MVSSA Annual Conference 2016: Increasing the relevance of the Mine Ventilation Profession

An evaluation of fuels and retrofit diesel particulate filters to reduce diesel particulate matter emissions in an underground mine

M.C. Wattrus
Sasol, South Africa

M. Biffi
Anglo American, South Africa

C.J. Pretorius
CSIR, South Africa

D. Jacobs
Deutz Dieselpower, South Africa

ABSTRACT: Through an industry wide collaborative project, this paper explores what potential exists for South African underground mines to reduce diesel particulate emissions, where the starting point is a mine using older engine technology (Tier 1 emission level compliant) and a diesel containing 500ppm sulphur. Comprehensive engine exhaust emissions tests were carried out in a test cell on seven diesel fuels and two retrofitted diesel particulate filters. For each evaluation, the engine was operated over a legislated non-road steady-state test cycle and a real-world transient cycle. The transient cycle was obtained from a recording of a working Load-Haul-Dump vehicle in an underground mine, which was used to replicate real-world emissions in a controlled environment. The emission data thus obtained was used also to assess the effectiveness of current dilution rates used in a typical underground mechanized platinum mine to meet proposed occupational exposure levels.

1 BACKGROUND

Improving the health and safety of underground miners by reducing their exposure to hazards has been a major driver behind the increasing prevalence of mining mechanisation. In recent years, the negative health effects of worker exposure to emissions from diesel-powered equipment underground have become more conclusive. This has led to many first world countries adopting defined and increasingly stringent occupational exposure levels (OEL) for diesel particulate matter (DPM) emissions in underground mines. The South African legislators will soon be following this example. Once implemented, non-compliance with this OEL will result in mining operations being halted. It is, therefore, prudent for South African underground mines to seek proactive solutions to lower DPM emissions from diesel-powered equipment.

The industry-wide collaborative project partly described in this paper explored, amongst other objectives, the potential for the reduction of DPM emissions in South African underground mines using current engine technology, filtration systems, fuel quality and applied fresh air dilution rates. The starting point is defining the operation of an older technology engine (Tier 1 emission level compliant) using diesel fuel containing 500 ppm sulphur as a base-line case. Comprehensive engine exhaust emissions tests were carried out in a test cell using seven different diesel fuels with and without two retrofitted diesel particulate filters. For each evaluation, the engine was operated over a legislated non-road steady-state test cycle and a real-world transient cycle. The transient cycle was obtained from recording the working cycle of a Load-Haul-Dump (LHD) vehicle in an underground, narrow reef platinum mine, which was used to generate real-world emissions results for each evaluation. This data then provided the inputs to model underground air quality for a platinum mine, which was compared against existing and future occupational exposure levels.

2 OBJECTIVE

The objective was to evaluate the effectiveness of seven fuels and two retrofitted diesel particulate filters (DPF), while recording other exhaust emissions to assess feasible short-term to long-term strategies for the effective reduction and management of diesel particulate matter emissions in underground mines. The recorded variation of DPM emissions was quantified in terms of fresh air dilution factors currently employed in underground platinum mines.

3 EXPERIMENTAL METHOD

This section provides details of the test engine, evaluated retrofit exhaust after-treatment products, and test fuels. A detailed description of the test protocol is also given below.

3.1 *Test engine*

One of the most prevalent engines in the Platinum mines considered for this test is the Deutz BF 6M 1013 E engine (Tier 1 emission level compliant), which was therefore selected for this project. The basic details of this engine are provided in Table 1.

Table 1. Test engine specifications.

Engine model	Deutz BF 6M 1013 E
Emission level	Tier 1
Type	6 cylinder, water-cooled, turbo-charged
Displacement	7.146 L
Compression ratio	17.6
Injection system	Single injection pumps for each cylinder
Power rating	137 kW @ 2300 rpm
Torque rating	702 Nm @ 1400 rpm

3.2 *Retrofit exhaust after-treatment selection*

The selection of exhaust gas after-treatment systems suited for retrofitting onto an LHD depends on various requirements. Engine emission performance varies from manufacturer to manufacturer, with operational cycles, fuel, oil and additive quality and the engine emission certification level (Tier 1 to 4, or Stage 1 to 4). As such, after-treatment needs to be selected on a case by case basis for each engine family.

There is a large range of approved after-treatment retrofit suppliers that can be found on the VERT® list (an association dedicated to the promotion of “Best Available Technology” for emission control), the US EPA Verified Technologies List for Clean Diesel, or the US Mine Safety and Health Administration (MSHA) website. After-treatment systems that are not listed on one of these lists have not had their performance independently certified, and should be avoided.

The two exhaust after-treatment options that have been selected by Deutz Dieselpower for the evaluation are described below.

3.2.1 *Partial flow SMF®-CRT®*

The efficiency of the partial flow diesel particulate filter (DPF) is claimed to be between 30-60% depending on raw exhaust gas composition and soot load. The system is based on a continuous regenerating trap (CRT) design and utilizes a sintered metal filter (SMF). Due to the diesel oxidation catalyst (DOC) integrated in this unit, the fuel sulphur content is restricted to a maximum of 50 ppm but an extended life and improved performance will be attained by using 10 ppm diesel. This system uses passive regeneration, i.e. the heat energy in the exhaust stream is used to oxidise the diesel particulate matter trapped in the filter.

Figure 1 below shows the SMF-CRT unit used in the test cell at the Sasol Fuels Application Centre in Cape Town.

Figure 1. SMF-CRT diesel particulate filter fitted to the engine in a test cell at the Sasol Fuels Application Centre.

3.2.2 *Wall-flow SMF®-AR®*

The efficiency of the electronically controlled wall flow actively regenerating (AR) sintered metal (SMF) DPF is claimed to be 99%. It makes use of a fuel borne catalyst (FBC) which is an organometallic chemical compound that is dosed into the vehicle’s fuel tank during operation. This FBC, along with electric heaters integrated in the unit, allows the DPF to actively regenerate, or burn-off, the trapped DPM under almost any conditions. The system contains no platinum group metals which allow its operation with high sulphur diesel fuels.

Figure 2 shows of the SMF-AR unit installed in the test cell at the Sasol Fuels Application Centre.

