Published in final edited form as:
J Occup Environ Hyg. 2016 ; 13(4): 293–302. doi:10.1080/15459624.2015.1116695.

Effects of hydrotreated vegetable oil on emissions of aerosols and gases from light-duty andmedium-duty older technology engines

Aleksandar D. Bugarski, **Jon A. Hummer**, and **Shawn Vanderslice**
National Institute for Occupational Safety and Health, Office of Mine Safety and Health Research, Pittsburgh, Pennsylvania

Abstract

This study was conducted to assess the potential of hydrotreated vegetable oil renewable diesel (HVORD) as a control strategy to reduce exposure of workers to diesel aerosols and gases. The effects of HVORD on criteria aerosol and gaseous emissions were compared with those of ultralow sulfur diesel (ULSD). The results of comprehensive testing at four steady-state conditions and one transient cycle were used to characterize the aerosol and gaseous emissions from two older technology engines: (1) a naturally aspirated mechanically controlled and (2) a turbocharged electronically controlled engine. Both engines were equipped with diesel oxidation catalytic converters (DOCs). For all test conditions, both engines emitted measurably lower total mass concentrations of diesel aerosols, total carbon, and elemental carbon when HVORD was used in place of ULSD. For all test conditions, the reductions in total mass concentrations were more substantial for the naturally aspirated than for the turbocharged engine. In the case of the naturally aspirated engine, HVORD also favorably affected total surface area of aerosols deposited in the alveolar region of human lungs (TSAADAR) and the total number concentrations of aerosols. In the case of the turbocharged electronically controlled engine, for some of the test conditions HVORD adversely affected the TSAADAR and total number concentrations of aerosols. In the majority of the test cases involving the naturally aspirated mechanically controlled engine, HVORD favorably affected carbon dioxide (CO_2), nitrogen oxides (NO_X), and nitric oxide (NO) concentrations, but adversely affected NO_2 and total hydrocarbon concentrations, while the effects of the fuels on carbon monoxide (CO) concentrations were masked by the effects of DOC. In the case of the turbocharged electronically controlled engine, the CO_2, CO, NO_X, NO, and total hydrocarbon concentrations were generally lower when HVORD was used in place of ULSD. The effects of the fuels on NO_2 concentrations were masked by the more prominent effects of DOC.

Keywords

Diesel aerosols; diesel gases; hydrotreated vegetable oil renewable diesel; underground mining

---

CONTACT Aleksandar D. Bugarski, abugarski@cdc.gov, National Institute for Occupational Safety and Health, Office of Mine Safety and Health Research, 626 Cochrans Mill Rd., Pittsburgh, Pennsylvania 15236.

Disclaimer

The findings and conclusions in this article are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health (NIOSH). Mention of company names or products does not constitute endorsement by NIOSH.

Introduction

Due to mounting concern over various adverse health outcomes that diesel aerosols and gases have on the pulmonary system,[1] cardiovascular system,[2] and brain,[3,4] extensive efforts are being made to reduce exposures of the general population and workers to diesel aerosols. The exposure to diesel aerosols and gases is of particular concern in the confined spaces of occupational settings such as underground mines, tunnel construction sites, and tracking depots.[5]

Changing the fuel supply from petroleum diesel to alternative fuels is considered to be a viable strategy to reduce exposure of workers in underground metal and nonmetal mines to diesel particulate matter (DPM).[6] Until recently, the U.S. underground mining industry has been almost exclusively using biodiesel fuels made from various vegetable oils and animal fats through the process of transesterification.[7] Those fuels are made of long-chain, fatty-acid methyl esters (FAME). FAME biodiesels are oxygenated fuels with approximately 11% oxygen content. Properties of FAME biodiesels are very dependent on feedstock.

The effects of FAME biodiesel and FAME biodiesel blends with petroleum diesel on regulated and nonregulated emissions from heavy-duty diesel engines have been previously extensively evaluated in laboratories[8–10] and in various environments.[11,12] When compared to low sulfur and ultralow sulfur diesels (LSD and ULSD), FAME biodiesel fuels were found to reduce mass emissions of total DPM and nonvolatile fractions of DPM[13–17] and to be effective strategy for reducing mass concentrations of diesel aerosols, total carbon, and elemental carbon in underground mines.[6,16] FAME biodiesels were shown to reduce emissions of CO and certain hydrocarbons.[14,18,19] However, the use of FAME biodiesel fuels as a control strategy has several potential drawbacks: combustion of FAME fuels was found to produce aerosols with smaller median diameters and in some cases higher peak concentrations than petroleum diesel fuels.[6–8,20] The FAME biodiesels were also found to modestly increase nitrogen oxides ($NO_X = NO + NO_2$) emissions, and under certain engine operating conditions the particle-bound volatile organic fraction of DPM.[10,16] In addition, several studies showed that aerosols produced by diesel engines combusting FAME biodiesels in place of petroleum-derived diesel fuels might have higher pulmonary[21–23] and reproductive[24] toxicity. The increase in oxidative stress with the use of FAME fuels was linked to a larger presence of oxygenated organic species in FAME aerosols than in petroleum-derived aerosols.[25] When used in high concentration blends, the FAME fuels were known to cause operational problems associated with stability, engine oil dilution, and formation of deposits in fuel injection systems.[26]

Alternative renewable fuels to FAME biodiesels are hydrotreated vegetable oil renewable diesel (HVORD). These are fuels derived from vegetable and algae oils and animal fats via the hydrogenation and isomerization process.[27] HVORD is almost exclusively made of paraffinic and iso-paraffinic hydrocarbons and is virtually free of aromatic hydrocarbons, metals, sulfur, nitrogen, and oxygen-containing compounds.[7,26,27] When compared with ULSD, HVORD fuels have a lower density, a higher cetane number, higher net heat of combustion on a mass basis, and lower net heat of combustion on a volume basis.[26]

Several studies showed that, when compared with EN590 petroleum-derived diesel, HVORD, in general, has favorable effects on particulate matter (PM) mass and NO_X emissions, and minor effects on CO and total hydrocarbon emissions (25,28,29). When compared with FAME biodiesel fuels, HVORD produced lower NO_X and higher CO, total hydrocarbons, and PM mass and number emissions.[28,29] It appears that those effects varied widely with the type of engine and engine settings. Several studies showed that regulated emissions can be further reduced via optimization of fuel injection and other engine parameters.[26,30]

HVORD blends were recently introduced in underground metal mining operations in the western part of the U.S. This study was conducted to expand on the limited body of knowledge on the effects of HVORD on regulated and unregulated emissions from older technology light-duty and medium-duty nonroad diesel engines. This information should shed more light on the potential of this fuel as a control strategy for reducing exposure of underground miners to diesel aerosols and gases.

