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# The Effects of Depth on Diesel Engine Emissions in an Underground Mine

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## ABSTRACT

The effects of depth on diesel engine emissions were measured on an in-use, heavy-duty articulated loader vehicle operating in an underground mine. The engine emissions were measured using a portable gas analyzer bench at various depths from surface to 7000 ft below sea level. Generally, the carbon monoxide (CO) and diesel particulate matter (DPM) emissions decreased with depth due to the increase in the air density and overall air/fuel ratio. Oxides of nitrogen (NOx) emissions increased with depth, likely due to the pressure effect on in-cylinder NO formation.

## INTRODUCTION

The effects of depth on the performance and emissions of diesel engines are not well known. As mines begin production activities at significant depth (below 10 000ft, or 3000m) it is expected that some consideration will have to be given to possible changes in emissions quality and engine performance.

Air density decreases with higher altitude, and makes the engine's combustion fuel/air mixture more fuel-rich. This potentially increases the toxicity of the emissions, and is compensated for by reducing fuel rate or by increasing ventilation rate. The nature of these effects has been well studied in the literature, and most mining regulatory agencies and engine manufacturers publish guidelines for engine operation at high altitude[1,2].

Conversely, in deep mines, air density increases with depth, and makes the fuel/air mixture less fuel rich. Although at first glance, this might seem to be an opportunity to decrease the toxicity of emissions, and allow increases in fuel rate, in practice the behavior of modern engines is more difficult to predict. This phenomenon will also depend on the type of engines (naturally aspirated, or turbocharged engines and electronically-controlled) and their application in the environment. Further, the engine specification data (e.g. engine power) and exhaust emissions are normally based on standard air conditions at sea level, and will change (engine power and emissions) when the engine is used in an environment with significant variation from the standard, such as in deep mines.

The quantity of such a variation is not well documented in the literature and must be studied to ensure the proper working of the equipment and protection of workers in deep mines. The Deep Mining Research Consortium (DMRC) has funded the Diesels at Depth Project to obtain a preliminary study of the potential effects of depth on diesel engine emissions.

## CURRENT REGULATORY GUIDELINES

There are currently no regulations covering changes in use or modification of diesel equipment based on elevation below sea level. There are, however, several regulations and guidelines for high altitude operation. The effect of high altitude operation on diesel engines is better documented for naturally aspirated engines.

Engine deration and fuel adjustment guidelines are well established for engine operation high above sea level. In Canada, Natural Resources Canada, CANMET-MMSL provides information on altitude operation, but does not have a regulatory role. Table 1 shows the CANMET-MMSL fuel deration guidelines for diesel engine operation at altitude.

| Altitude | | Fuel rate factor |
|---|---|---|
| feet | metres | |
| sea level | sea level | 1.00 |
| +2000 | +610 | 0.94 |
| +4000 | +1220 | 0.89 |

Table 1: CANMET-MMSL recommended fuel injection settings for altitude variation[1]

In the U.S. the Mine Safety and Health Administration (MSHA) provides information and regulation for high altitude operation of diesel engines. Generally, MSHA requires a 3% fuel reduction for every 1000 ft. above 1000 ft. elevation to maintain the fuel / air (F/A) ratio at the approved level.

The engine manufacturer specifies a fuel setting and a fuel deration curve for the engine during the approval process. The fuel deration curve ensures the fuel rate does not exceed the maximum allowable fuel to air ratio at any altitude.[2]

MSHA has the authority to require retrofits of diesel engine components that are found to exceed the maximum fuel air ratio at altitude. MSHA has a research program investigating the effects of high altitude operation on diesel engine emissions.

## LITERATURE SURVEY

### High Altitude Operation

Prediction of naturally aspirated engine performance at altitude is relatively simple[3]. However, the widespread use of turbocharging has made the analysis of these engines at altitude more difficult.

Generally, turbocharging can provide some compensation for the loss of air density at altitude by increasing the boost pressure via a higher turbine speed. This occurs because the pressure difference across the turbine increases as the ambient pressure decreases.[4]

However, engine performance will usually still decrease with altitude, although not as fast as for naturally aspirated engines. As the turbocharger is optimized for performance near sea level, there is a danger that performance limits for the engine-turbo match can be approached at altitude. As turbo speed increases, the compressor can approach the surge limit. This is an area of highly unstable operation for the turbo and should be avoided.[4]

If the engine is to remain at high altitudes, the turbocharger can be resized for optimal performance. If this is not possible, or cost effective, a wastegated turbo system can be used.

A wastegate can control boost pressure at lower altitudes by bypassing some of the exhaust gas around the turbine. Wastegated turbo engines can support near full performance at altitude until the critical limit is reached where the wastegate is completely closed.[5]

Most engine manufacturers publish altitude deration curves for their engines.[6] This information is freely available from all engine manufacturers. Most engine manufacturers will provide guidance for mines operating engines at altitude.[7]

In summary, engines equipped with turbochargers and aftercooling can compensate for significant loss of air density at altitude. Some turbocharged engines can operate without deration to relatively high altitudes. However, the turbocharger cannot compensate at all engine-operating points. At lower loads, the turbo is not as efficient and the maximum fuel / air ratio can be exceeded.

### MSHA High Altitude Research

Although the performance of naturally aspirated engines can generally be predicted, the adoption of high pressure turbocharging and sophisticated electronic controls for modern diesel engines has raised some new questions.

This technology has greatly improved the ability of these engines to compensate for lower air density; however, the degree of compensation varies widely.

Figure 1 shows the effect of increasing altitude on fuel/air ratio for an older, naturally aspirated engine. A Caterpillar 3306PCNA engine was tested at simulated altitudes of 1000 and 7000ft above sea level.

First, the fuel/air ratio was allowed to increase with air density to 7000 ft. This ratio was then corrected according to the MSHA guidelines in order to attempt to reduce the emissions.

