Hydrotreated Vegetable Oil Renewable Diesel as a Control Strategy to Reduce Exposure of Underground Miners to Diesel Aerosols and Gases

By

Aleksandar D. Bugarski, Jon A. Hummer, and Shawn Vanderslice

National Institute for Occupational Safety and Health (NIOSH)

Office of Mine Safety and Health Research (OMSHR)

21st Mining Diesel Emissions Council (MDEC) Conference
Toronto, Canada, October 5-8, 2015

Introduction

- Changing the fuel supply from petroleum diesel to neat or blended biodiesel fuels is considered by a number of underground metal and nonmetal mine operators in the U.S. to be a viable method for controlling diesel particulate matter (DPM) emissions.
- Until recently, underground mines in the U.S. using biodiesel fuels are exclusively using fatty-acid methyl ester (FAME) biodiesels, which are made from various vegetable oils and animal fats through the process of transesterification.
- Recently, some underground operations started fueling their diesel-powered vehicles with blends of renewable diesel fuel produced via the process of hydrotreatment of vegetable oils.
- This fuel is know as hydrotreated vegetable oil renewable diesel (HVORD).

3

Introduction

- The objective of the study was to assess the potential of HVORD as a control strategy for reducing exposure of underground miners to diesel aerosols and gases.
- Results of comprehensive testing were used to characterize aerosol and gaseous emissions from an older technology engine operated using:
  - neat HVORD, and
  - ultralow sulfur diesel (baseline fuel).

4

Fuels

- The neat HVORD evaluated in this study was supplied by Neste Oil.
- The locally acquired ULSD was used as a baseline fuel.
- The fuel analysis was performed on the samples of HVORD and ULSD by Cashman Fluids Laboratory, Sparks, NV.

Fuel Properties	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 [˚C]	ASTM D93	62.5	86.6
Sulfur, by UV [ppm]	ASTM D5453	7.4	0.0
Cetane Number	ASTM D613	44.5	75.2
API Gravity @ 15.6 ˚C [˚API]	ASTM D1298	36.9	49.9
Heat of Combustion [BTU/gal]	ASTM D240	139945.0	141638.0

HVORD vs. ULSD

5

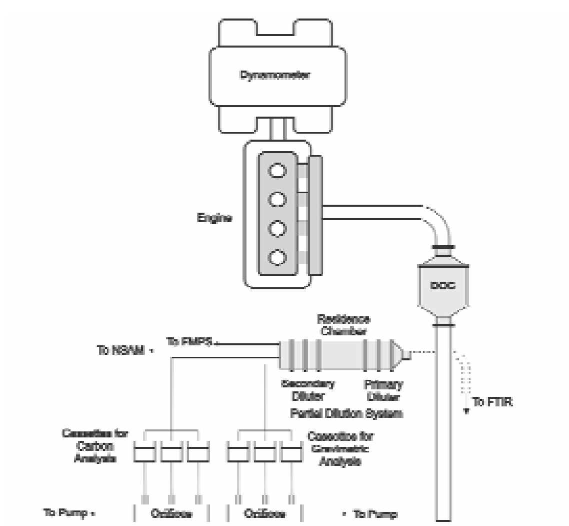
- Chemically, HVORD is a mixture of paraffinic hydrocarbons, free of sulfur and aromatic hydrocarbons.
- HVORD has substantially higher API gravity than ULSD.
- HVORD has energy content similar to ULSD and a substantially higher Cetane number.

Fuel Properties	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 [˚C]	ASTM D93	62.5	86.6
Sulfur, by UV [ppm]	ASTM D5453	7.4	0.0
Cetane Number	ASTM D613	44.5	75.2
API Gravity @ 15.6 ˚C [˚API]	ASTM D1298	36.9	49.9
Heat of Combustion [BTU/gal]	ASTM D240	139945.0	141638.0

Methodology

6

- Testing took place at the diesel laboratory of the National Institute for Occupational Safety and Health (NIOSH), Office of Mine Safety and Health Research (OMSHR).
- The layout of the sampling and measurement systems used in this study is shown here.