Methodology

The aerosol and gaseous emissions for two older technology engines were characterized when those engines were fueled with (1) neat HVORD and (2) petroleum-derived ULSD. The neat HVORD was supplied by Neste Oil's Porvoo refinery. The locally acquired ULSD was used as a baseline fuel. The results of analysis performed on HVORD and ULSD by Cashman Fluids Laboratory (Sparks, NV) are summarized in Table 1.

Two non-road diesel engines were used in this study: (1) a 1999 Isuzu C240 (Isuzu Motors Limited), a mechanically controlled, naturally aspirated directly injected light-duty engine that conforms to U.S. EPA Tier 1 standards (Engine 1), and (2) a 2004 Mercedes Benz OM 904 LA, an electronically controlled, turbocharged medium-duty engine that conforms to U.S. EPA Tier 2 standards (Engine 2). Those engines were not adjusted to compensate for the substantial differences in physical and chemical properties between test fuels. Independent studies[26,30] have shown that engines with modifications made to compensate for changes in fuel properties, such as increasing injection pressure, theoretically, have the potential for relatively minor additional reductions in DPM emissions on top of those achieved by using HVORD in place of ULSD. The practices with FAME biodiesel fuels showed that mine operators in the U.S. are unlikely to invest into optimization of in-use engines to specific fuels.

Engine 1 was retrofitted with a diesel oxidation catalytic converter (DOC) supplied by Lubrizol (Purifier; Newmarket, Ontario, Canada). The ECS Purifier is representative of DOCs traditionally marketed to the underground mining industry for effective control of CO and hydrocarbon emissions. Engine 2 was retrofitted with a DOC supplied by AirFlow Catalyst Systems (Model MinNoDOC; Rochester, NY). The washcoat on the metal substrate of MinNoDOC was impregnated with a catalyst formulation that was specifically formulated to allow for the effective control of CO and hydrocarbon emissions from contemporary diesel engines while also controlling NO_2 emissions.[31]

Engine 1 and Engine 2 were coupled to the 150 kW and 400 kW water-cooled eddy-current dynamometers supplied by SAJ (Pune, India), respectively. Both engines were tested at four steady-state operating conditions (Table 2) and over the transient cycle shown for Engine 1 and ULSD in Figure 1. The fuel measurements systems supplied by Max Machinery, Inc. were used to measure fuel consumption of Engine 1 and Engine 2, respectively.

For all four steady-state operating conditions, Engine 1 generated comparable torque and consumed on average slightly more HVORD than ULSD by volume and slightly less HVORD than ULSD by mass (Table 2). For I50 and R50 operating conditions, Engine 2 generated comparable torque and consumed on average slightly more HVORD than ULSD by volume and slightly less HVORD than ULSD by mass (Table 2). For I100 and R100 operating conditions, respectively, Engine 2 generated 4.3 and 4.2% less torque and consumed on average slightly more HVORD than ULSD by volume and slightly less HVORD than ULSD by mass.

In an attempt to quantify effects of the fuels for conditions more representative of actual production scenarios, testing was done for the engines operated over a custom, transient mining cycle. This cycle has been recreated from field data to simulate operation of an engine in underground mining load-haul-dump vehicles. In the case of transient mining cycle tests, on average, Engine 1 generated comparable torque and consumed on average 7.6 percent more HVORD than ULSD by volume, and consumed a comparable amount of HVORD and ULSD by mass. On average, Engine 2 generated 11.5% less torque and consumed 2.4% less of HVORD than ULSD by volume and 9.6% less of HVORD than ULSD by mass.

The aerosol samplings and measurements were conducted in exhaust diluted approximately 30 times using a partial dilution system supplied by Dekati, Tampere, Finland (Model FPS4000). The results of aerosol measurements shown in this manuscript are normalized to a nominal dilution ratio of 30. Triplicate samples for gravimetric and carbon analysis were collected from the dilution system using custom-designed sampling systems. The effects of fuels on total mass concentrations of DPM were assessed using the results of gravimetric analysis. The results of thermal optical transmittance-evolve gas analysis (TOT-EGA) were used to study the effects of fuels on total mass concentrations of total and elemental carbon. Total number concentrations and size distributions of aerosols in diluted exhaust were measured using a TSI Fast Mobility Particle Sizer, Model 3091.[32] 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). Total surface area of aerosols deposited in the alveolar region (TSAADAR) of human lungs was measured in the diluted exhaust using a TSI Nanoparticle Surface Area Monitor (NSAM), Model 3550.[33]

The effects of the fuels on concentrations of CO, CO_2, NO, NO_2, and hydrocarbons were determined using results of measurements in raw exhaust downstream of the DOCs using a Fourier transform infrared analyzer (Gasmet, Model DX-4000). The concentrations of the following hydrocarbons were combined to obtain total hydrocarbon concentrations: ethane, propane, butane, pentane, hexane, octane, ethylene, acetylene, propene, 1,3-butadiene, formaldehyde, acetaldehyde, benzene, and toluene.

Three 2-hr test runs were executed for each combination of fuels and engine operating conditions. The filter samples for gravimetric and carbon analysis were collected for the duration of each of the tests. Size distributions, TSAADAR, total number concentrations, and concentrations of criteria gases were measured concurrently. However, only data collected during the last 30 min of each test were used to calculate the averages and standard deviation of means presented in this article.

Results

Aerosol emissions

The results of gravimetric and carbon analyses were used to calculate the total mass concentrations of DPM, total, and elemental carbon in diluted exhaust (dilution ration of 30) of Engine 1 (Figure 2a) and Engine 2 (Figure 2b). In order to compensate for slight variations in dilution rate, the values were normalized to a dilution rate of 30. In all cases for Engine 1, the average total mass concentrations of DPM, total, and elemental carbon were reduced by more than 39% when the engine was fueled with HVORD in place of ULSD. The magnitude of reductions was similar for all but the R100 conditions, for which HVORD provided substantially higher advantages. In the Engine 2 tests, the average reductions in total mass concentrations of DPM, total, and elemental carbon for HVORD compared to those for ULSD were somewhat lower than those observed for tests conducted using Engine 1. The reductions were between 13 and 24% for all but the I50 condition. For this condition, the effects of fuels on the mass emissions between fuels were not practically discernable.

For both test fuels, the elemental carbon was found to make up over 85% of the total carbon emitted by Engine 1 and Engine 2 (Figure 3). For the majority of Engine 1 cases, the average fraction of elemental carbon in total carbon was slightly higher for HVORD than ULSD. The exception was the ULSD I100 condition, where a higher fraction of elemental carbon in total carbon was observed for ULSD than for HVORD. For the majority of Engine 2 cases, the fraction of elemental carbon in total carbon was comparable or slightly higher for HVORD than for ULSD.