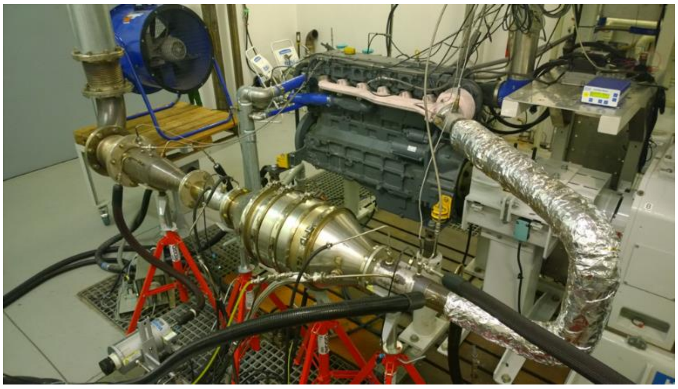


Figure 2. SMF-AR diesel particulate filter fitted to the engine in a test cell at the Sasol Fuels Application Centre.

3.3 *Test fuels*

Another objective of these collaborative tests was the evaluation of fuels that have the potential to reduce DPM emissions. The base-line case was a SANS 342 compliant diesel fuel containing 500 ppm sulphur, as this represents currently the most widely used fuel in the commercial sector due to cost. The selection of the other fuels in the tests was hypothesised on the assumption that that they would yield reductions in diesel particulate matter emission due to their inherent properties.

The full fuel analyses, shown in Appendix A, show that all fuels were supplied to specification, with two exceptions. These were the 500 ppm and 50 ppm diesel fuels which were intentionally blended up to their respective limits. These fuels exceeded the SANS 342 sulphur limits slightly, but were considered acceptable for the purposes of these tests to demonstrate the effect of sulphur on emissions.

3.3.1 *European certification diesel*

Since the test engine would have been certified in Europe against the relevant legislation, a diesel fuel conforming to the European specification EN590 was included to ensure the engine was compliant prior to the start of testing. (Test fuel name: EN590)

3.3.2 *500 ppm diesel*

This is a crude oil-derived South African diesel containing 500 ppm sulphur (SANS 342 compliant). This test fuel was produced at the NATREF refinery in Sasolburg. It was intentionally blended up from around 300 ppm to the 500 ppm limit with high sulphur diesel for the purposes of this project. Sulphur content in typical market fuels varies quite considerably so the decision was taken to fix the content at the upper limit of the SANS342 specification to determine the effect of sulphur on various emissions. This test fuel was blended and supplied by Sasol. (Test fuel name: 500ppm)

3.3.3 *50 ppm diesel*

This is a crude oil-derived South African diesel containing 50 ppm sulphur (SANS 342 compliant). The base fuels used to arrive at this blend were the European certification diesel and the 500 ppm diesel fuels. Consisting largely of the EN590-compliant diesel fuel, this product was blended up to the 50 ppm limit of the low sulphur diesel grade in South Africa. It is important to note that this fuel will typically exhibit a lower final boiling point and lower aromatic content than SANS 342-compliant diesel fuels. This test fuel was blended and supplied by Sasol. (Test fuel name: 50ppm)

3.3.4 *Sasol turbodiesel^{TM} ULS 10 ppm diesel*

This is a fully-synthetic South African diesel fuel containing less than 10 ppm sulphur (SANS 342 compliant). This test fuel was sourced from a Sasol fuel retail site directly outside the Sasol refinery in Secunda. (Test fuel name: 10ppm)

3.3.5 *Sasol GTL diesel*

This is a highly-paraffinic synthetic diesel containing less than 10 ppm sulphur. This commercially available GTL (Gas-to-Liquid) diesel fuel was obtained from the ORYX GTL production facility in Qatar, where Sasol is the technology supplier and equity partner. This fuel meets the requirements of the EN15940 specification. (Test fuel name: GTL)

3.3.6 *50 ppm diesel with 7% SME biodiesel*

Soy methyl ester (SME) was added to 50 ppm diesel base, at a 7% v/v ratio to generate this biodiesel fuel mixture. This blend ratio was guided by the maximum allowable limit imposed by most engine manufacturers. (Test fuel name: SME7)

3.3.7 *50 ppm diesel with 7% PME biodiesel*

Palm oil methyl ester (PME) was added to 50 ppm diesel base fuel, at a 7% v/v ratio to generate this biodiesel fuel mixture. This blend ratio was guided by the maximum allowable limit imposed by most engine manufacturers. (Test fuel name: PME7)

3.4 *Laboratory Analytical Equipment*

In addition to the instrumentation used for measuring engine torque and speed, pressures, temperatures, and air flow rates, the following specialised instrumentation was employed during the tests:

- Fuel consumption was measured using a mass flow meter employing a Coriolis-mass flow sensor and fuel temperature conditioning (AVL735S and AVL753C).
- All testbed data as well as engine control module (ECM) parameters were logged by the test cell automation system at a frequency of 10 Hz.
- Raw exhaust gas was sampled simultaneously before and after the DPF to measure concentrations of NOx (nitrogen oxides), CO (carbon monoxide), THC (total hydrocarbons), and CO_2 (carbon dioxide) using standard raw gas emissions benches (Horiba MEXA Series 7000).
- Dilute and bag emission measurements were made from a CVS (Constant Volume Sampler, Horiba CVS7000), using a dilute emissions bench (Horiba MEXA series 7000).
- A double dilution system with a full flow primary dilution tunnel, conditioned primary and secondary dilution air, and single, heated, 47 mm diameter sample filters was used for particulate sampling.
- Particulate matter (PM) sample filters were preconditioned in a humidity and temperature controlled room before the pre- and post-test weighing. A Mettler Toledo XP2U microbalance

(readability of 0.1 µg) was used to weigh each filter.

- Pre- and post-DPF speciated emission measurements were made by means of two on-line FTIR (Fourier Transform Infra-red) analysers (Peus SESAM).
- Real-time measurements of soot concentration in the undiluted exhaust were performed by means of a photo-acoustic soot sensor (AVL483 Micro Soot Sensor). Soot measured in this way corresponds to the insoluble or non-volatile portion of the particulate matter (primarily elemental carbon).
- Particle number emissions were measured in the dilution tunnel with a PMP (Particle Measurement Programme) compliant system that comprises an engine exhaust condensation particle counter (TSI 3790), and Dekati DEED 300 dilutor.
- Exhaust samples were also collected directly from the exhaust pipe onto a quartz-fibre filter using a mini dilution tunnel for post analysis using the NIOSH 5040 method. This method determines the mass of elemental and organic carbon captured on the filter using thermal-optical analysis.

3.5 *Test protocol*

All engine tests were performed with the engine fully warmed up, and, where applicable, emission tests were conducted in compliance with EPA emission standards for non-road diesel engines (published in the US Code of Federal Regulations, Title 40, Part 89). The US non-road emission standards are harmonized to a certain degree with European non-road emission standards.