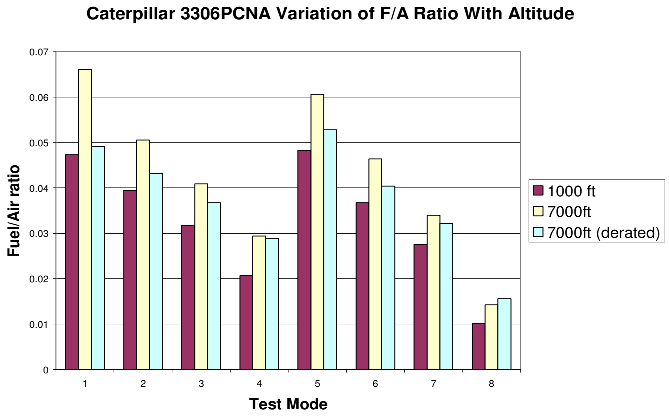


Figure 1: Variation of FA ratio with altitude: Caterpillar 3306PCNA (ISO8178)[8]

The uncontrolled fuel/air ratio increased by 39% at rated power and 42% at peak torque, and on average, by 32% (weighted ISO8178). This had a significant effect on emissions. The increase in fuel air ratio significantly affected DPM emissions as shown by Figure 2. However, it was possible to reduce the DPM emissions back to the sea level values by derating the engine according to the MSHA guidelines.

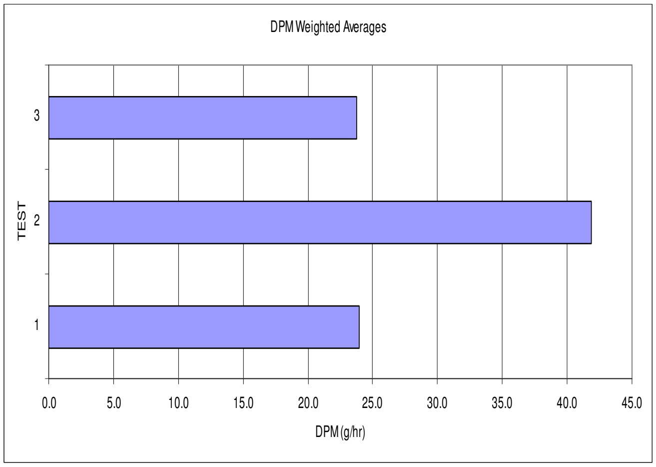


Figure 2: Caterpillar 3306PCNA DPM Emissions at Simulated Altitudes[8].

At a baseline of 1100ft, (Test 1) the DPM emissions are 24 grams per hour. When the engine is operated at a simulated altitude of 7000 ft (Test 2), the DPM emissions increase to 42 g/h. When the engine fuel rate is decreased according to the MSHA regulation of 3% per 1000ft above 1000ft, (Test 3) the DPM emissions return to the baseline levels.

The altitude compensation of turbocharged engines was also tested in a simulator. A Cummins CTAA8.3-C turbocharged and aftercooled engine was tested at various altitudes to 8000ft. Figure 3 shows the variation in fuel air ratio with altitude. Although the turbocharger system is able to minimize the increase in fuel air ratio, there is still a noticeable increase, with the associated changes in emissions.

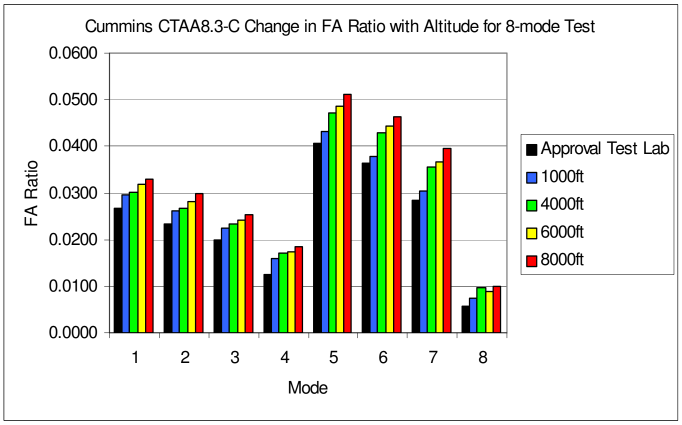


Figure 3: Variation of FA ratio with altitude: Cummins CTAA8.3C (ISO8178)[8]

Figure 4 shows the DPM emissions from the Cummins engine at a variety of altitudes. The turbocharger system can provide reasonable altitude compensation up to 4500ft. Above that, the DPM performance degrades and deration is required. In addition to DPM, the CO was affected by the changes in fuel air ratio. Figure 5 shows the variation in CO at different altitudes.

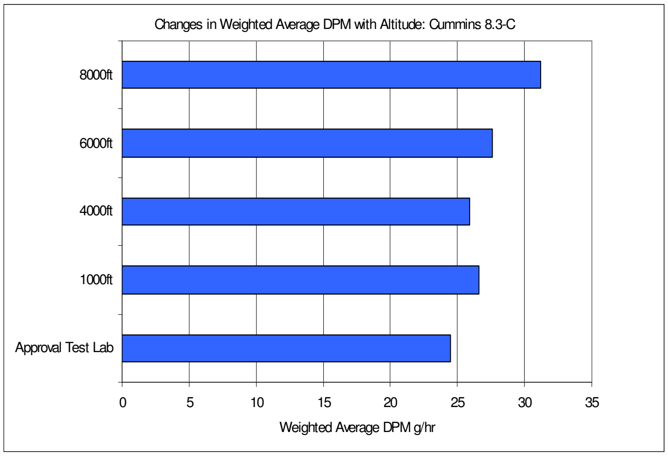


Figure 4: Cummins CTAA8.3-C DPM Emissions at Simulated Altitudes[8]

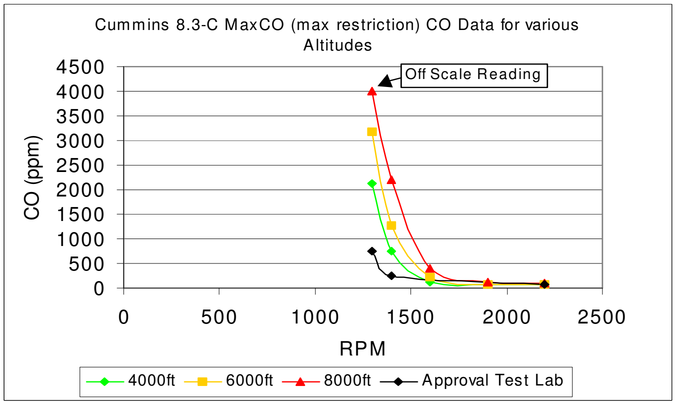


Figure 5: Lug curve carbon monoxide (CO) Cummins CTAA8.3C[8]

The CO increased with fuel air ratio at all points on the lug curve. In addition the severity of the spike in CO at very high fuel / air ratio operating points was much worse at higher altitudes. An effect on oxides of nitrogen (NOx) was also found. This trend was found to be the opposite of CO and DPM. NOx decreased with increasing altitude. Figure 6 shows the variation in NOx vent rate with altitude for a Deutz engine.