The TSAADAR in the diluted exhaust of Engine 1 and Engine 2 for ULSD and HVORD are shown in Figure 4. For the tests where Engine 1 was operated at I100, concentrations in the diluted exhaust substantially exceeded the upper measurement range of the NSAM instrument (10,000 $\mu m^2/cm^2$), and therefore were not reported. For the other three test conditions conducted using Engine 1, the use of HVORD favorably affected TSAADAR. The highest average reduction of 41% in TSAADAR was observed for the R100 conditions. For Engine 2, the use of HVORD adversely affected TSAADAR for I50 conditions, and did not have a measurable effect on TSAADAR for I100, R50, and R100 conditions. The average increase in TSAADRA of 35 percent was observed for the I50 conditions.

The results of direct measurements of total number concentrations with the FMPS for Engine 1 and Engine 2 tests are summarized in Figure 5. In the case of Engine 1, the use of HVORD favorably affected total number concentrations of aerosols. The highest average reduction (28%) in total number concentrations was observed for the R50 conditions. In the case of the test conducted on Engine 2, the use of HVORD adversely affected total number concentrations for the I50 and R100 conditions, and did not have a measurable effect on total number concentrations for the I100 and R50 conditions. The highest increase in total number concentrations (25%) was observed for the I50 conditions.

The effects of the fuels on size distributions of aerosols were examined via the results of selected measurements performed in diluted exhaust from Engine 1 and Engine 2 (Figure 6). The concentrations were normalized to dilution ratio of 30. For both tested fuels, aerosols emitted by Engine 1 and Engine 2 were distributed in single accumulation mode (Figure 6 and Table 3). For Engine 1, the size distributions for the HVORD tests were characterized with the smaller count median diameters (CMDs) and lower total and peak concentrations of aerosols by comparison to the corresponding ULSD tests (Figure 6a and Table 3). For Engine 2, the aerosols emitted while the engine was supplied with HVORD in place of ULSD were characterized with the smaller or equivalent CMDs and higher or equivalent total and peak concentrations of aerosols (Figure 6b and Table 3).

Gaseous emissions

The CO_2 concentrations in the exhaust from Engine 1 and Engine 2 were slightly lower for HVORD than for ULSD (Figure 7). The lower CO_2 emissions corresponded with the lower mass fuel consumption of HVORD than ULSD (Table 2).

For all test conditions, the DOC retrofitted to Engine 1 was found to be much more effective in oxidizing CO and NO_2 than the one retrofitted to Engine 2. The resulting DOC-out concentrations of CO in the exhaust of Engine 1 were very low and it was not possible to quantify the effects of fuels, if any, on CO emissions. In the case of Engine 2, for the I50 and R50 engine operating conditions, the CO concentrations were 51 and 41%, respectively, lower when HVORD was used in place of ULSD (Figure 7b). In the case of the I100 and R100 conditions, the CO emissions for HVORD were quite comparable to those for ULSD.

With the exception of the case when Engine 1 was operated at the R50 conditions, HVORD favorably affected NO_X concentrations (Figure 7c). Since for all test conditions NO made up the major fraction of NO_X, the effects of the fuels on NO emissions were quite similar to the effects of those on NO_X emissions (Figure 7d). The reductions in average NO_X and NO concentrations were up to 20 and 30%, respectively.

Since the DOC retrofitted to Engine 1 was very effective in oxidizing NO to NO_2, the NO_2 levels in the exhaust of Engine 1 fueled with ULSD, particularly when operated at the I100 and R100 conditions, were relatively high. The NO_2 concentrations were found to be even higher when HVORD was used in place of ULSD (Figure 7e). Since the NO_2 concentrations in the exhaust of Engine 2 were generally very low and the DOC retrofitted to Engine 2 was not very effective in oxidizing NO to NO_2, the resulting DOC-out concentrations of NO_2 for Engine 2 were too low to allow for quantification of the effects of fuels on NO_2 concentrations.

In the case of Engine 1, HVORD produced higher total hydrocarbon emissions than ULSD for the I50, I100, and R100 conditions, while total hydrocarbon emissions were lower for the

R50 conditions. HVORD slightly reduced concentrations of total hydrocarbons in DOC-out exhaust of Engine 2 for all conditions.

Discussion

According to the results of this study and similar results reported elsewhere,[26,28,29] fueling diesel-powered vehicles with HVORD in place of ULSD should result in lower total mass concentrations of DPM, total, and elemental carbon emitted. However, based on the results of concurrent testing of two different types of engines, this study uniquely demonstrated that the reductions in total mass concentrations could differ between a naturally aspirated mechanically controlled (Engine 1) and a turbocharged electronically controlled engine (Engine 2) operated under similar conditions.

The effects of HVORD on TSAADAR and total number concentration of aerosols were found to be substantially different between the tested engines and engine operating conditions: for all test conditions, HVORD reduced TSAADAR and total number concentration of aerosols in the exhaust of Engine 1. With the exception of the R100 conditions, HVORD increased TSAADAR aerosols in the exhaust of Engine 2. The use of HVORD also adversely affected total number concentration in the exhaust of Engine 2 for I50 and R100 conditions, but not for I100 and R50 conditions. The differences in the CMDs of aerosols in the exhaust of both engines for HVORD and ULSD were rather minor.

The results on the effects of HVORD on regulated gaseous emissions are in general agreement with results of previously published studies.[26,28–30] However, the majority of those studies reported effects of the NO_X emissions, but none reported separately the effects on two major NO_X components: NO and NO_2. Due to the relatively high toxicity[34] and technical and economic issues related to ventilation, the NO_2 emissions are of particular concern in the case of confined occupational environments. This study showed that HVORD has the potential to adversely affect NO_2 emissions from naturally aspirated engines equipped with certain types of DOCs.

Conclusion

This study showed that fueling vehicles powered with older technology diesel engines with HVORD might help current efforts to reduce workers' exposure to diesel aerosols and transition toward more universal solutions to this issue provided by advanced engine technologies.[35,36] However, further investigations are needed to expand on the limited knowledge[28] available on the health outcomes associated with exposure to these aerosols and gases.

Acknowledgments

We would like to acknowledge the contributions of Neville Fernandes of Neste Oil, Charles Westover of Newmont USA Ltd., and Larry Patts of NIOSH OMSHR for supplying and handling the fuels used in this study.