For Tier 1 to 3, non-road engine emissions are measured on a steady-state test cycle that is equivalent to the ISO 8178 C1, 8-mode steady-state test cycle. This cycle is also known as the non-road steady cycle (NRSC). There is an additional requirement for Tier 4 compliant engines to measure emissions on the non-road transient cycle (NRTC). As the selected test engine complies with Tier 1 emission standards, only emissions compliance over the non-road steady-state test cycle was established.

As part of the project's objectives, there was a need to measure emissions over a real-world transient duty cycle for a LHD vehicle. The test cycle approximating real-world operation was obtained by recording the operation of an LHD at Anglo Platinum's Bathopele mine using a portable data logger (VBOX IISX data logger). The recorded data was replicated in the engine test cell using a transient dynamometer. Figure 3 shows the logger mounted on the LHD.

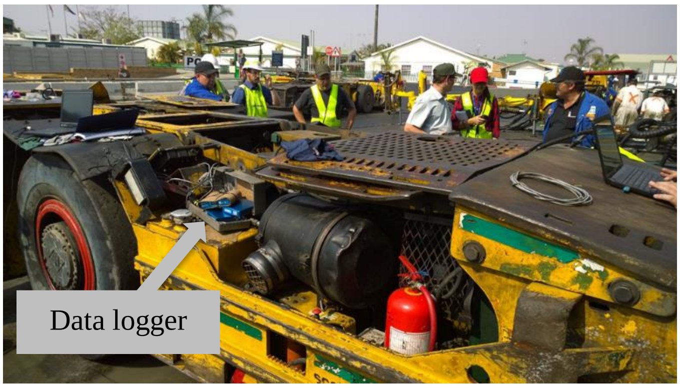


Figure 3. Data logger mounting position on LHD at Bathopele mine in Rustenburg

Some 17 hours of data were recorded over the course of one and a half shifts. In consultation with the project members, a representative segment was extracted from this dataset and used as the underground mining transient cycle (UMTC). The extracted test cycle contained a balanced quantity of repetitive idle, loading, hauling, and dumping segments. Figure 4 shows the speed and load profiles for the selected 24 minute test cycle.

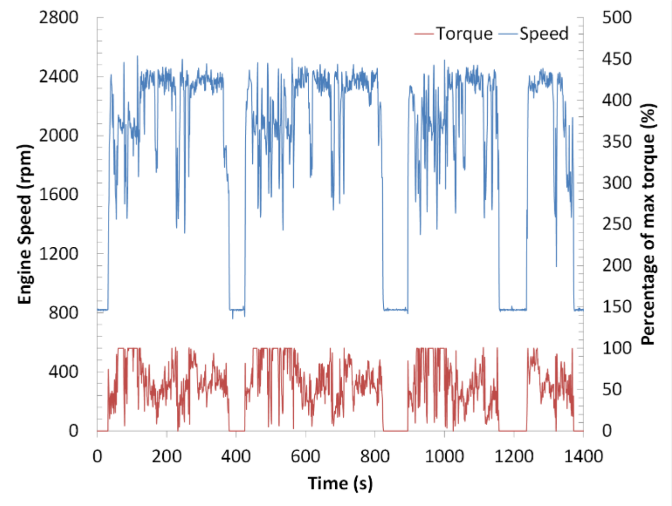


Figure 4. Speed and torque profile of the selected underground mining transient cycle

All fuels and DPFs were evaluated by subjecting the test engine to the above transient cycle. This generated the primary dataset that was used for comparison. Although the transient cycle represents a close approximation of real-world operation, it cannot fully guarantee that real-world emissions will be reproduced accurately. Only a direct comparison of emissions recorded on vehicles and during engine test cell runs may be used to verify accuracy. The legislated non-road steady cycle was also used during the evaluations in order to assess the level of emissions compliance against the Tier 1 certification limits. Table 2 shows the torque and speed set points for this test cycle.

Table 2. Non-road steady cycle

Mode Number	Speed	Load	Torque	Weighting Factor
	Rpm	%	Nm	-
1	2300	100	Max	0.15
2	2300	75	393	0.15
3	2300	50	262	0.15
4	2300	10	52	0.1
5	1500	100	Max	0.1
6	1500	75	483	0.1
7	1500	50	322	0.1
8	Idle	0	Idle	0.15

The maximum torque values (524 Nm and 645 Nm for the 2300 rpm and 1500 rpm speeds, respectively) in Table 2 were determined during a power curve test using the European certification diesel fuel described in section 3.3 above. These set-points were used also for the other test fuel runs. The expectation was that the other fuels would produce varying torque values at maximum load based on the fuel's volumetric energy density.

3.6 *Test sequence*

This project was separated into two phases which allowed a more focused assessment of each option's ability to reduce diesel particulate matter (DPM) emissions. Phase 1 focused on a fuel-only solution where no capital investment would be required to reduce DPM emissions. In this phase, no exhaust after-treatment was used during the engine test runs to assess the engine's emissions in its original Tier 1 specification. All seven test fuels detailed in section 3.3 were evaluated in Phase 1 using a pseudo-randomised test sequence, shown in Table 3. Results presented later in the paper are the average of the three tests and error bars indicate the data's standard deviation. Student's T-test (95% confidence level) was used to determine whether differences between the averaged results were statistically significant or not.

Table 3. Fuel only evaluation test sequence

Test block 1	Test block 2	Test block 3	Test block 4
EN590	EN590	EN590	EN590
500ppm	SME7	GTL	
50ppm	10ppm	PME7	
10ppm	PME7	SME7	
GTL	500ppm	10ppm	
SME7	50ppm	50ppm	
PME7	GTL	500ppm	

It can be seen that EN590 diesel was always tested first in each test block and was used again a fourth time. This was done intentionally to check if any drift occurred throughout the test sequence and constituted a "bracket test" to ensure the engine was performing in the last test at a similar level as the first test.

Phase 2 focused on the evaluation of the performance of two retrofitted DPFs and was aimed to provide a hardware solution to reduce DPM emission while using cost-effective and freely available market fuels that meet the minimum requirements of the DPFs. The SMF-CRT required a diesel fuel that contains less than 50 ppm sulphur and therefore, the 50 ppm and 10 ppm diesel fuels were used. The SMF-AR was tolerant of high sulphur diesel fuels and was thus tested with the 500 ppm, 50 ppm, and 10 ppm diesel fuels. Table 4 and Table 5 show the test sequences for Phase 2.

