicle with a DOC, but without a DPF or other pollution control device. Operational underground mining settings typically include multiple pieces of heavy equipment operating simultaneously, each with a variety of source controls. Further study, therefore, with additional vehicles and pollution control configurations is needed to determine whether our results are representative of other types of equipment.

The number of exposures monitored for GD was also limited in comparison to those for diesel and B75, with GD exposures limited to 100 min compared to 200 min for diesel and B75. Additionally, a smaller portion of GD exposure sessions occurred as second sessions, potentially underestimating the observed exposure concentrations. However, we do not believe that these differences could fully explain the marked reduction in exposures that we measured in association with GD use.

Unlike an operational underground mine, our study was conducted in a naturally ventilated area with fairly novice LHD operators. In addition, the specific job tasks performed may or may not be representative of those found in 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 bias our results.

The acetaldehyde samples experiencing breakthrough all occurred during use of diesel fuel and their exclusion likely underestimates overall diesel exposure concentrations. Finally, we did not study the health effects of GD exposure; 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.

The differences observed across fuel types are likely a function of the fuels' chemical composition, vehicle engine conditions, such as temperature of combustion and concentration of oxygen present, and emission source controls, such as DOCs and DPFs. For example, observed differences in DPM could be due to more complete combustion from higher engine temperatures, or impurities and hydrocarbon chain lengths found in each fuel. In addition, variation in NOx concentrations could be due to higher combustion temperatures as well as interaction with our 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 alternative fuels, and GD in particular, 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

While our study was limited to a single vehicle with limited pollution controls, and further evaluation with additional vehicles with more recent pollution controls is needed, both B75 and GD significantly reduced rDPM, with GD demonstrating an advantage over B75. These results suggest that use of alternative fuels has the potential to significantly reduce harmful emissions from diesel engines.

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