Acronyms

ACGIH	American Conference of Governmental Industrial Hygienists

API	American Petroleum Institute
ASTM	ASTM International, an international standards organization that develops and publishes voluntary consensus technical standards
CMD	count median diameter
CO	carbon monoxide
CO_2	carbon dioxide
DOC	diesel oxidation catalytic converter
D_p	particle diameter
DPM	diesel particulate matter
FAME	fatty-acid methyl esters
FMPS	Fast Mobility Particle Sizer
HVORD	hydrotreated vegetable oil renewable diesel
I50	intermediate speed 50% load (ISO M8)
I100	intermediate speed 100% load (ISO M6)
ISO	International Organization for Standardization
LSD	low sulfur diesel
MSHA	Mine Safety and Health Administration
N	Number
NIOSH	National Institute for Occupational Safety and Health
NO	nitric oxide
NO_2	nitrogen dioxide
NO_X	nitric oxides ($NOx = NO+NO_2$)
NSAM	Nanoparticle Surface Area Monitor,
OMSHR	Office of Mine Safety and Health Research
PAH	polycyclic aromatic hydrocarbons
R50	rated speed 50% load (ISO M3)
R100	rated speed 100% load (ISO M1)
SAE	Society of Automotive Engineers
SCR	selective catalyst reduction

TC	total carbon
TLV	threshold limit values (ACGIH)
TOT-EGA	thermal optical transmittance-evolve gas analysis
TSAADAR	total surface area of aerosols deposited in the alveolar region of human lungs
ULSD	ultralow sulfur diesel
U.S. EPA	U.S. Environmental Protection Agency
UV	Ultraviolet
σ	log-normal distribution spread

References

1. IARC. Press Release N^{o} 213. International Agency for Research on Cancer, World Health Organization; Jun 12. 2012 Diesel Engine Exhaust Carcinogenic.
2. Mills NL, Törnqvist H, Robinson SD, et al. Diesel exhaust inhalation causes vascular dysfunction and impaired endogenous fibrinolysis: An explanation for the increased cardiovascular mortality associated with air pollution. Circulation. 2005; 112(25):3930–3936. [PubMed: 16365212]
3. Power MC, Weiskopf MG, Alexeeff SE, et al. Traffic-related air pollution and cognitive functions in a cohort of older men. Environ Health Perspect. 2011; 119:682–687. [PubMed: 21172758]
4. Lung S, Cassee FR, Gosen I, Campbell A. Brain suppression of AP-1 by inhaled diesel exhaust and reversal by cerium oxide nanoparticles. Inhal Toxicol. 2014; 26(1):636–641. [PubMed: 25144478]
5. Pronk A, Coblea J, Stewart PA. Occupational exposure to diesel engine exhaust: a literature review. J Exp Sci Envir Epid. 2009; 19:443–457.
6. Bugarski AD, Janisko SJ, Cauda EG, et al. Aerosols and Criteria Gases in an Underground Mine that Uses FAME Biodiesel Blends. Ann Occup Hyg. 2014; 58(8):971–982. [PubMed: 25060241]
7. Smagala TG, Christensen E, Christonson KM, Mohler RE, Gjersing E, McCormick RL. Hydrocarbon renewable and synthetic diesel fuel blendstocks: Composition and properties. Ener Fuels. 2013; 27:237–246.
8. Tsolakis A. Effects on particles size distribution from the diesel engine operating on RME-biodiesel with EGR. Ener Fuels. 2006; 20:1418–1424.
9. Mueller CJ, Boehman AL, Martin GC. An Experimental Investigation of the Origins of Increased NO_X Emissions when Fueling a Heavy-Duty Compression-Ignition Engine with Soy Biodiesel. SAE Technical Paper 2009-01-1792. 2009
10. Hajbabaei M, Jornson KC, Okamoto RA, Mitchell A, Pulman M, Durbin TD. Evaluation of the impact of biodiesel and second generation of biofuels on NO_X emissions for CARB diesel fuels. Environ Sci Technol. 2012; 46:9163–9173. [PubMed: 22788711]
11. Durbin DT, Cocker DR III, Sawant AA, et al. Regulated emissions from biodiesel fuels from on/off-road applications. Atmos Environ. 2007; 41:5647–5658.
12. Walkowicz K, Na K, Robertson W, et al. On-Road and In-Laboratory Testing to Demonstrate Effects of ULSD, B20, and B99 on a Retrofit urea-SCR After Treatment System. SAE Technical Paper 2009-01-2733. 2009
13. Williams A, McCormick RL, Hayes R, Ireland J, Fang HL. Effects of Biodiesel on Diesel Particulate Filter Performance. SAE Technical Paper 2006-01-3280. 2006
14. Yuan CS, Lin HY, Lee WJ, Lin YC, Wu TS, Chen KF. A new alternative fuel for reduction of polycyclic aromatic hydrocarbon and particulate matter emissions from diesel engines. J Air Waste Manage Assoc. 2007; 57:465–471.

15. Bugarski, AD., Hummer, JA., Robb, GM. Diesel Oxidation Catalytic Converters for Underground Mining Applications. In: Jong, E.Sarver, E.Schafrik, S., Luxbacher, K., editors. Proceeding of 15th North American Mine Ventilation Symposium. Blacksburg, VA: Virginia Tech; 2015. p. 289-296.
16. Tsai JH, Chen S-J, Huang K-L, et al. PM, carbon, and PAH emissions from a diesel generator fuelled with soy-biodiesel blends. J Haz Mat. 2010; 179:237–243.
17. Bugarski AD, Cauda EG, Janisko SJ, Hummer JA, Patts LD. Aerosols emitted in underground mine air by diesel engine fueled with biodiesel. J Air Waste Manage Assoc. 2010; 60:237–244.
18. Monyem A, van Gerpen JH. The effect of biodiesel oxidation on engine performance and emissions. Biomass Bioener. 2001; 20(4):317–325.
19. Correa SM, Arbilla G. Aromatic hydrocarbons emissions in diesel and biodiesel exhaust. Atmos Environ. 2006; 40:6821–6826.
20. Chung A, Lall AA, Paulson SE. Particulate emissions by a small non-road diesel engine: biodiesel and diesel characterization and mass measurements using the extended idealized aggregates theory. Atmos Environ. 2008; 42:2129–2140.
21. Shvedova AA, Yanamal N, Murray AR, et al. Oxidative stress, inflammatory biomarkers, and toxicity in mouse lung and liver after inhalation exposure to 100% biodiesel of petroleum diesel emissions. J Tox Environ Health Part A. 2013; 76(15):907–921.
22. Yanamala N, Hatfield MK, Farcas MT, et al. Biodiesel versus diesel exposure: Enhanced pulmonary inflammation, oxidative stress, and differential morphological changes in the mouse lung. Tox Appl Pharm. 2013; 272:373–383.
23. Fukagawa NK, Li M, Poynter ME, et al. Soy biodiesel and petrodiesel emissions differ in size, chemical composition and stimulation of inflammatory response in cell s and animals. Environ Sci Technol. 2013; 47:12496–12504. [PubMed: 24053625]
24. Kisin ER, Yanamala N, Farcas MT, et al. Abnormalities in the male reproductive system after exposure to diesel and biodiesel blend. Environ Molec Mutag. 2015; 56(2):265–276.
25. Stevanovic S, Miljevic B, Surawski NC, et al. Influence of oxygenated organic aerosols (OOAs) on the oxidative potential of diesel and biodiesel particulate matter. Environ Sci Technol. 2013; 47:7655–7662. [PubMed: 23763365]
26. Aatola H, Larmi M, Sarjovaara T, Mikkonen S. Hydrotreated Vegetable Oil (HVO) as a RD Fuel: Trade-off between NOX Particulate Emissions, and Fuel Consumption of a Heavy Duty Engine. SAE Technical Paper 2008-01-2500. 2008
27. Huber GW, O'Connor P, Corma A. Processing biomass in conventional oil refineries: Production of high quality diesel by hydrotreating vegetable oils in heavy vacuum oil mixtures. App Cat A: Gen. 2007; 329:120–129.
28. Westphal GA, Krahl J, Munack A, et al. Combustion of hydrotreated vegetable oil and jatropha methyl ester in a heavy-duty engine: Emissions and bacterial mutagenicity. Environ Sci and Technol. 2013; 47:6038–6046. [PubMed: 23647143]
29. Kim D, Kim S, Oh S, No S-Y. Engine performance and emission characteristics of hydrotreated vegetable oil in light duty diesel engines. Fuel. 2014; 125:36–43.
30. Happonen M, Heikkilä J, Murtonen T, et al. Reductions in particulate and NO_X emissions by diesel engine parameter adjustment with HVO fuel. Environ Sci Technol. 2012; 46:6198–6204. [PubMed: 22568591]
31. Bugarski, AD., Hummer, JA., Robb, GM. Diesel Oxidation Catalytic Converters for Underground Mining Applications. In: Luxbacher, K., editor. Proceeding of 15th North American Mine Ventilation Symposium. Blacksburg, VA: Jun 19–23. 2015 p. xxx-yyy.
32. Johnson T, Caldow R, Pöcher A, Mirme A, Kittelson D. A New Electrical Mobility Particle Sizer Spectrometer for Engine Exhaust Particle Measurements. SAE Technical Paper 2004-01-1341. 2004
33. Fissan H, Neumann S, Trampe A, Pui DYH, Shin WG. Rationale and principle of an instrument measuring lung deposited nanoparticle surface area. J Nanopart Res. 2007; 9:53–59.
34. NIOSH. Pocket Guide to Chemical Hazards. Department of Health and Human Services, Centers for Disease Control and Prevention National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 2005-149; 2007. p. 228