Table 4. SMF-CRT evaluation test sequence

Test block 1	Test block 2	Test block 3	Test block 4
50ppm	10ppm	50ppm	10ppm
10ppm	50ppm	10ppm	

Table 5. SMF-AR evaluation test sequence

Test block 1	Test block 2	Test block 3	Test block 4
500ppm	50ppm	50ppm	10ppm
50ppm	10ppm	500ppm	
10ppm	500ppm	10ppm	

Due to the limited number of test fuels in each of these evaluations, drift was not checked at the start of each test block, as in the Phase 1. However, a bracket test on 10 ppm diesel was included, and the conventional gravimetric sample filter paper, used to sample diesel particulate matter from the full-flow dilution tunnel, was replaced with a quartz-fibre filter in order to measure the ratio of elemental to organic carbon using the NIOSH 5040 method with each DPF technology. This analysis was also done in Phase 1 but the sample was drawn directly from the exhaust pipe.

Each fuel evaluation for Phases 1 and 2 entailed testing the fuel, with the engine fully warmed up and running, over the non-road steady cycle and the underground mining transient cycle. At each fuel change, the fuel system was flushed using the next test fuel. Thereafter, a pre-conditioning test was run on the engine before starting the evaluation of the next test fuel

4 RESULTS AND DISCUSSION

4.1 *Engine condition and operation*

The Deutz BF 6M 1013 E engine used in this study is one of the most prevalent engines in Anglo Platinum's mines. The specific engine that was used in the test cell was originally new, but underwent a severe run-in period at the Deutz Dieselpower workshop before being supplied to Sasol for testing. This is an important step to ensure that the engine will not introduce any drift in the emissions results between the first and last tests.

The health of this engine was considered to be very good and, as expected therefore, it was found to be fully compliant with Tier 1 emission limits. As the engine ages, an increase in the emissions can be expected but should, according to the emission requirements for which it is approved, remain compliant for the duration of the engine's useful life. According to the US Environmental Protection Agency (EPA), the useful life of a non-road engine with a power rating above 37 kW is 8000 hours or 10 years, whichever occurs first.

In order to approximate deterioration of engines' combustion efficiency over time and effect of less than adequate maintenance, deterioration factors (DF) were applied to the emission limits. For the purpose of these tests, the DFs were introduced to impact directly on the emitted mass of gases and particulates:

DF1: for new engines; Factor = 1.0;
DF2: for well-maintained engines at the end of their useful life; Factor = 1.2;
DF3: For poorly maintained engines at the end of their useful life; Factor =1.5.

It must be noted that DFs are specific to each engine and are to be determined by the engine manufacturers in accordance with good engineering practices. In the USA, for example, deterioration factors are subject to EPA approval. Typical DFs will not exceed 1.2 (20% increase) for older engine technology since the absolute emission limits are relatively high. A DF of 1.2 is realistic for a well maintained engine at the end of its useful life. When maintenance is not rigorously carried out in an underground mine, there could be a much larger deterioration in emissions. A comprehensive maintenance plan based on an engine OEM's advice, which is verified through routine in-field emission condition monitoring, is crucial to ensure high underground air quality is maintained. Failure to ensure that the engines are well maintained, will undo any improvement made by retrofitting exhaust after-treatment or switching to a low emission diesel fuel.

4.2 *Fuels evaluation*

The seven diesel fuels evaluated during this study represented a selection of commercially available as well as of a few alternative fuels. The emission results showed the extent of possible improvements achievable by mines even only by switching fuel type for an existing vehicle fleet. This by no means represents the limit of what can be accomplished with a "fuel-only solution" as there are other fuel formulations that will further reduce emissions. However, these formulations are typically not commercially available yet, or will, in addition to a higher cost price, introduce significant handling and operational challenges.

Although reduction of DPM emissions was the primary objective in this study, emphasis was also placed on limiting emission levels of other pollutants and at containing fuel consumption.

4.2.1 *Emissions performance*

As outlined in the experimental setup section, all regulated engine emissions (DPM, NOx, CO, THC) and speciated emissions (e.g. NO_2, NO, SO_2, etc.) were measured during testing, however due to the large quantity of data only DPM, CO, NO_2, and SO_2 will be presented below as they specifically pertain to the occupational exposure levels that are set to govern air quality.

4.2.1.1 Diesel particulate matter emissions

The engine's particulate matter (PM) emissions, which were the primary focus in this research work, comprise four major portions: (1) carbonaceous particulates (also known as soot or elemental carbon), (2) liquid hydrocarbons that are adsorbed on to the carbon particles and are referred to as the organic carbon (OC) portion or the soluble organic fraction (SOF), (3) sulphates (SO_4) and bound water, and (4) ash (inorganic material).

PM emissions measured during the tests are presented in Figure 5 in relation to the base-line fuel's emission levels.

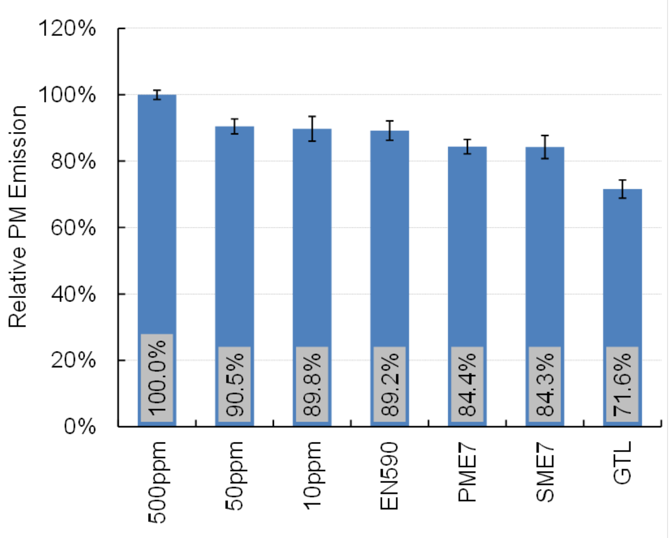


Figure 5. Relative PM emissions for a LHD fitted with a Deutz BF6M1013 engine.

The results showed that diesel PM emissions were reduced by approximately 10% when switching from a diesel containing 500 ppm sulphur to ultra-low sulphur diesel (50 ppm, 10 ppm, or EN590 diesel). A further reduction of 5% was achieved when adding 7% biodiesel (SME or PME) to 50 ppm diesel; a similar benefit would have been observed if the biodiesel were added to the EN590, 10 ppm, or

500 ppm diesel fuels. The largest reduction was recorded when switching to a highly-paraffinic synthetic diesel (GTL diesel), where PM emissions were reduced by 28.4% when compared to the 500 ppm diesel level.

All fuels produced emissions below the Tier 1 emission limit. GTL diesel managed to lower the PM emissions to below the Tier 2 and 3 limits.