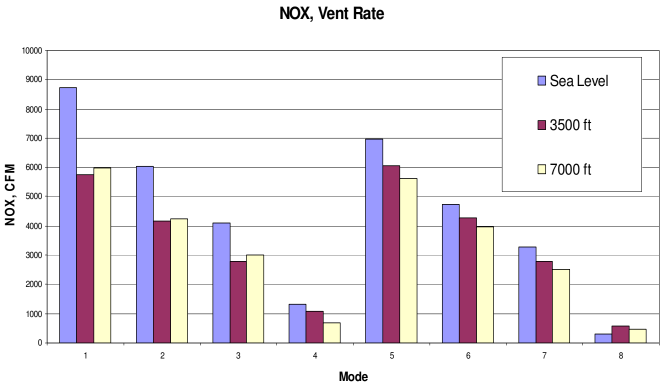


Figure 6: Variation in legislated NOx ventilation rate with altitude: Deutz BF4M1013C (ISO8178)[8]

The MSHA work is the most recent and comprehensive data available on altitude effects. The general trend is for CO and DPM to increase with altitude due to the increase in fuel air ratio. Although turbocharged engines can compensate for this to a certain degree, the trend remains detectable. NOx emissions conversely tend to decrease with altitude, likely due to the pressure effect on in-cylinder NO formation[9].

### Operation at Depth

There have been almost no studies of diesel engine operation at depths significantly below sea level.

The deepest mining operations in the world are in South Africa where there is little or no dieselization of the mining process. Up until recently, mines in North America had not reached a depth where diesel engine operation and emissions were a concern.

As deep mine developments become production areas, it is expected that higher power, turbocharged diesel production equipment will begin to be used. Already, some turbocharged engines in deep Canadian mines have experienced operational problems. This is the main justification for this research project.

The only research available on diesel operation at depth has been done by the Thyssen Noordseewerke and others working on air independent propulsion (AIP) for diesel-electric submarines[10]. Although these systems are operated at depth, the density of the air supplied to the engine is regulated by addition of stored oxygen. Thus, the system never communicates with the local atmospheric pressure. This research was not applicable to the DMRC Diesels at Depth Project.

### DMRC Diesels at Depth Research Project

Comparable to operation at altitude, the prediction of naturally aspirated engine performance at depth is relatively simple to calculate. The behavior of turbocharged engines at depth, however, is almost unknown. High altitude research suggests that turbocharger system response could vary widely as air inlet density changes. The DMRC Diesels at Depth project investigated the operation of a modern, turbocharged and aftercooled diesel engine at depth in a Canadian mine.

As air pressure increases at depth, the pressure differential across the turbine will decrease causing the turbo speed to decrease also. Depending on the turbo system configuration and matching, this may cause the boost pressure to decrease, negatively affecting emissions. Unlike operation at altitude, wastegate systems may not be able to compensate for this loss.

The electronic control systems that govern diesel engine operation can become confused at depth due to pressure sensors falling out of the programmed range. This can cause engines to set error codes or reduce engine output.

## TEST PLAN & PROCEDURE

The Xstrata Kidd Creek mine was chosen as the test site due to is large size and depth. In addition the mine is served by a ramp that leads from surface down to 8000 ft below sea level. Figure 7 shows the Kidd Mine elevation. Table 2 shows the test site locations and ambient conditions.

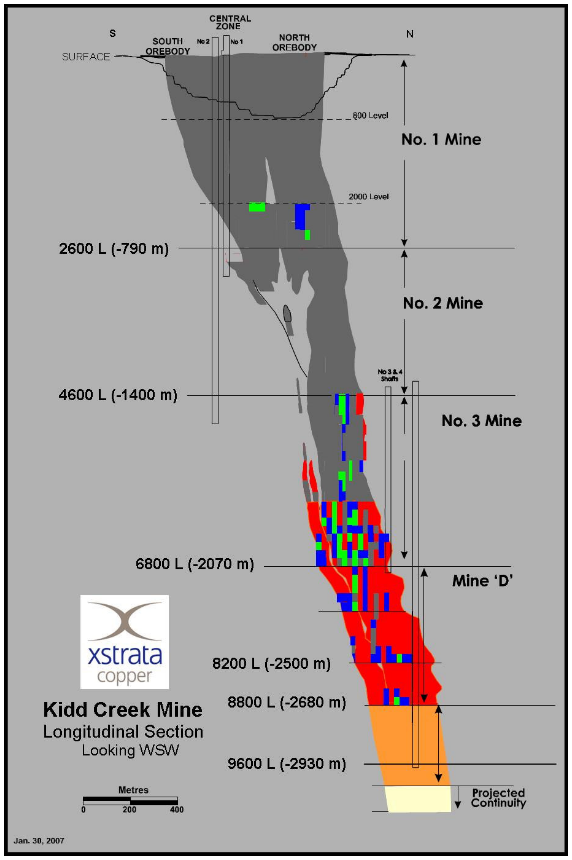


Figure 7: Kidd Creek Mine Elevation WSW

| Mine Level | Elevation (ft) | Pressure (kPa) | % Relative Humidity | Dry Bulb Temp.(C) | Wet Bulb Temp.(C) |
|---|---|---|---|---|---|
| Surface | +1000ft | 99.10 | 65.2 | 1.0 | -1.0 |
| 2200 | -1200ft | 106.23 | 89.3 | 13.2 | 12.3 |
| 4700 | -3700ft | 113.73 | 69.3 | 28.9 | 24.3 |
| 6900 | -5900ft | 121.42 | 74.0 | 28.8 | 25.0 |
| 8000 | -7000ft | 126.94 | 67.3 | 31.6 | 26.4 |

Table 2: Test site locations and local ambient conditions (Nov. 8-10, 2006)

In this paper, mine levels are identified by the distance below ground surface, rounded to the nearest "hundred" of feet. Mine levels and depths will be referenced to a ground surface datum elevation of "0". All graphs and analysis of emissions data will be based on elevation relative to mean sea level, where the mine surface elevation is at 1000ft above mean sea level.