35. Bugarski, AD., Janisko, S., Cauda, EG., Noll, JD., Mischler, SE. The Controlling Exposure – Diesel Emissions in Underground Mines. Englewood, CO: Society for Mining, Metallurgy, and Exploration Inc; 2012. Integrated, Multifaceted Approach Toward Controlling Exposure to Particulate Matter and Gasess From Diesel Engines; p. 63

36. Scheepers PT, Vermeulen RCH. Diesel engine exhaust classified as a human lung carcinogen. How will this affect occupational exposure? Occ Envir Med. 2012; 69(10):691–693.

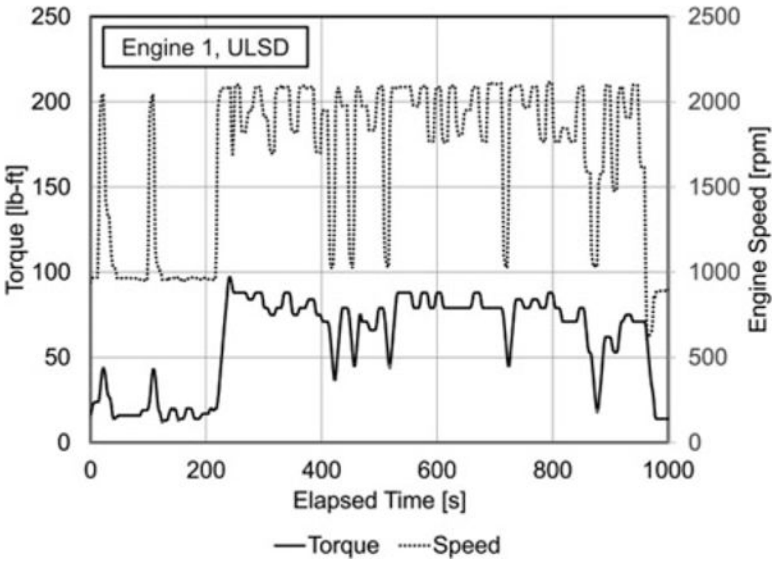
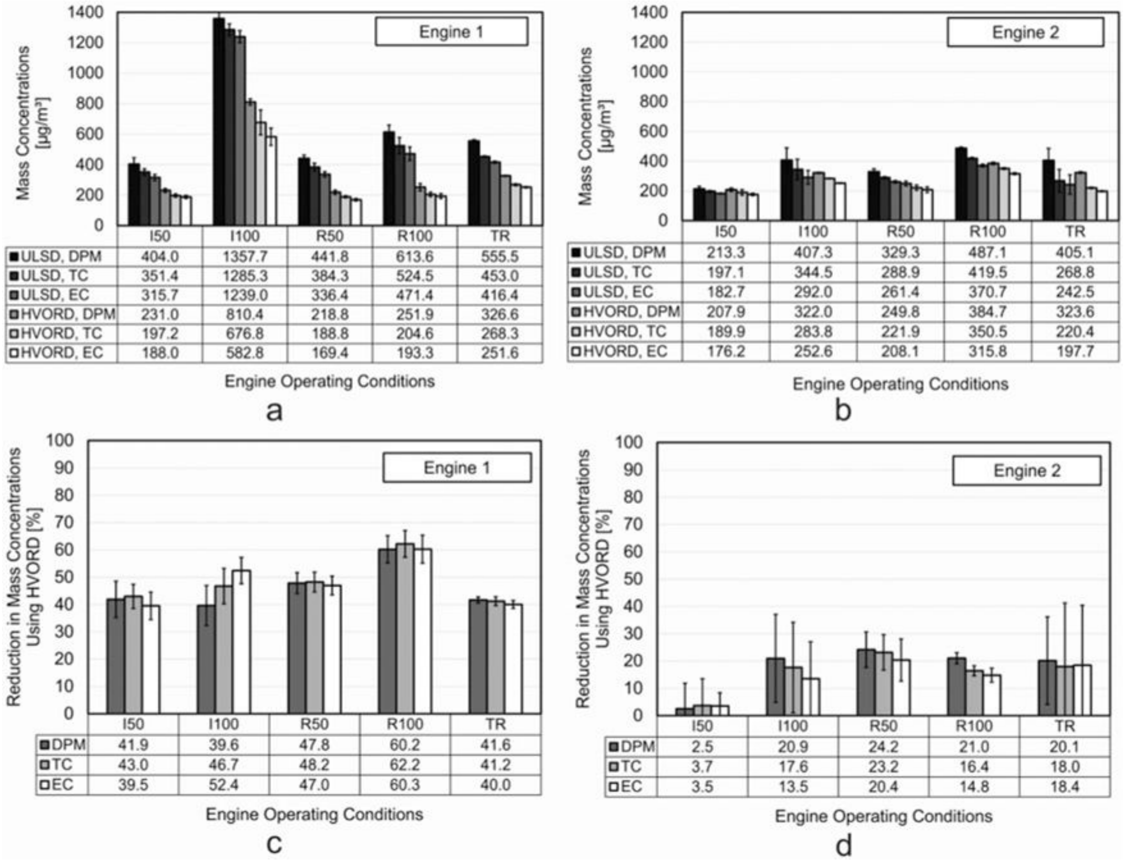


Figure 1.