Diesel particulate matter analysis (using NIOSH 5040) for this engine indicated an average elemental carbon to total carbon ratio of 0.71 for all fuels, and an average elemental carbon to total particulate matter ratio of 0.60.

NIOSH 5040 showed reductions in the mass of PM that corresponded well with the gravimetric PM results presented in Figure 5.

4.2.1.2 Carbon monoxide emissions

Carbon monoxide (CO) emissions are formed mainly due to incomplete combustion, which is exacerbated by lack of oxidants, reduced temperature, and shortened residence time. As combustion proceeds to completion, oxidation of CO to CO_2 occurs through recombination reactions between CO and various oxidants. If these recombination reactions are incomplete due to a lack of oxidants or due to low gas temperatures, CO will be left without oxidation (Henein and Patterson 1972).

CO emissions are presented in Figure 6.

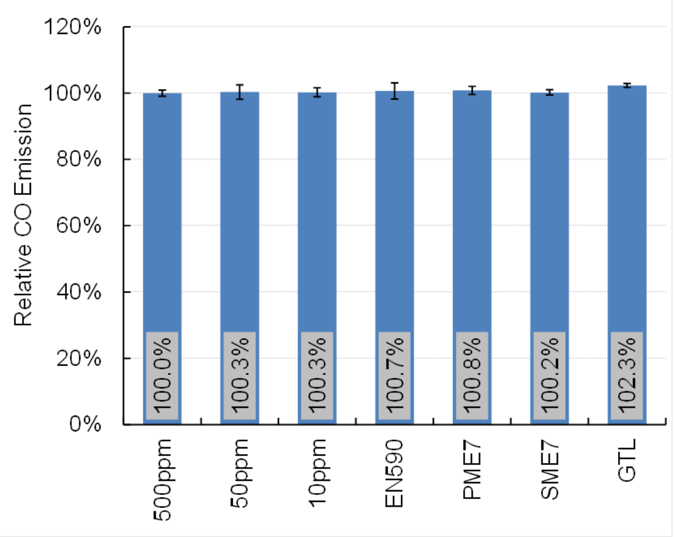


Figure 6. Relative CO emissions for a LHD fitted with a Deutz BF6M1013 engine.

CO emission results showed no statistically significant difference between fuels. Furthermore, CO emissions from the test engine in this study, for all fuels, were substantially below the Tier 1 limit, and well under the Tier 4 limit.

4.2.1.3 Nitrogen dioxide emission

Nitrogen dioxide (NO_2) on its own is not a regulated exhaust emission that engine manufacturers are required to limit; rather NOx is regulated as the sum of NO_2 and nitric oxide (NO). NO_2 is, however, regulated in restricted ventilation environments by various occupational health and safety laws around the world.

NO_2 emissions are presented in Figure 7.

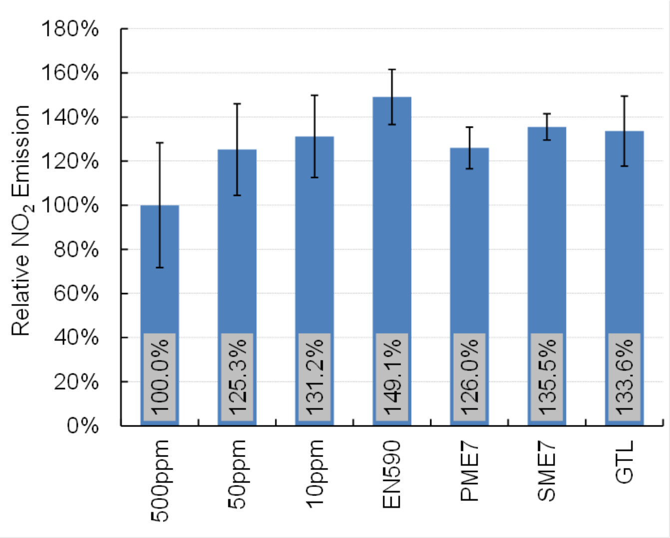


Figure 7. Relative NO_2 emissions for a LHD fitted with a Deutz BF6M1013 engine.

Due to the very low concentration levels, and therefore poor repeatability in measuring NO_2, there were no statistically significant differences between fuels. There was, however, a general increase in these emissions from all fuels when compared to 500 ppm diesel.

4.2.1.4 Sulphur dioxide emissions

Similar to NO_2 emissions, sulphur dioxide (SO_2) emissions are also not a regulated engine exhaust emission. SO_2 emissions are effectively controlled by reductions in the fuel sulphur levels. At the time Tier 1 emissions legislation was promulgated, the diesel fuel sulphur levels were between 3000 ppm and 5000 ppm; currently in South Africa there are two grades of diesel, 500 ppm and 50 ppm.

The effect of lowering fuel sulphur levels from 500 ppm to less than 10 ppm on SO_2 emissions is presented in Figure 8.

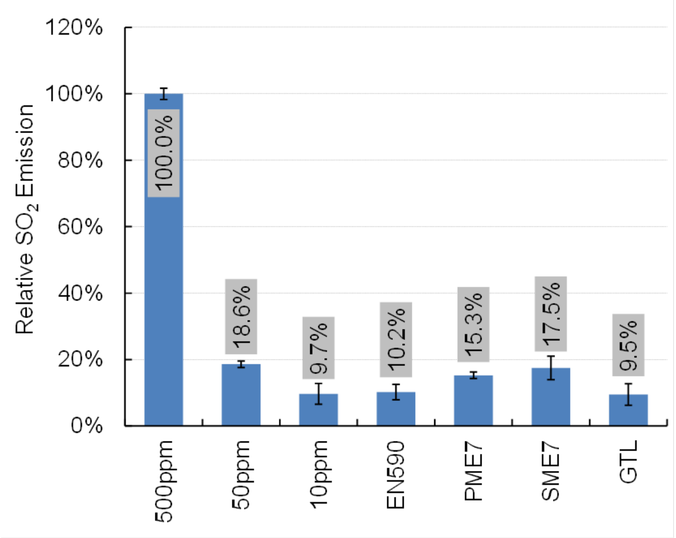


Figure 8. Relative SO_2 emissions for a LHD fitted with a Deutz BF6M1013 engine.

When lowering fuel sulphur levels from 500 ppm to 50 ppm, an 81.4% reduction in SO_2 emissions was recorded. Lowering fuel sulphur further to 10 ppm effectively halved the SO_2 emissions from 50 ppm diesel. The addition of 7% PME or SME (which are both sulphur-free fuels) slightly lowered the SO_2 emissions of the 50 ppm. There were no statistically significant changes between the 10 ppm, EN590, and GTL diesel fuels, which are all near sulphur-free fuels. The low levels of SO_2 that remain when running an engine on a near sulphur-free diesel are produced from the combustion of the engine lubricant—which typically contains sulphurous compounds.