Engine

7

- 1999 Isuzu C240 (Isuzu Motors Limited), a mechanically controlled, naturally-aspirated directly-injected light duty engine conforms to U.S. EPA Tier 1 standards.
- The engine was retrofitted with a DOC supplied by Lubrizol, New Market, ON (Model Purifier). The Purifier is representative of DOCs traditionally marketed to the underground mining industry for effective control of CO and hydrocarbon emissions.
- The engine was not recalibrated or adjusted for the substantial differences in density and Cetane number, and to potentially take full advantage of HVORD.
- Isuzu C240 was coupled to the SAJ SE150 (Pune, India), 150 kW water-cooled eddy-current dynamometer.

The aerosol sampling and measurements were conducted in exhaust diluted approximately 30 times using a partial dilution system.

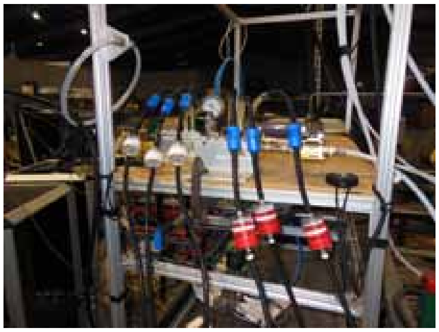
8

- The partial dilution system used in this study was supplied by Dekati, Tampere, Finland (Model FPS4000).
- Exhaust was diluted in two stages:
  - the primary dilution occurred in a perforated disk diluter and
  - the secondary dilution was provided by an ejector diluter.
- The residence chamber was inserted between those two stages to allow for potential formation of nucleation aerosols.

The effects of fuels on mass concentrations were assessed using results of carbon and gravimetric analysis.

9

- Triplicate samples for gravimetric and carbon analysis were collected from the dilution system using a custom designed sampling systems.
- The effects of fuels on mass concentrations of diesel particulate matter (DPM) were assessed using the results of gravimetric analysis.
- The effects of fuels on mass concentrations of total carbon (TC) and elemental carbon (EC) were assessed using the results of thermal optical transmittance-evolve gas analysis (TOT-EGA).



Number Concentrations, Size Distributions, and Surface Area Concentrations of Aerosols.

10

- Number concentrations and size distributions of aerosols in diluted exhaust were measured using Fast Mobility Particle Sizer (TSI, Model 3091).
- Surface area of aerosols deposited in alveolar region of human lungs in diluted exhaust was measured using a Nanoparticle Surface Area Monitor (TSI, Model 3550 NSAM).

Engine Operating Conditions

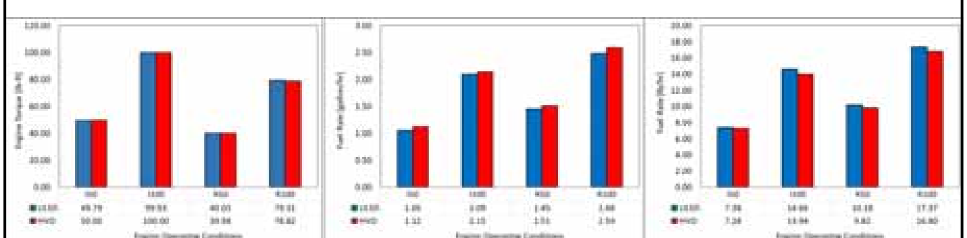
11

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

Engine Operating Conditions and Fuel Consumption

12

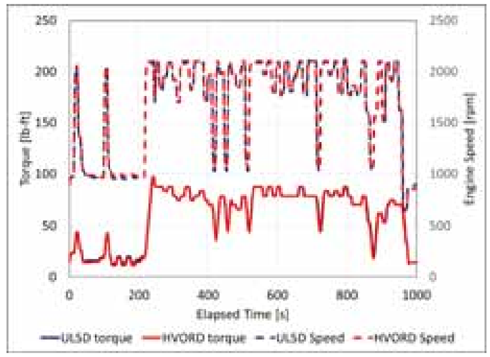
- The tests were done for four steady-state operating conditions and over one transient cycle.
- The steady-state conditions (I50, I100, R50, and R100) used in this study are part of the International Standards Organization for Standardization (ISO) 8178 8-mode test cycle.
- For all steady-state operating conditions, the engine generated comparable torque and consumed on average slightly more HVORD than ULSD by volume and slightly less HVORD than ULSD by mass.