Transient mining cycles for Engine 1 fueled with ULSD.



a

	I50	I100	R50	R100	TR
■ULSD, DPM	404.0	1357.7	441.8	613.6	555.5
■ULSD, TC	351.4	1285.3	384.3	524.5	453.0
■ULSD, EC	315.7	1239.0	336.4	471.4	416.4
▨HVORD, DPM	231.0	810.4	218.8	251.9	326.6
☐HVORD, TC	197.2	676.8	188.8	204.6	268.3
☐HVORD, EC	188.0	582.8	169.4	193.3	251.6

b

	I50	I100	R50	R100	TR
■ULSD, DPM	213.3	407.3	329.3	487.1	405.1
■ULSD, TC	197.1	344.5	288.9	419.5	268.8
■ULSD, EC	182.7	292.0	261.4	370.7	242.5
▨HVORD, DPM	207.9	322.0	249.8	384.7	323.6
☐HVORD, TC	189.9	283.8	221.9	350.5	220.4
☐HVORD, EC	176.2	252.6	208.1	315.8	197.7

c

	I50	I100	R50	R100	TR
■DPM	41.9	39.6	47.8	60.2	41.6
▨TC	43.0	46.7	48.2	62.2	41.2
☐EC	39.5	52.4	47.0	60.3	40.0

d

	I50	I100	R50	R100	TR
■DPM	2.5	20.9	24.2	21.0	20.1
▨TC	3.7	17.6	23.2	16.4	18.0
☐EC	3.5	13.5	20.4	14.8	18.4

Figure 2.

Effects of the fuels on total mass concentrations of diesel aerosols in diluted exhaust (dilution ratio of 30): (a) gravimetric DPM, total carbon (TC), and elemental carbon (EC) for Engine 1, (b) gravimetric DPM, TC, and EC for Engine 2, (c) changes in total mass concentrations for Engine 1, and (d) changes in total mass concentrations for Engine 2.

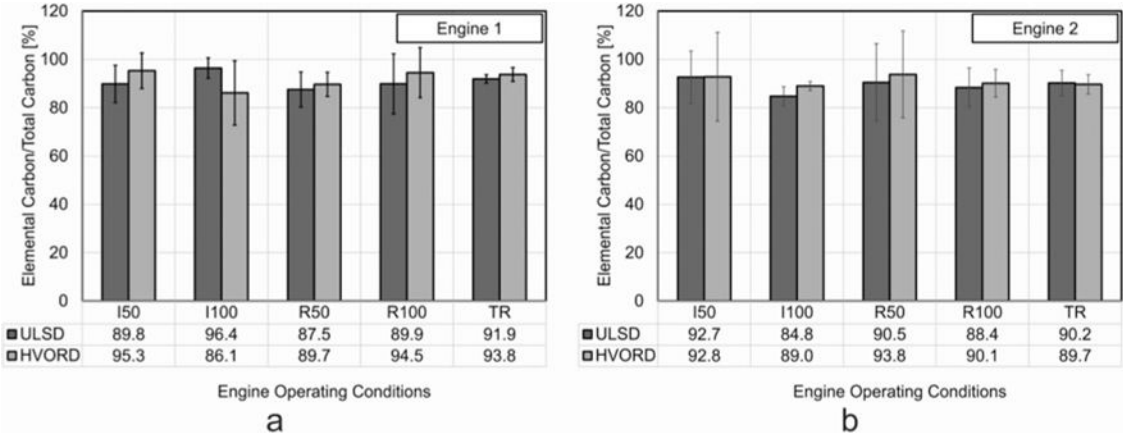


Figure 3.

Effects of the fuels on split between carbon fractions: (a) Engine 1 and (b) Engine 2.

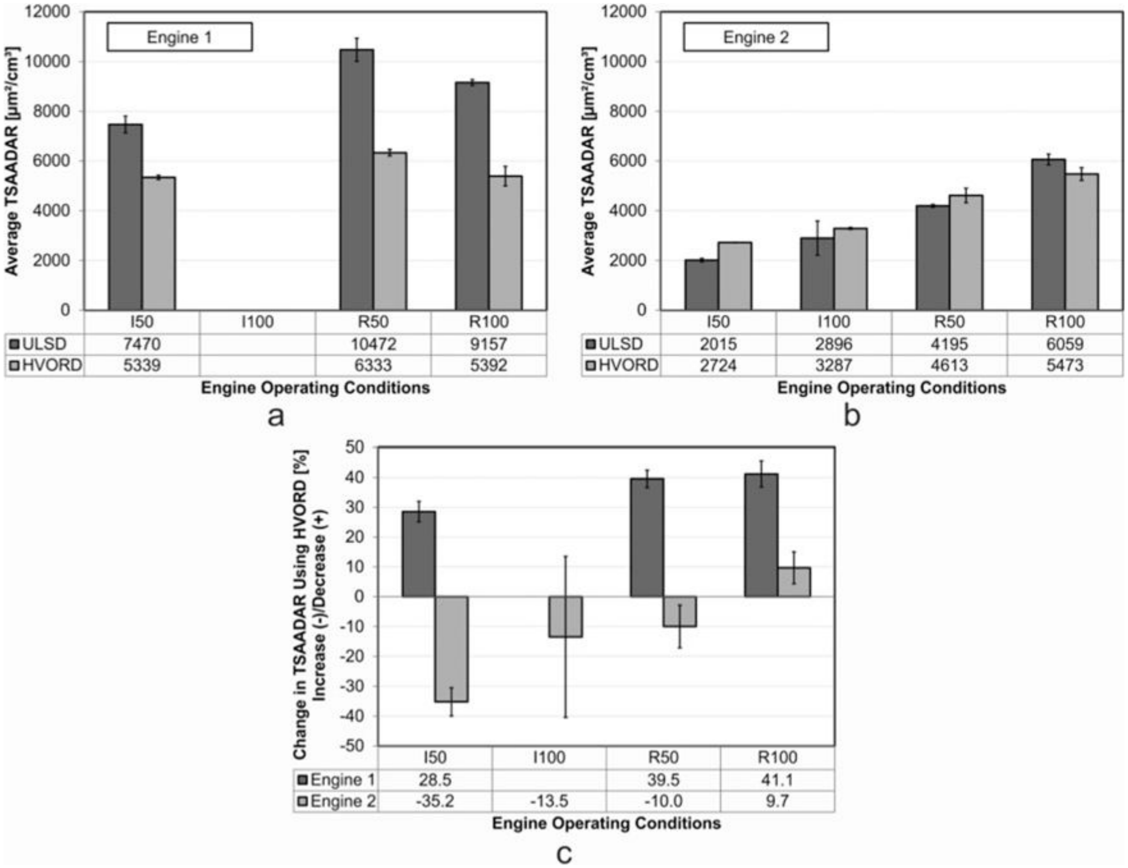


Figure 4.