4.2.2 *Fuel formulation and additive optimisation*

This study focused on selection of conventional diesel fuels that are commercially available in the market. If the cost of retrofitting exhaust after-treatment onto existing vehicle fleets is undesirable, customised fuel formulations and additive optimisation are other avenues available to achieve even greater DPM emission reductions. Some examples are provided below.

Commercially supplied combustion improver additives that claim to reduce DPM emissions can be blended into commercially available diesel (500 ppm, 50 ppm, 10 ppm diesel). These additives are metal-free, completely organic, and added at very low treat rates of less than 300 ppm. This ensures there are no secondary emissions formed after combustion when using them in engines without exhaust gas after-treatment.

Aftermarket combustion improver additives are available but are often not metal-free or organic, and are treated at significantly higher dosage rates (dosage rates should typically not exceed 1000 ppm). These products may yield DPM emission reductions, but their secondary emissions potential must be assessed. The combustion of metal-based additives would generate ash particles that pose a health risk unless captured in a diesel particulate filter. Any additive should be registered with institutions such as the United States Environmental Protection Agency (EPA). The EPA requires that all fuels and additives are registered under “40 CFR Part 79 - Fuel and Fuel Additive Registrations (FFARs)”. For example, the fuel borne catalyst (satacen®1 produced by Innospec Fuel Specialties) used in conjunction with the SMF-AR diesel particulate filter, which was used in this study, is approved with the EPA. This fuel borne catalyst (FBC) is an organometallic chemical compound that must not be used without a wall-flow diesel particulate filter, since the FBC generates ash particles that would otherwise exit into the atmosphere.

Water diesel emulsions are very effective at reducing DPM (and NOx) emissions, although some emissions such as CO may increase, DPM emission reductions up to 70% may be achieved. Any claims regarding improved engine efficiency are likely to be untrue. There are many valid concerns regarding their practical application, these include: applications where high fuel temperatures are experienced (as is the case in most modern, high pressure fuel injection systems, or engines with fuel supply rails built into the engine block – such as the test engine in this study), fuel handling, storage stability, cold weather vehicle operability, power loss, and equipment durability.

Increasing the biodiesel content up to 20% in an ultra-low sulphur diesel will further reduce DPM emissions. This option would have to be implemented in consultation with the original equipment manufacturer (OEM) of the engine, since most OEMs will void warranties when using fuel containing more than 7% biodiesel. High biodiesel blends can increase the rate of oil dilution, will increase volumetric fuel consumption, and increase the likelihood of the biodiesel handling challenges that were highlighted above. GTL diesel and biodiesel blends work very well together, where DPM emission reductions of up to 40% have been measured. This practice negates the need to add lubricity additives to neat GTL diesel.

With all the above mentioned fuel formulations and additives, laboratory testing and validation is critical. In-field testing of new fuels or additives is highly discouraged due to the difficulty in controlling engine load between fuel or additive comparisons repeatedly. Often inaccurate emission analysers are also used which cannot provide a definitive answer required to support a business case.

4.3 *Diesel particulate filter evaluation*

The diesel particulate filter (DPF) evaluation phase of this study assessed the performance of two systems supplied by Deutz Dieselpower to reduce DPM emissions, namely the SMF-CRT and SMF-AR diesel particulate filters. The partial-flow SMF-CRT has a claimed efficiency of between 30 to 60%, and has an integrated diesel oxidation catalyst (DOC) which reduces carbon monoxide and unburned hydrocarbons. The wall-flow SMF-AR has a claimed filtration efficiency of 99%, and has no integrated DOC.

4.3.1 *Emissions performance*

Similar to the fuels evaluation, only DPM, CO, NO_2, and SO_2 will be presented below as they specifically pertain to the occupational exposure levels that are set to govern air quality. The following series of figures compares the performance of the SMF-CRT (shown with a prefix CRT) and SMF-AR (shown with a prefix AR) exhaust after-treatment systems against an engine without after-treatment using 500 ppm diesel.

4.3.1.1 Diesel particulate matter emissions

Both exhaust after-treatment systems achieved their respective design filtration efficiencies during testing; the actual PM emission reductions are shown below in Figure 9.

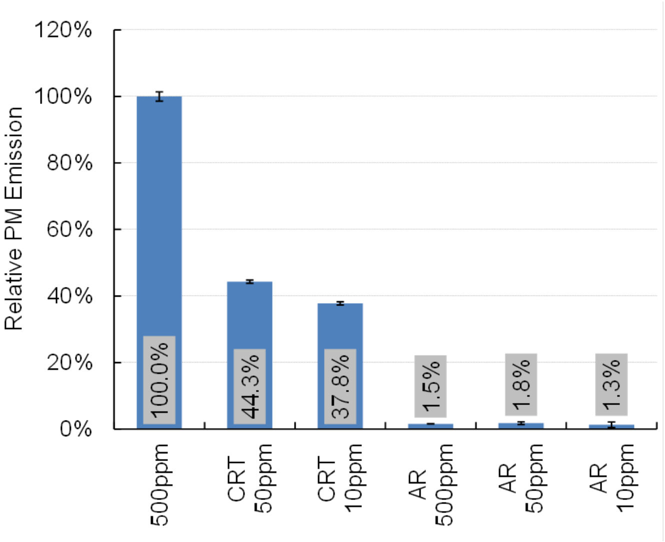


Figure 9. Relative PM emissions for a LHD fitted with a Deutz BF6M1013 engine with after-treatment fitted.

The SMF-CRT system achieved filtration efficiencies towards the upper bound of its claims in real-world operating conditions; 55.7% filtration efficiency was achieved when operating the engine on 50 ppm diesel, and 62.2% filtration efficiency for 10 ppm diesel. The SMF-AR system also achieved filtration efficiencies around its design claims of around 98% with all fuels tested on it.

4.3.1.2 Carbon monoxide emissions

CO emissions are presented in Figure 10.