## TEST VEHICLE – LHD 658

The test vehicle was a Toro Tamrock 501D load-haul-dump (LHD) vehicle. The LHD mass was 35 650 kg and it was equipped with a 325 horsepower Detroit Diesel Series 60 diesel engine.

The engine had 502 hrs. Figure 8 shows a picture of the LHD 658 vehicle. Table 3 lists the engine specifications. Engine data was collected via the J1708 / J1939 data link.

Figure 8: Toro Tamrock load-haul-dump (LHD) vehicle.

| | |
|---|---|
| **Make** | Detroit Diesel |
| **Model** | Series 60 (EPA Tier II) |
| **Type** | Inline 6 cylinder |
| **Combustion** | DI, Electronic |
| **Aspiration** | Turbo, aftercooled |
| **Bore** | 5.12 in (130mm) |
| **Stroke** | 5.47 in (137mm) |
| **Displacement** | 11.1 litres |
| **Rated Power** | 325 hp @ 2100 rpm |
| **Peak Torque** | 1150 lbft @ 1200 rpm |
| **Idle speed** | 600 rpm |
| **Vehicle** | Toro Tamrock 501D LHD |
| **Hours** | 502 |

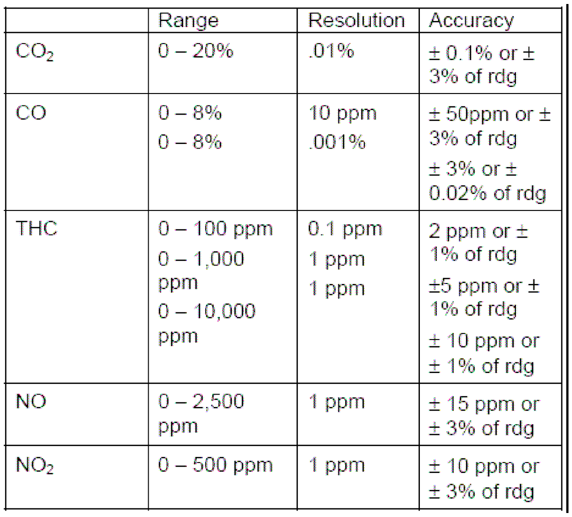
Table 3: Detroit Diesel Series 60 engine specifications.

## 7.0) GAS ANALYZER SYSTEM

The gas analyzer system was a Sensors, Inc. SEMTECH-D portable. The analyzer was mounted directly on the LHD as shown in Figure 9.

Figure 9: SEMTECH-D portable gas analyzer

The SEMTECH-D is specifically designed for in-use emissions measurement for diesel vehicles and is used by the US EPA for compliance audits. The SEMTECH-D measures total hydrocarbons (THC) using a heated flame ionization detector, CO and $CO_2$ with a non-dispersive infrared analyzer and NO, $NO_2$ using a non-dispersive ultraviolet (UV) resonant absorption analyzer. Table 4 shows the unit specifications.



| | Range | Resolution | Accuracy |
|---|---|---|---|
| $CO_2$ | 0 – 20% | .01% | ± 0.1% or ± 3% of rdg |
| CO | 0 – 8%<br>0 – 8% | 10 ppm<br>.001% | ± 50ppm or ± 3% of rdg<br>± 3% or ± 0.02% of rdg |
| THC | 0 – 100 ppm<br>0 – 1,000 ppm<br>0 – 10,000 ppm | 0.1 ppm<br>1 ppm<br>1 ppm | 2 ppm or ± 1% of rdg<br>±5 ppm or ± 1% of rdg<br>± 10 ppm or ± 1% of rdg |
| NO | 0 – 2,500 ppm | 1 ppm | ± 15 ppm or ± 3% of rdg |
| $NO_2$ | 0 – 500 ppm | 1 ppm | ± 10 ppm or ± 3% of rdg |

Table 4: SEMTECH-D analyzer specifications

Diesel particulate emissions were measured by weighing the gas analyzer filter element. Several clean glass fibre filter elements were pre-weighed before the test and exposed to DPM emissions by exchanging with the main element during the measured test sequences.

The exposed elements were weighed again and the average DPM emissions were calculated from the collected particulate mass and analyzer gas flow rate. Obviously this is not as accurate as standard dilution-based DPM measurement; however, it was used to compare DPM emissions as a function of depth, keeping in mind that these are not absolute values.

The analyzer was calibrated at each level to correct any possible drift. Figure 10 shows the SEMTECH calibration. The unit calibration did not vary significantly during the test. This analyzer was much better that an electrochemical cell-based analyzer used in the preliminary study which required significant correction for depth.

Figure 10: Technicians calibrating the SEMTECH-D analyzer

The SEMTECH-D emissions analyzer data was used in this report. This unit is reliable and durable; however the FID would not stay lit below -5900ft. Consequently no THC emissions are reported below this level.

This may have been due to fuel / air ratio error caused by the increased air density at greater depth. Only the FID was affected, and the THC data from those levels was discarded. The other analyzer bench components worked normally.

## RESULTS – LEVEL PRODUCTION DUTY CYCLES

To try to accurately collect real-work representative data, the emissions from the LHD were measured while the vehicle was performing its normal production work. The effect of depth was measured by operating the LHD on multiple levels from 8000 Level (-7000ft) to the surface (1000ft). Figure 11 shows the LHD in operation on 8000 Level.

Figure 11: LHD in operation dumping ore on 8000 Level (-7000ft).

In some cases, due to necessity of obtaining data at a wide range of levels, the LHD was sent deeper into Mine D (see Figure 7) and higher into the old mine than it normally would. Enough ore and waste material was stockpiled at these locations to provide a representative cycle.

The engine duty cycles and selected emissions are shown below. A summary of the cycle emissions in g/kg fuel (emissions index) is shown also.

### Surface (+1000ft)

The vehicle was operated on the surface (approximately 1000ft above sea level) moving material from the backfill plant to the crusher. The tramming distance was 420 meters round trip.

Figure 12 shows the engine speed and load duty cycle for the surface test. Figure 13 shows the NOx, CO and THC emissions in ppm.