Effects of the fuels on TSAADAR: (a) TSAADAR in diluted exhaust (dilution ration of 30) of Engine 1, (b) TSAADAR in diluted exhaust (dilution ration of 30) of Engine 2, and (c) changes in TSAADAR for Engine 1 and Engine 2.

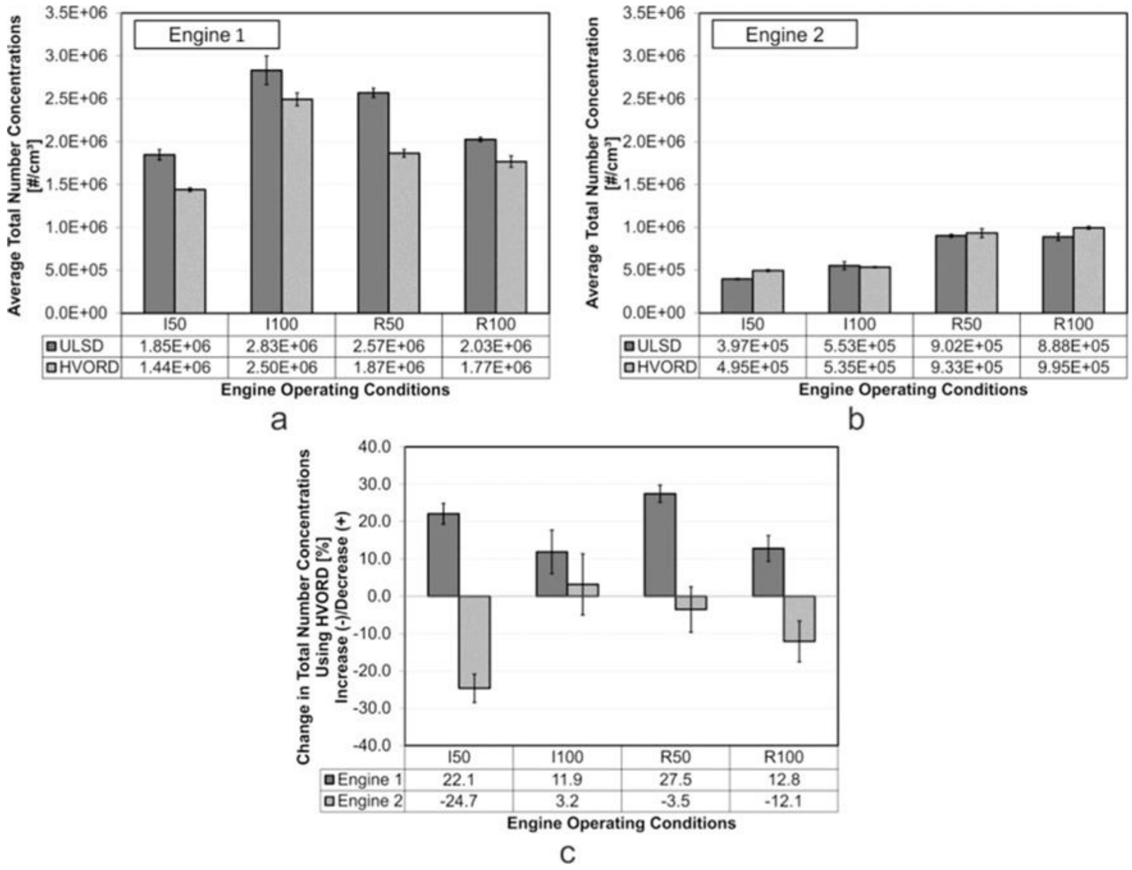


Figure 5.

Effects of the fuels on total number concentrations in diluted exhaust (dilution ration of 30): (a) Engine 1, (b) Engine 2, and (c) changes for Engine 1 and Engine 2.

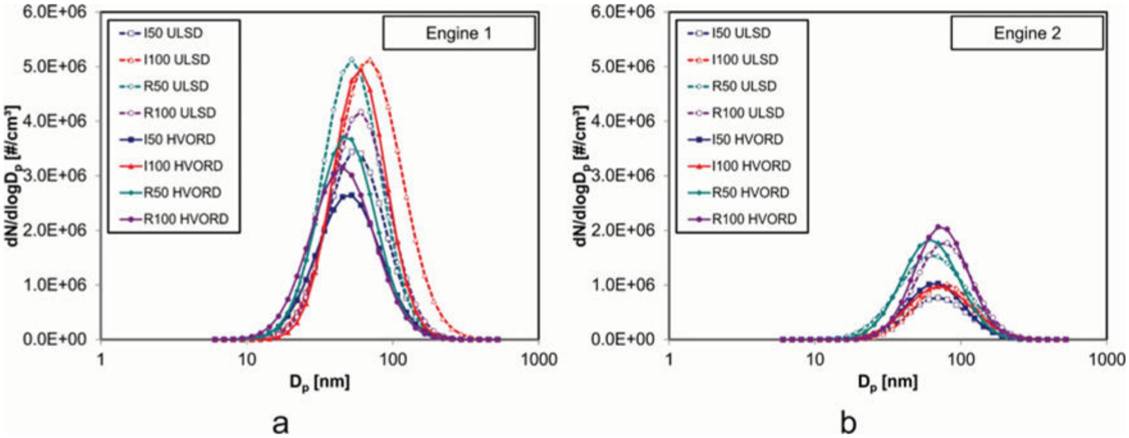


Figure 6.

Effects of the fuels on sized distribution of aerosols in diluted exhaust (dilution ratio of 30) of: (a) Engine 1 and (b) Engine 2.