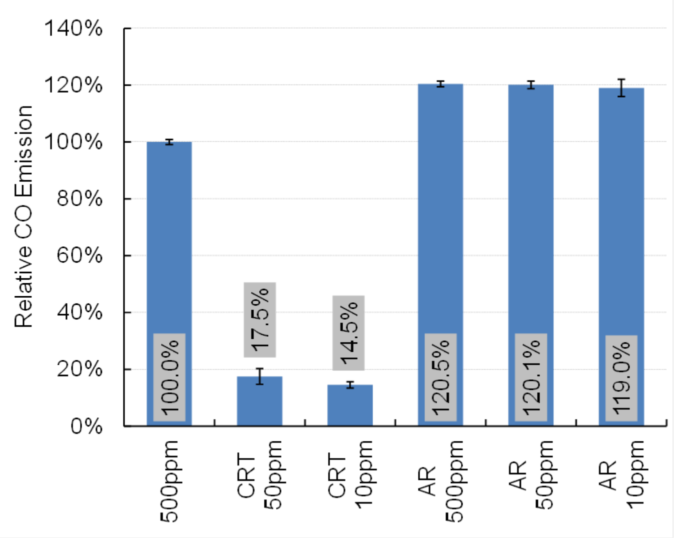


Figure 10. Relative CO emissions for a LHD fitted with a Deutz BF6M1013 engine with after-treatment fitted.

Due to the diesel oxidation catalyst (DOC) built into the SMF-CRT system, reductions in CO and THC emissions were achieved. A reduction of 82.5% was achieved with 50 ppm diesel compared to the base 500 ppm diesel case. 10 ppm diesel further reduced CO emissions to 85.5% below the 500 ppm base case. This represents a 17.1% reduction from the 50 ppm diesel result.

Due to the lack of any DOC function in the SMF-AR, this system did not reduce CO emissions but rather increased them by approximately 20%. It is not fully understood why this occurred, but these higher levels of incomplete combustion could be related the increased exhaust backpressure created by the SMF-AR; the SMF-CRT also raised CO emissions before the after-treatment, when compared to operating the engine without after-treatment, but were then substantially reduced over the integrated diesel oxidation catalyst - which the SMF-AR did not have.

4.3.1.3 Nitrogen dioxide emissions

NO_2 emissions are presented in Figure 11.

The DOC built into the SMF-CRT increased oxidation rates of nitric oxide (NO) resulting in a large NO_2 emission increase was seen compared to 500 ppm diesel levels. This NO_2 emission increase would be similar to one observed in a vehicle fitted only with a DOC, such as is common practice in most underground mines.

The SMF-AR did, however, decrease NO_2 emissions by 99% from levels seen without the SMF-AR fitted.

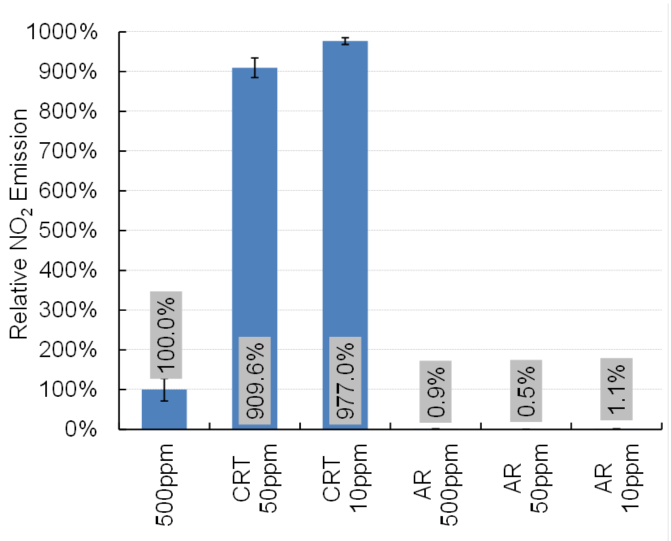


Figure 11. Relative NO_2 emissions for a LHD fitted with a Deutz BF6M1013 engine with after-treatment fitted.

4.3.1.4 Sulphur dioxide emissions

SO_2 emissions are presented in Figure 12 below.

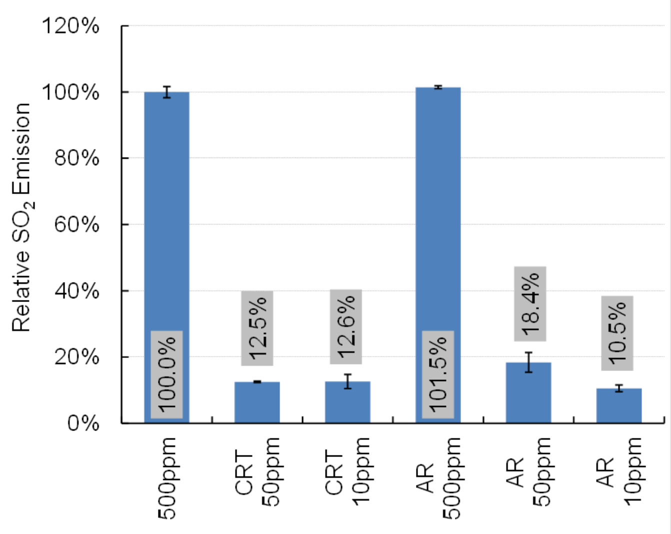


Figure 12. Relative SO_2 emissions for a LHD fitted with a Deutz BF6M1013 engine with after-treatment fitted.

SO_2 emissions are purely a function of the sulphur content in the fuel and engine lubricant. As a result, the SO_2 emissions with the SMF-CRT were similar to an engine without after-treatment, albeit a little lower.

Similarly, the SMF-AR could not affect these emissions in any way. Only when switching from 500 ppm diesel to 10 ppm diesel, was a 90% decrease in SO_2 emissions recorded.

4.4 *Predicted underground mine air quality*

In the preceding two sections, several routes to lowering underground emissions were presented; be it a fuel-only solution, or a more capital intensive hardware retrofit solution. It can quickly become a complex decision when deciding which pollutant is a higher priority, while along the way needing to balance the chosen path against fuel consumption penalties. In order to add some context to the raw exhaust emission results presented above, an exercise was carried out where the experimental data were translated into a mass of pollutant emitted underground by one LHD over the course of the operating cycle.

The data-sets were used to calculate fresh air volumetric flow-rates that would be able to dilute the measured emissions for the different configurations to levels below the occupational exposure levels (OEL) being currently considered by the Department of Mineral Resources for South African mining operations. The goal was to determine levels of compliance for all pollutant OELs, and understand what roadmap could be set up to achieve the impending diesel particulate matter OEL that is set to be progressively reduced over a three year period in South Africa.

4.4.1 *LHD emissions per shift*

For the purpose of these studies, it was decided to focus on the following pollutants: DPM, CO, NO_2, and SO_2. The engine emission results (in g/kWh) from the 24 minute underground transient test were multiplied by the test cycle work (in kWh), and then divided by 24 to obtain mass of emission per minute of operation.