12

Engine Operating Conditions and Fuel Consumption

- In an attempt to quantify effects of the DOCs for more production-representative conditions, the engine was operated over a 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 TR cycle tests, on average the engine generated comparable torque and consumed on average 7.6 percent more HVORD than ULSD by volume, and consumed comparable amount of HVORD and ULSD by mass.

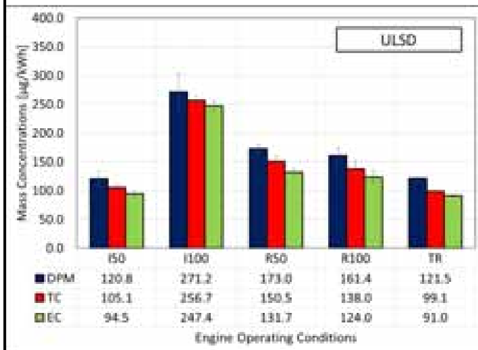


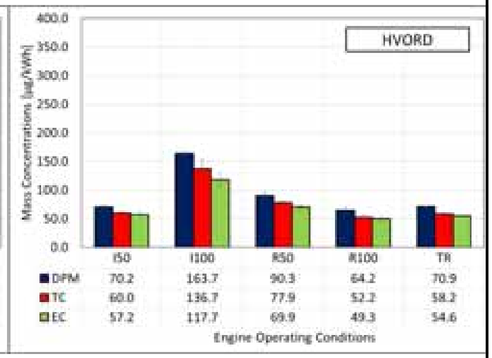
Effects of the Fuels on Aerosols

Effects of the Fuels on Total Mass Concentrations (TMC) of Aerosols

15

- The results of gravimetric and carbon analysis were used to assess the effects of ULSD and HVORD on total mass concentrations of DPM, TC, and EC.
- The average TMC for ULSD and HVORD are summarized below.

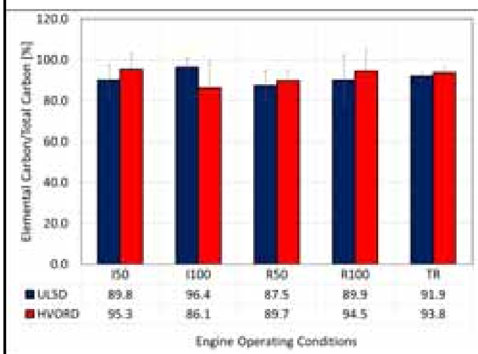


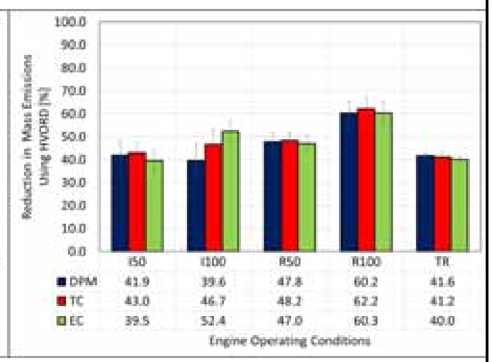


Effects of the Fuels on TMC of Aerosols

16

- For the majority of cases, the fraction of EC in TC was slightly higher for HVORD than for ULSD.
- The exception was the ULSD I100 test, where higher fraction of EC in TC was observed for ULSD than for HVORD.
- In all cases, the average mass concentrations of DPM, TC, and EC were more than 39 percent lower when the engine was fueled with HVORD than with ULSD.

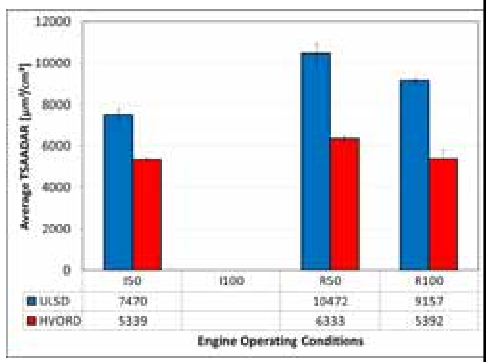




Effects of the Fuels on Total Surface Area of Aerosols Deposited in Alveolar Region (TSAADAR)