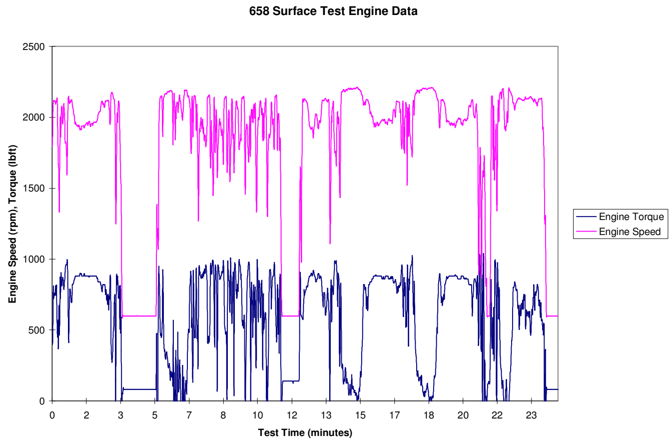


Figure 12: Vehicle duty cycle (speed/load) on surface (1000ft).

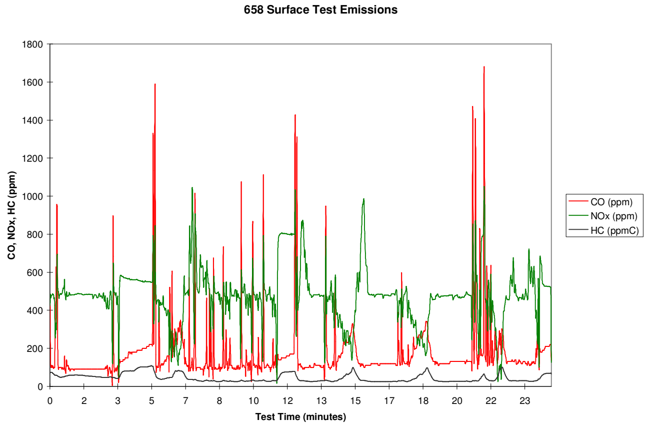


Figure 13: Cycle CO, NOx and HC emissions on surface (1000ft).

Table 5 shows the average normalized emission rates of $CO_2$, CO, NO, $NO_2$, NOx, THC in g/kg fuel and DPM in $mg/m^3$ over the test cycle on surface.

| Average Emissions Index (g/kg fuel)<br>Surface (+1000ft) | | | | | | |
|---|---|---|---|---|---|---|
| CO | $CO_2$ | NO | $NO_2$ | NOx | THC | DPM (mg/$m^3$) |
| 10.0 | 3394.7 | 32.7 | 1.9 | 34.5 | 1.4 | 49.6 |

Table 5: Cycle averaged emissions – Surface (1000ft).

## 2200 Level (-1200ft)

The vehicle was operated on 2200 level (approximately 1200ft below sea level), moving waste material from 2200 north end to the 2500 rock crusher. The tramming distance was 2334 meters round trip.

Figure 14 shows the engine speed and load duty cycle for the 2200 Level test. Figure 15 shows the NOx, CO and THC emissions in ppm.

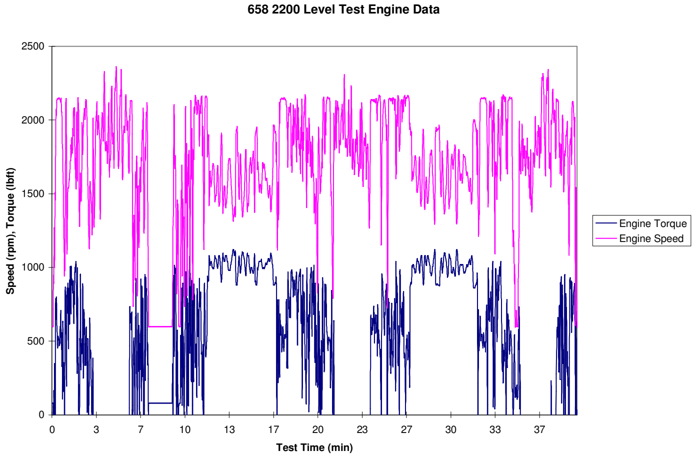


Figure 14: Vehicle duty cycle (speed/load) on 2200 Level (-1200ft).

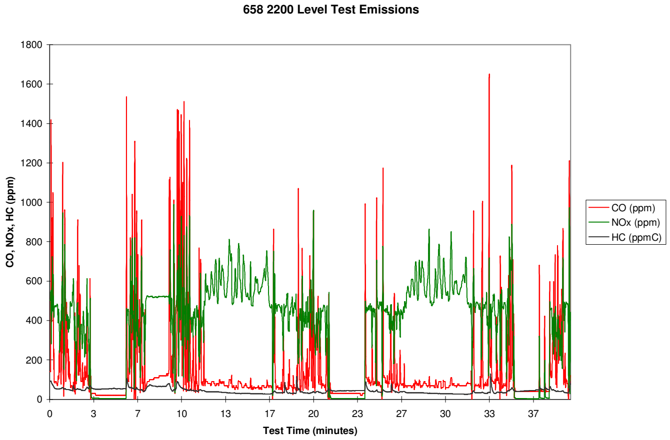


Figure 15: Cycle CO, NOx and THC emissions on 2200 Level (-1200ft).

The average normalized emission rates of $CO_2$, CO, NO, $NO_2$, NOx, THC and DPM were not available due to an error in the SEMTECH post-processor.

## 4700 Level (-3700ft)

The vehicle was operated on 4700 level from the ore pass to the transfer raise as shown in Figure 16. The tramming distance was 158 meters round trip.

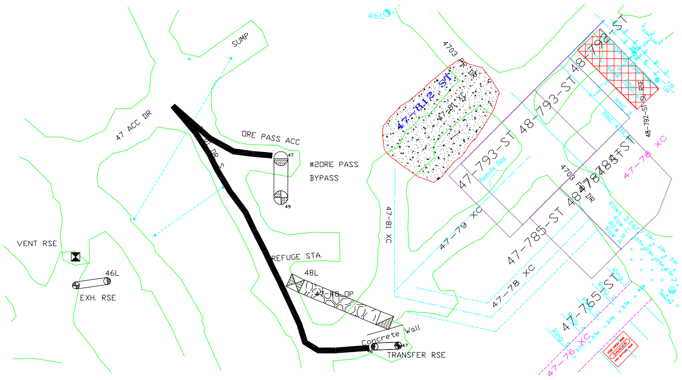


Figure 16: Mine 4700 Level plan showing tramming route in black.