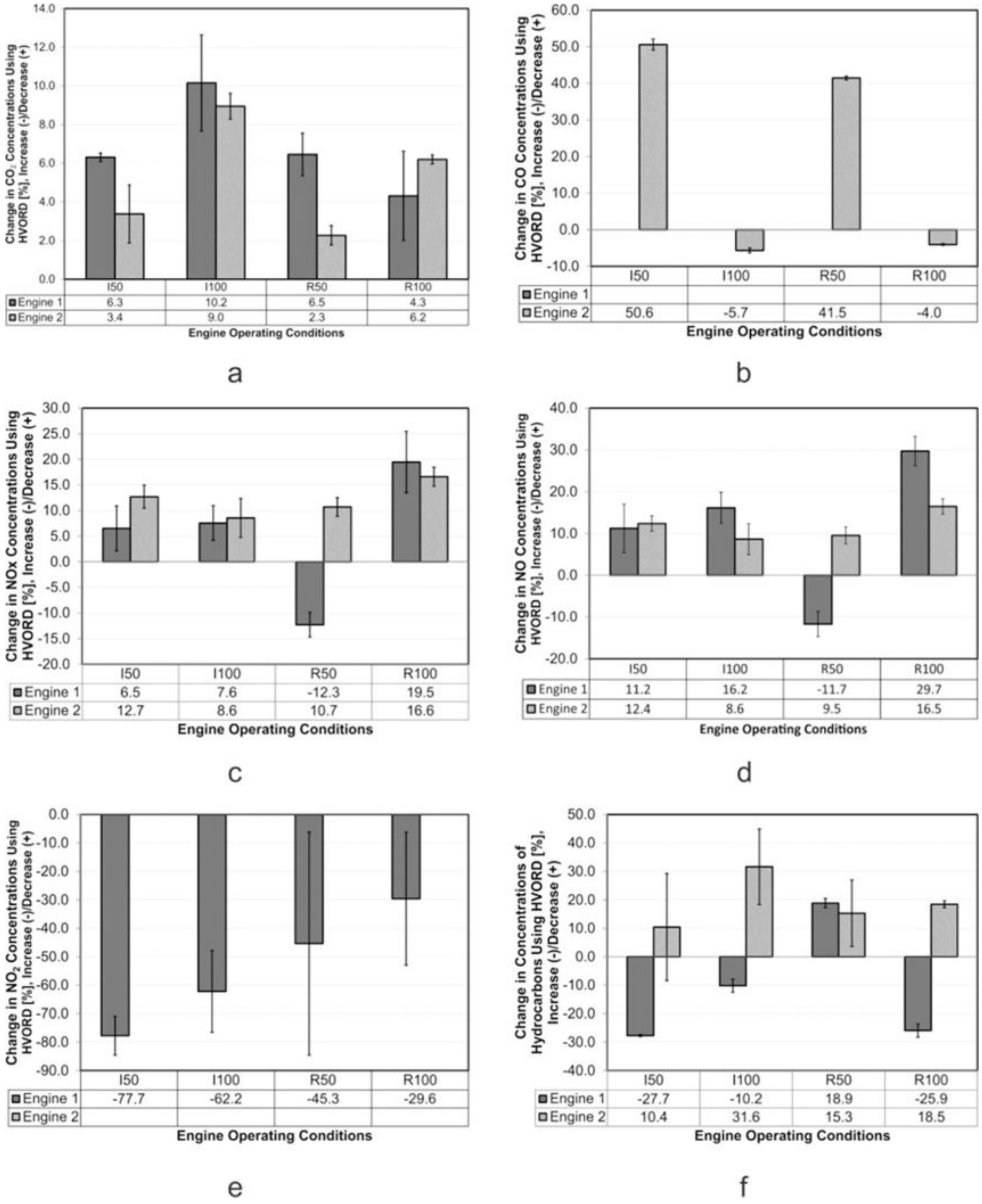


Figure 7.

Changes in concentrations of criteria gases emitted by Engine 1 and Engine 2: (a) CO_2, (b) CO, (c) NO_X, (d) NO, (e) NO_2, and (f) total hydrocarbons.

Table 1

Fuel properties.

Fuel Property	Test Method	ULSD	HVORD
Aromatics [vol %]	ASTM D1319	24.2	<5.0
Olefins [vol %]	ASTM D1319	1.6	1.2
Saturates [vol %]	ASTM D1319	74.2	>95.0
Flash Point, Closed Cup [K]	ASTM D93	335.7	359.8
Sulfur, by UV [ppm]	ASTM D5453	7.4	0.0
Viscosity @ 40°C [cSt]	ASTM D445	2.4	3.0
Sim. Dist., 50% Recovery [K]	ASTM D2887	505.0	562.0
Sim. Dist., 90% Recovery [K]	ASTM D2887	608.6	585.9
Cetane Index	ASTM D4737	43.9	93.2
Cetane Number	ASTM D613	44.5	75.2
Density [kg/m^3]	ASTM D1298	0.84	0.78
Heat of Combustion [MJ/kg]	ASTM D240	50.1	50.7

Table 2

Engine operating conditions and parameters for Engine 1 and Engine 2 operated on ULSD and HVO.

		ULSD				HVORD			
Engine	**Engine Operating Conditions**	**Engine Speed [rpm]**	**Torque [Nm]**	**Fuel Rate [ml/s]**	**Fuel Rate [g/s]**	**Engine Speed [rpm]**	**Torque [Nm]**	**Fuel Rate [ml/s]**	**Fuel Rate [g/s]**
Engine 1	I50	2000	68	1.1	0.9	2000	68	1.2	0.9
	I100	2000	135	2.2	1.9	1990	136	2.3	1.8
	R50	2950	54	1.5	1.3	2950	54	1.6	1.2
	R100	2950	108	2.6	2.2	2950	107	2.7	2.1
Engine 2	I50	1400	319	3.4	2.8	1400	319	3.6	2.8
	I100	1400	637	6.4	5.4	1400	610	6.4	5.0
	R50	2200	258	4.9	4.1	2200	258	5.3	4.1
	R100	2200	515	8.6	7.2	2200	495	8.8	6.8

Table 3

Statistical parameters for the size distributions of aerosols in diluted exhaust (DR = 30) from Engine 1 and Engine 2.

		Engine 1			Engine 2		
Fuel	EOC	Total Number Concentration #/cm^3	CMD nm	σ –	Total Number Concentration #/cm^3	CMD nm	σ –
ULSD	I50	1.75E+06	55	1.59	3.77E+05	69	1.63
	I100	2.90E+06	68	1.68	6.04E+05	81	1.56
	R50	2.52E+06	52	1.57	9.02E+05	64	1.71
	R100	2.08E+06	59	1.58	8.62E+05	73	1.69
HVORD	I50	1.45E+06	50	1.65	4.76E+05	65	1.57
	I100	2.26E+06	59	1.52	5.20E+05	75	1.55
	R50	1.86E+06	48	1.58	9.01E+05	62	1.57
	R100	1.72E+06	45	1.65	9.47E+05	73	1.52