17

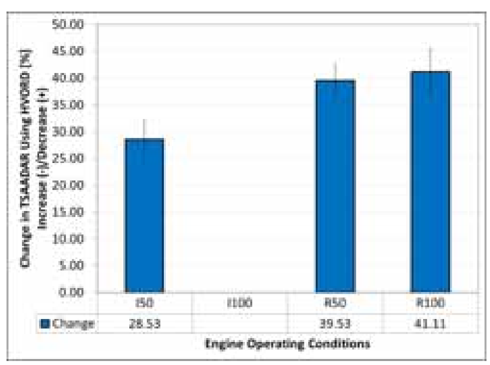
- The TSAADAR was measured using the NSAM.
- The averages and standard deviation of means were calculated using results of measurements performed during the last 30 minutes of each of three runs made for each of the test conditions.
- For the tests where the engine was operated at I100, concentrations exceeded the upper measurement range of the NSAM instrument (10,000 µm²/cm²) and, therefore were not reported.



Effects of the Fuels on Total Surface Area of Aerosols Deposited in Alveolar Region (TSAADAR)

18

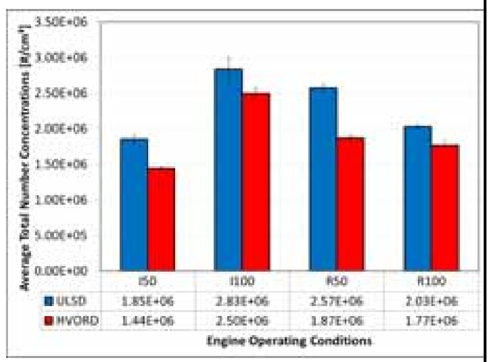
- The use of HVORD favorably affected TSAADAR.
- The highest average reduction (41%) in TSAADAR was observed for R100 conditions.



Effects of the Fuels on Total Number Concentrations (TNC) of Aerosols

19

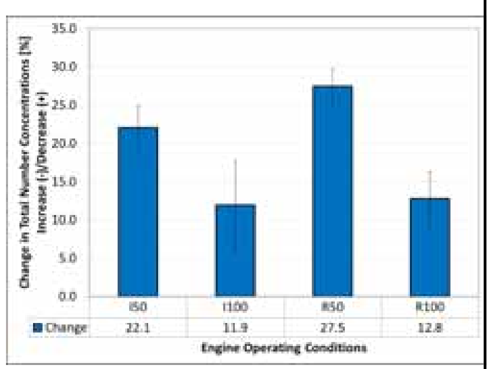
- The results of continuous measurements with the FMPS were used assess the effects of fuels on TNC.
- The averages and standard deviation of means were calculated using results of measurements performed during the last 30 minutes of each of three runs made for each of the test conditions.



Effects of the Fuels on Total Number Concentrations (TNC) of Aerosols

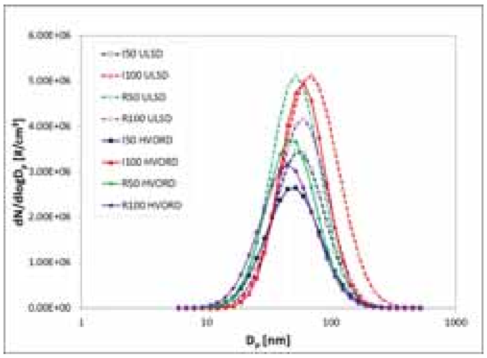
20

- The use of HVORD favorably affected TNC of aerosols.
- The highest average reduction (28%) in TNC was observed for R50 conditions.



Effects on the Fuels on Size Distributions of Aerosols

- The effects of the fuels on size distributions of aerosols in the diluted exhaust were examined on the results of selected measurements performed with FMPS.
- For both tested fuels, the aerosols were distributed in single accumulation mode.
- When fueled with HVORD in place of ULSD, aerosols in the diluted exhaust were characterized with smaller median diameters and lower total and peak concentrations.