Figure 17 shows the engine speed and load duty cycle for the 4700 Level test. Figure 18 shows the NOx, CO and HC emissions in ppm.

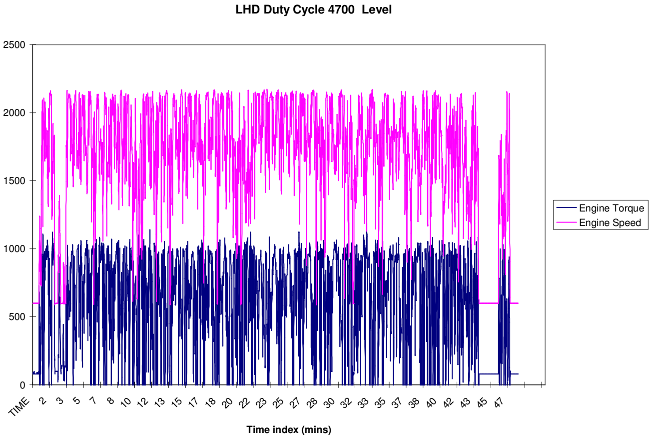


Figure 17: Vehicle duty cycle (speed/load) on 4700 Level (-3700ft).

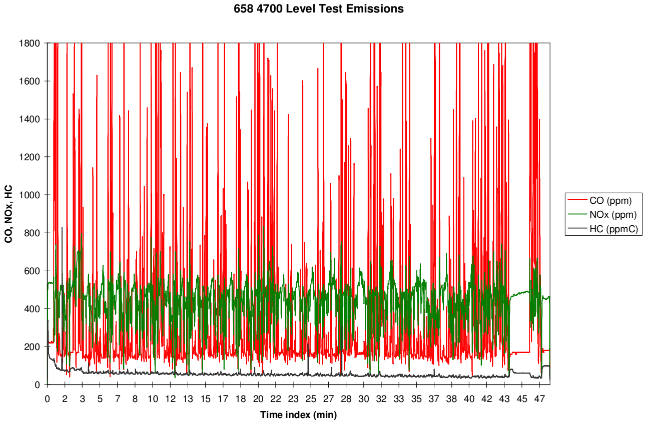


Figure 18: Cycle CO, NOx and THC emissions on 4700 Level (-3700ft).

Table 6 shows the average normalized emission rates of $CO_2$, CO, NO, $NO_2$, NOx, THC in g/kg fuel and DPM in $mg/m^3$ over the test cycle on 4700 level.

| Average Emissions Index (g/kg fuel) 4700 Level Test (-3700ft) | | | | | | |
|---|---|---|---|---|---|---|
| CO | $CO_2$ | NO | $NO_2$ | NOx | THC | DPM ($mg/m^3$) |
| 16.0 | 3382.6 | 32.6 | 3.1 | 35.7 | 1.3 | 61.7 |

Table 6: Cycle averaged emissions – 4700 Level (-3700ft).

## 6900 Level (-5900ft)

The vehicle was operated on 6900 Level from the #2 ore pass as shown in Figure 19. The tramming distance was 356 meters round trip.

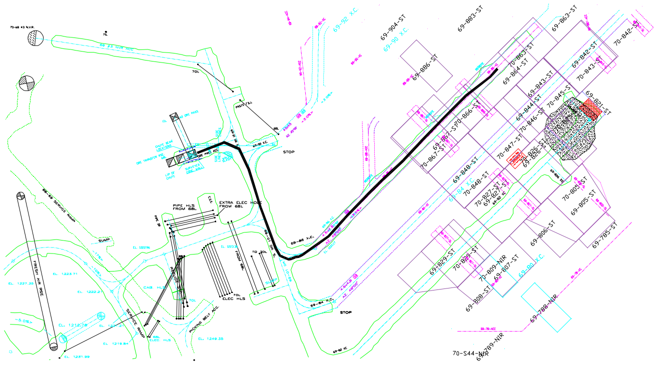


Figure 19: Mine 6900 Level plan showing tramming route in black.

Figure 20 shows the engine speed and load duty cycle for the 6900 Level test. Figure 21 shows the NOx, CO and THC emissions in ppm.

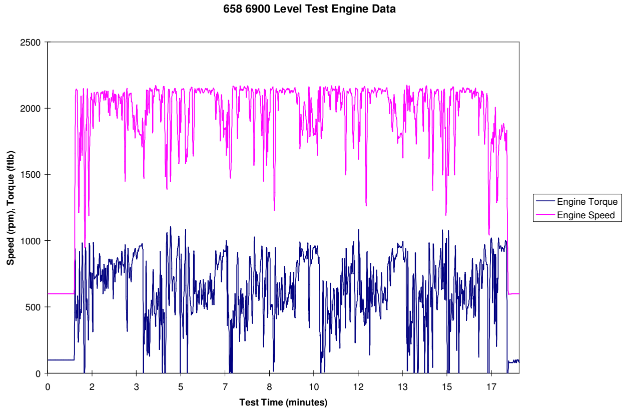


Figure 20: Vehicle duty cycle (speed/load) on 6900 Level (-5900ft).

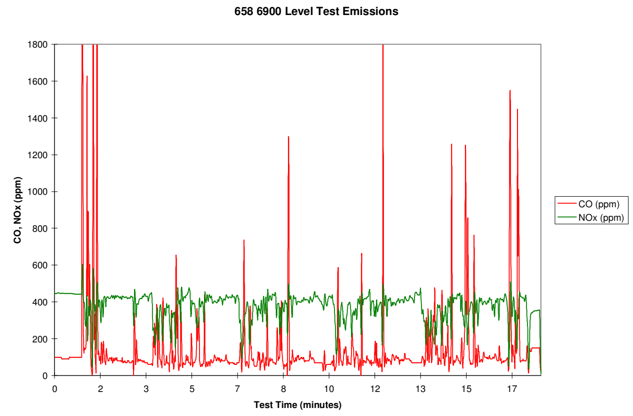


Figure 21: Cycle CO and NOx emissions on 6900 Level (-5900ft).