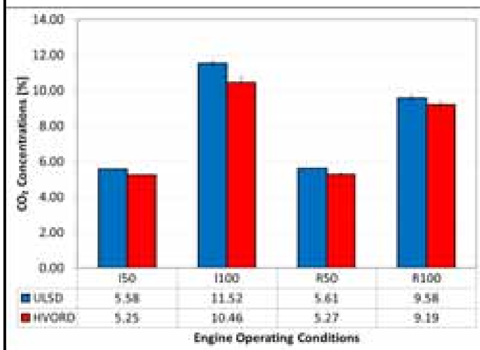
Fuel	EOC	Total Conc.	CMD	σ
		#/cm³	nm	-
ULSD	I50	1.75E+06	55.4	1.59
	I100	2.90E+06	68.0	1.68
	R50	2.52E+06	52.1	1.57
	R100	2.08E+06	59.1	1.58
HVO	I50	1.45E+06	49.7	1.65
	I100	2.26E+06	59.1	1.52
	R50	1.86E+06	47.9	1.58
	R100	1.72E+06	44.9	1.65

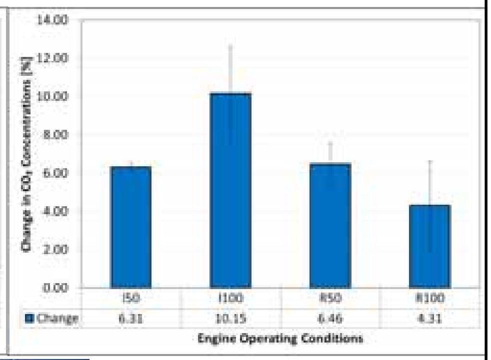
Effects of the Fuels on Emissions of CO_2, CO, NO_X, NO, NO_2, and THC

Effects of the Fuels on CO_2 emissions

23

- The differences in average CO_2 concentrations were relatively minor.
- The CO_2 emissions decreased in spite of the increase in volumetric fuel consumption when HVORD was used in place of ULSD.

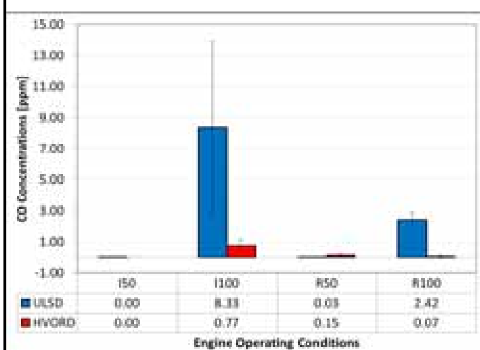


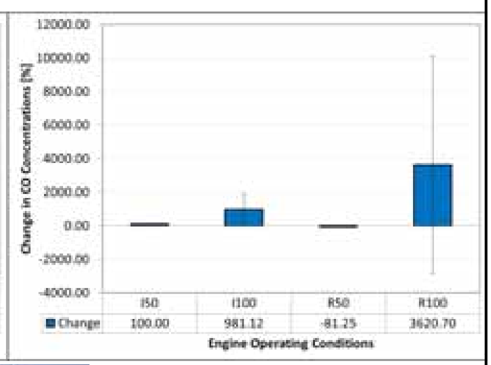


Effects of the Fuels on CO emissions

24

- The DOC retrofitted to the engine was very effective in oxidizing CO (and NO).
- Since the DOC-out concentrations of CO were very low, it was impossible to discern the effects of fuels, if any.

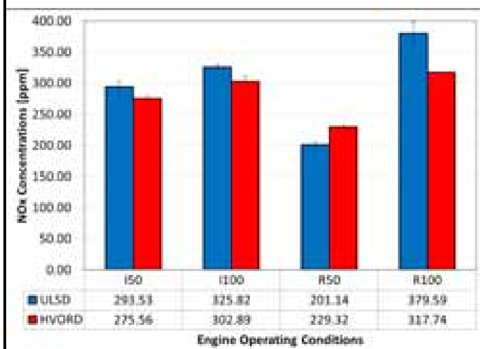


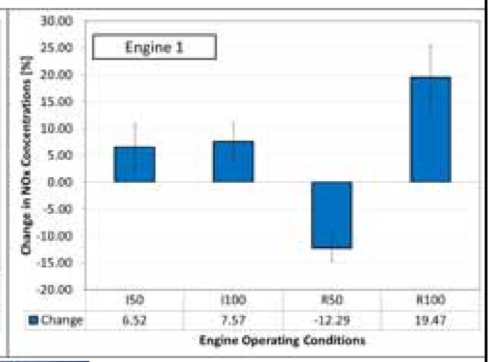


25

Effects of the Fuels on NO_X Concentrations

- With exception of the case when the engine was operated at R50 conditions, the HVORD favorably affected NO_X emissions.
- The reductions in average NO_X concentrations were highest for R100 conditions (~20 percent).

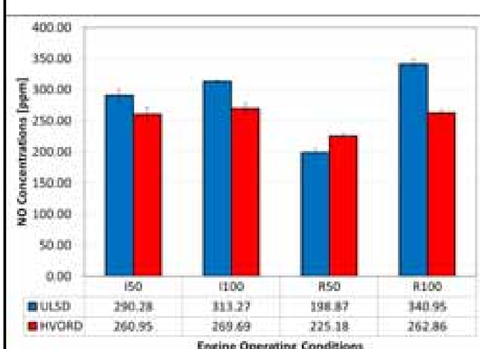


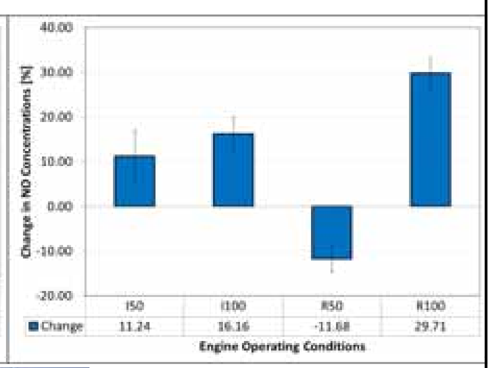


26

Effects of the Fuels on NO Concentrations

- Since NO made the major fraction of NO_X, the conclusions on the effects of fuels on NO emissions were similar to those for NO_X emissions.
- With exception of the case when the engine was operated at R50 conditions, the HVORD favorably affected NO emissions.
- The reductions in the average NO emissions were up to 30 percent.

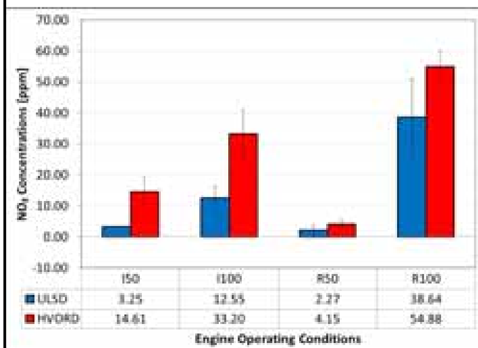


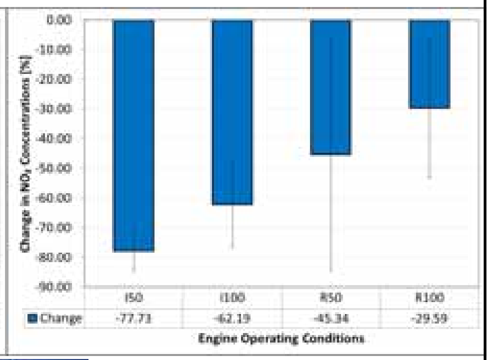


27

Effects of the Fuels on NO_2 Concentrations

- The DOC retrofitted to the engine was very effective in oxidizing NO (and CO).
- The NO_2 concentrations were substantially higher when HVORD was used in place of ULSD.

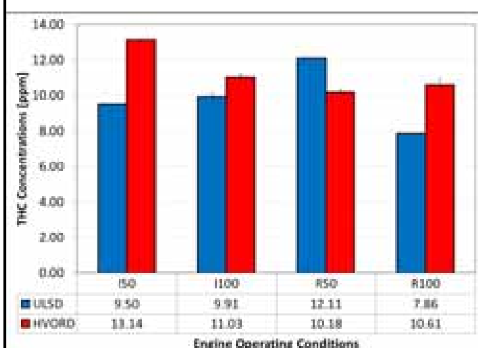


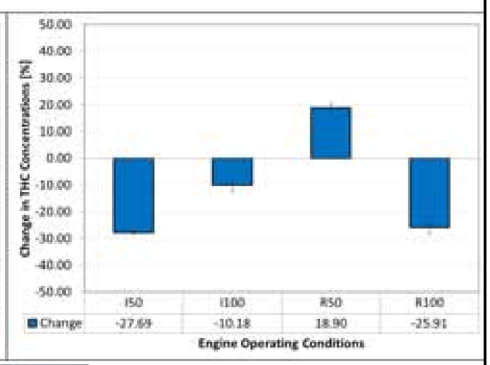


28

Effects of the Fuels on Concentrations of THCs

- The HVORD produced lower THC emissions than ULSD for I50, I100, and R100 conditions.
- For R50 conditions, the THC emissions were lower for ULSD than for HVORD.