Table 7 shows the average normalized emission rates of $CO_2$, CO, NO, $NO_2$, NOx, THC in g/kg fuel and DPM in $mg/m^3$ over the test cycle on 6900 level.

| Average Emissions Index (g/kg fuel) 6900 Level Test (-5900ft) | | | | | | |
|---|---|---|---|---|---|---|
| CO | $CO_2$ | NO | $NO_2$ | NOx | THC | DPM ($mg/m^3$) |
| 6.5 | 3400.7 | 28.9 | 2.5 | 31.3 | N/A | 27.8 |

Table 7: Cycle averaged emissions – 6900 Level (-5900ft).

## 8000 Level (-7000ft)

The vehicle was operated on 8000 Level from the #2 ore pass as shown in Figure 22. The tramming distance was 636 meters round trip.

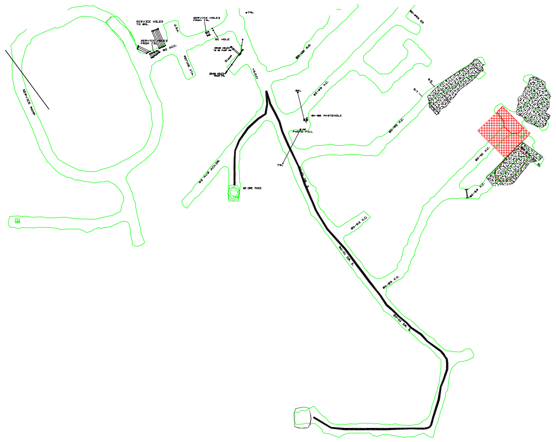


Figure 22: Mine 8000 Level plan showing tramming route in black.

Figure 23 shows the engine speed and load duty cycle for the 8000 Level test. Figure 24 shows the NOx, CO and THC emissions in ppm.

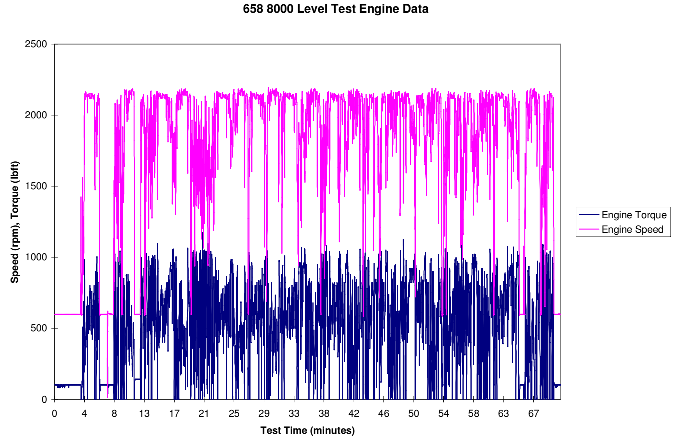


Figure 23: Vehicle duty cycle (speed/load) on 8000 Level (-7000ft).

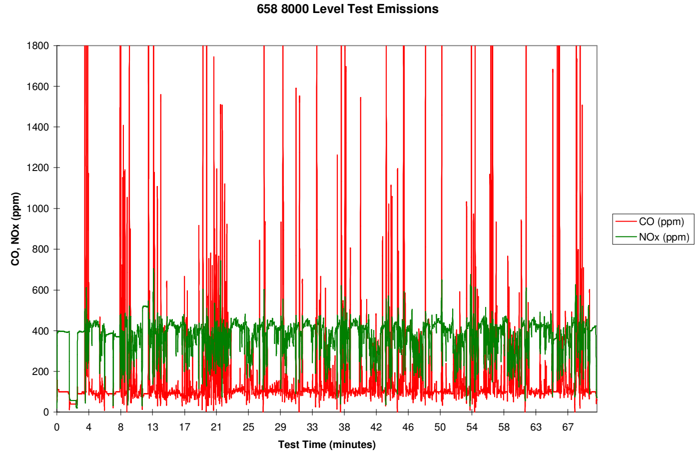


Figure 24: Cycle CO and NOx emissions on 8000 Level (-7000ft).

Table 8 shows the average normalized emission rates of $CO_2$, CO, NO, $NO_2$, NOx, THC in g/kg fuel and DPM in $mg/m^3$ over the test cycle on 8000 level.

| Average Emissions Index (g/kg fuel) 8000 Level Test (-7000ft) | | | | | | |
|---|---|---|---|---|---|---|
| CO | $CO_2$ | NO | $NO_2$ | NOx | THC | DPM ($mg/m^3$) |
| 9.9 | 3400.2 | 32.7 | 2.3 | 35.0 | N/A | 46.3 |

Table 8: Cycle averaged emissions – 8000 Level (-7000ft).

## Transient Load Cycle Summary

Table 9 shows a summary of the emissions index for the transient cycles on each level.

| | **Transient Cycle Average Emissions Index (g/kg fuel)** | | | | | | |
|---|---|---|---|---|---|---|---|
| *Depth (ft)* | *CO* | *$CO_2$* | *NO* | *$NO_2$* | *NOx* | *THC* | *DPM ($mg/m^3$)* |
| *1000* | 10.0 | 3394.7 | 32.7 | 1.9 | 34.5 | 1.4 | 49.6 |
| *-1200* | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| *-3700* | 16.0 | 3382.6 | 32.6 | 3.1 | 35.7 | 1.3 | 61.7 |
| *-5900* | 6.5 | 3400.7 | 28.9 | 2.5 | 31.3 | N/A | 27.8 |
| *-7000* | 9.9 | 3400.2 | 32.7 | 2.3 | 35.0 | N/A | 46.3 |

Table 9: Summary of cycle averaged emissions.

The observed duty cycles were under "real world" conditions. The underground loader cycle is well known to be highly transient in speed and load and this was reflected in the cycles measured in this study.

In particular, the 4700 Level (-3700ft) cycle was highly transient due to the very short tramming distance of 158 meters. This short tram time meant that a higher percentage of operating time was spent transitioning speed and loads. Transient engine operation often has a detrimental effect on fuel/air ratio sensitive emissions and this is reflected in the high CO and DPM shown in Table 9.

In contrast, the other level cycles had significant steady-state portions which contributed significantly to lower cycle resolved emissions.

The transient emissions did not follow any identifiable trend for depth. Clearly, the effect of transient load cycles, (rapid acceleration and loading), have a greater effect on mass emissions than the effects of depth alone. To determine the effects of depth, the transients were removed and the engine operated at steady state.

## RESULTS – STEADY-STATE ASCENT 8000-Surface (-7000 to 1000ft)

Although the transient levels cycles represent an important picture of the real world changes in emissions, it is necessary to look at the steady state case to confirm the effect of depth. For this study, steady-state engine loading was achieved by having the vehicle ascend the ramp from the 8000 Level to the Surface. The ramp is helical and approximately 17% grade.

Due to scheduling constraints, the ascent could not be made in one trip, but had to be broken up into three sections: 8000 to 4600, 4600 to 2200, and 2200 to surface. Gaseous emissions and engine parameters were recorded but DPM was not. The three ascent sections were combined into one chart. Small, linear adjustments were made to some sections due to the difficulty in matching start and end emissions concentrations. The engine power was recorded to verify steady-state operation.

### Composite 8000 Level to Surface (-7000 to 1000 ft)

Figure 25 shows the CO and NOx steady state emissions and engine power from 8000 Level to Surface (-7000 to 1000 ft). The CO and NOx exhibit a distinct change in emissions with depth. The CO increases as the fuel air ratio increases, while NOx decreases with decreasing ambient air density.

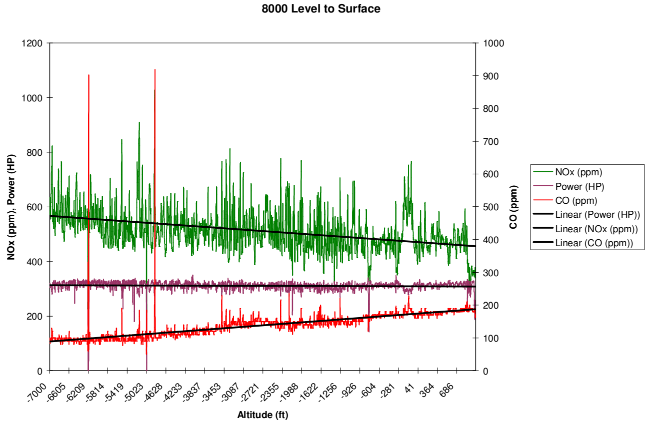


Figure 25: Steady-state CO, NOx emissions and engine power from 8000 Level to surface (-7000ft to 1000ft elevation).

## LINKAGE TO MSHA ALTITUDE

As described earlier, MSHA has conducted a series of studies on the effects of altitude on diesel engine emissions. When we compare the current DMRC work with comparable engine tests (ie. modern design, turbocharged and aftercooled, DI engines) we find that the trends in emissions are in the same direction. As air density increases with increasing depth, the fuel/air ratio sensitive emissions like CO and DPM decrease. Conversely, as air density increases, pressure sensitive emissions like NOx increase.

A Deutz BF4M1013C engine was selected from the MSHA test data as representative of the general trends found in their study and similarity to the DMRC engine. Although the engine is similar in combustion design to the Detroit Diesel engine used in this work, the engine out emissions were not identical. A linear adjustment was made to the Deutz engine out emissions to obtain a better match with the start and end points.

Figure 26 combines the DMRC and MSHA work into a continuous chart showing the changes in NOx CO and DPM as elevation is increase from 7000ft below sea level to 7000ft above sea level.

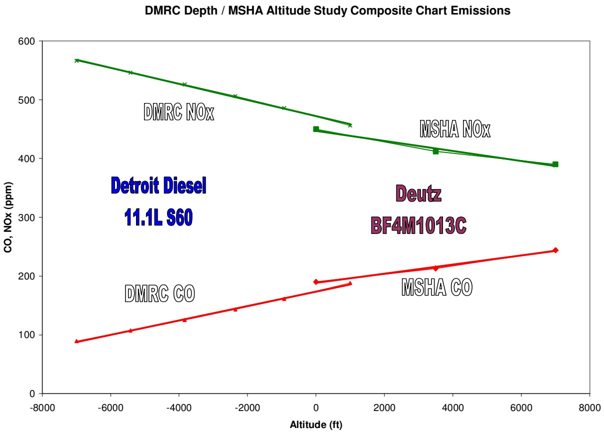


Figure 26: Steady-state CO, NOx emissions and engine power from -7000ft to +7000ft elevation (combined DMRC and MSHA data).

The trends for the present study (DMRC) and the MSHA study are in the same direction and at a similar rate. The effect of elevation on CO and NOx is the same for engines of similar combustion system.

## CONCLUSIONS

This study noted a significant change in steady state emissions with depth. Fuel / air ratio sensitive emissions like CO and DPM decreased with depth as the fuel / air ratio decreased due to the higher air density. Conversely, NOx emissions increased with depth likely due to the pressure effect on NO formation in-cylinder. These trends continued in the same direction at altitudes above sea level.

While the overall effect of depth on steady-state emissions is very important, this study also found that LHD vehicles generated high emission peaks during transient engine operating cycles. These peaks are large enough to obscure the depth pressure effect in deep mines. Clearly, reduction of transient operation through the use of throttle input control or hybrid vehicle implementation would be of significant benefit to the engine out emissions.

Vehicles which do not exhibit such highly transient cycles, such as haulage trucks, would demonstrate a much more noticeable change in emissions with depth.

## RECOMMENDATIONS

These tests were conducted in the real world on a single type of vehicle and engine. The noted effects need to be duplicated in a controlled laboratory environment in order to more rigorously determine the pressure effect correlations.

At the present time, a depth pressure simulator for engine testing does not exist. It is recommended that such a simulator be constructed to permit testing at finer depth intervals and lower depths as many mines in Canada are planning operations below -10 000ft.

During the course of the preliminary work for this study, a number of gas analyzers were evaluated for their performance at great depth. It was found that electrochemical cell-based analyzers required significant re-calibration at depth and often did not return to zero when brought back to surface.

Analyzers of this type are very common in the mining industry. A comprehensive study needs to be performed to ensure these analyzers will be suitable for use at depth.

Some mines have noted errors and failures in electronically controlled diesel engines caused by over-ranged pressure sensors sending erroneous data to the control unit or by the control unit rejecting good data as implausible. Such faults were not seen during the course of this study; however, a depth simulator could be used as part of the mining engine type approval process to ensure operation.

## ACKNOWLEDGEMENTS

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