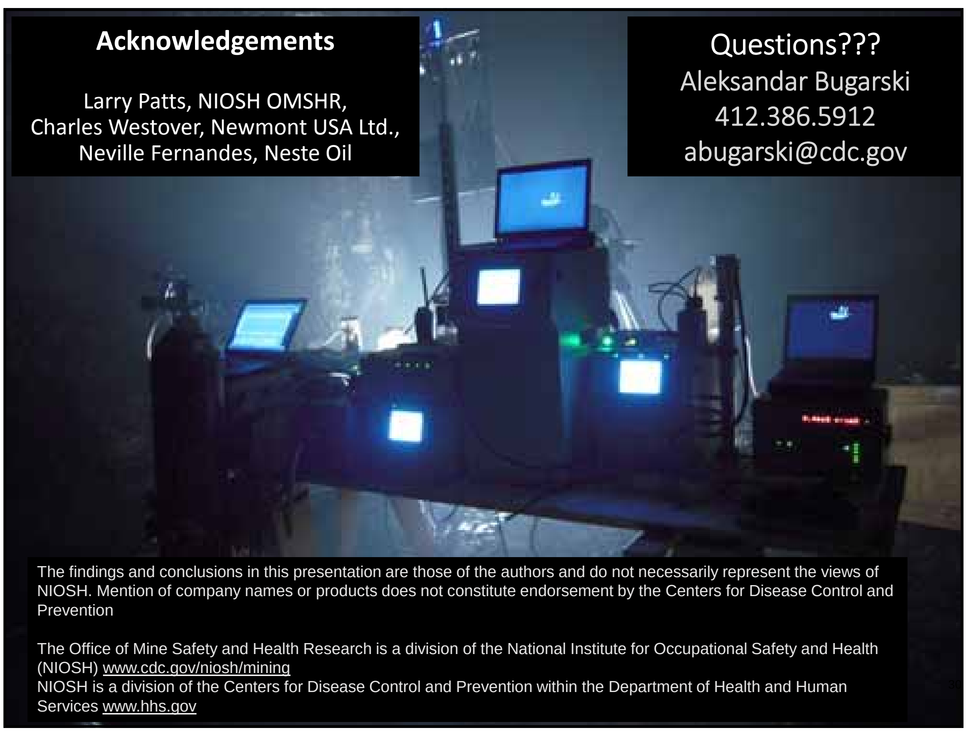




Summary and Future Work

29

- In general, the use of HVORD in place of ULSD resulted in lower total mass concentrations and specific mass emissions of aerosols (DPM, TC, and EC).
- The HVORD also favorably affected TSAC and TNC of aerosols.
- HVORD aerosols had smaller median diameters and lower total and peak concentrations than corresponding ULSD aerosols.
- The HVORD favorably affected CO_2 and adversely affected NO_2 emissions.
- The effects on NO_x, NO, and THC concentrations were a function of the engine operating conditions.
- The effects of fuels on CO concentrations were masked by the effects of the DOC.
- Additional testing will be done to assess the effects of HVORD on the emissions from an electronically controlled, turbocharged medium duty engine that conforms to U.S. EPA Tier 2 standards.



Abstract

The potential of hydrotreated vegetable oil renewable diesel (HVORD) as a control strategy to reduce exposure of underground miners to diesel aerosols and gases was assessed using results of series of laboratory emissions tests. 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 a naturally aspirated mechanically controlled engine equipped with diesel oxidation catalytic converters (DOCs). For all test conditions, the engine emitted measurably lower total mass concentrations of diesel aerosols, total carbon, and elemental carbon when HVORD was used in place of ULSD. 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. When fueled with HVORD, the engine emitted aerosols with smaller count median diameters. In the majority of the test cases, HVORD favorably affected carbon dioxide (CO_2), nitrogen oxides (NOX) 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.

Reference

- Bugarski, AD; Hummer, JA, Vanderslice, S (2015). Hydrotreated Vegetable Oil Renewable Diesel as a Control Strategy to Reduce Exposure of Workers to Diesel Aerosols and Gases. 21st Mining Diesel Emissions Council (MDEC) Conference, Toronto, Canada, October 5-8.