At this point it is appropriate to distinguish between exposure limits set for deterministic effects, typical of pollutants such as the three gases considered where the effect is based on a well-established response model, and stochastic effects, typical of carcinogenic substances such as particulates in the engine exhaust cocktail, where dose-and-effect relationships are not clear and where exposures should be kept “as low as reasonably possible or achievable” (ALARP or ALARA principles).

The distinction between the two effects is fundamental in establishing minimum ventilation rates. Emission values obtained from the 24 minute underground transient test were adapted to reflect the operational period assumed typical of the LHD vehicle, namely 4 hours and seven minutes, as determined from recorded vehicle data, over a nominal eight hour shift. Exposure of workers to gases, response to which is deterministic, would allow excursions above the respective OEL, but below the short term exposure limit or STEL, so that over an eight hour period the OEL is not exceeded. However, since “diesel emissions” are deemed to be carcinogenic, this assumption is not valid and the interpretation is that exposures must be below the exposure limit at all times. In actual fact, good practice requires the application of the ALARP principle to ensure that exposure to carcinogens is below such limits.

4.4.2 *Fresh air dilution factors*

In order to provide guidance as to the required minimum ventilation dilution rates based on these results, the recorded gas and particulate emissions were normalised to average air flow rates based on the respective OELs while considering the qualification indicated above.

For gaseous emissions, dilution rates are invariable very low and reflect the properties of the fuels and of the exhaust after-treatment systems used. Figure 13 depicts the indicated fresh air dilution quantities applicable to the test results to meet the OEL for Carbon Monoxide (35mg/m^3).

Figure 13 indicates the impact of increased exhaust backpressure induced by the use of the active regeneration (AR) DPF requiring additional dilution. The catalytic oxidation effect of the continuous regenerating trap unit (CRT) on the carbon monoxide is also evident from the reduced dilution requirements.

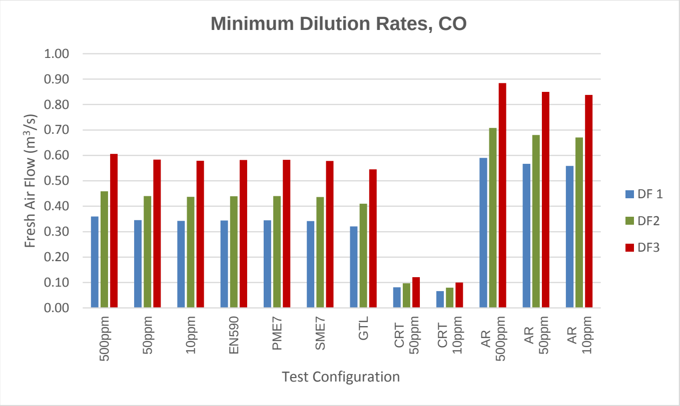


Figure 13: Fresh air dilution factors for emitted Carbon Monoxide

Figure 14 summarises the fresh air dilution requirements based on the sulphur dioxide emissions to meet the OEL (5mg/m^3).

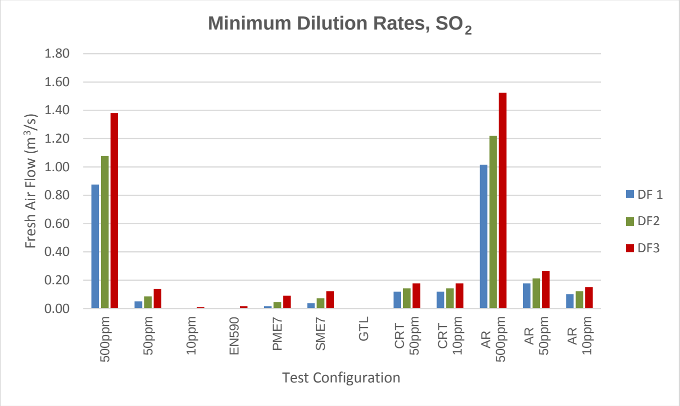


Figure 14: Fresh air dilution factors for emitted Carbon Monoxide

The results indicated in Figure 14 show clearly the effect that the introduction low sulphur fuel has in reducing fresh air requirements.

Figure 15 indicates the required dilution rates to reduce emitted levels of nitrogen dioxide to below the OEL (5mg/m^3).

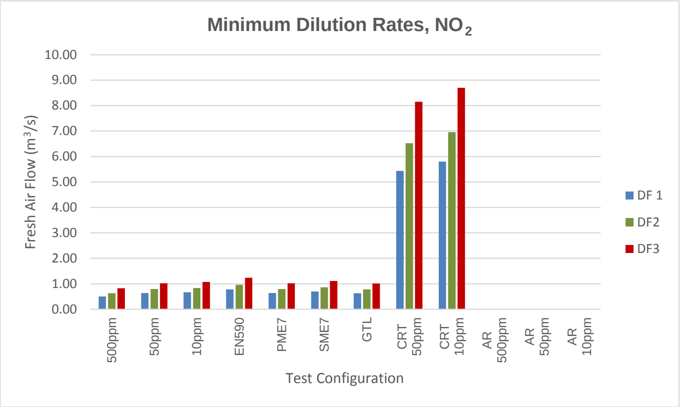


Figure 15: Fresh air dilution factors for emitted Nitrogen Dioxide

In deciding air-flow requirements as guided by Figures 13, 14 and 15 one would have to consider the type of fuel utilized, the condition of the engine as well as the type of exhaust after-treatment system employed, if any, and then select the highest flow-rate. The re-use of air used to dilute engines' exhaust streams requires careful consideration as to the gases contained, temperature and humidity of the air for any further use, dilution or mixing down-stream.

A similar analysis was made for the particulate matter emissions. The total measured particulate matter (TPM) measured over one shift was converted to a total carbon fraction for each of the test sets. These results were converted to mass emissions per unit time and compared to the anticipated OEL of 160µg/m$^3{}_{TC}$ to verify the validity of using the "accepted" design dilution factor of 0.06m^3/s/kW of nominal power at the point of application.

Figure 16 shows the derived fresh air dilution flow-rates. Figure 17 shows the same results normalised for the rated power of the test engine, 137kW, in order to yield results comparable to the above design dilution factor (indicated by a purple line).

In all cases, it is significant to note the impact that engine age and poor maintenance may have on the quality of the exhaust stream and the impact these factors would have on fresh air demand and related ventilation system capital and operational costs.

These results also show the benefit of using particulate filters in reducing the required fresh air dilution quantities. Of concern in these findings is the apparent inadequacy of using a dilution factor of 0.06m^3/s/kW of nominal power at the point of application without due consideration of the vehicle, fuel and exhaust after-treatment provided. This might affect the ability of older diesel engine technology and fuels to meet the proposed DPM OEL.

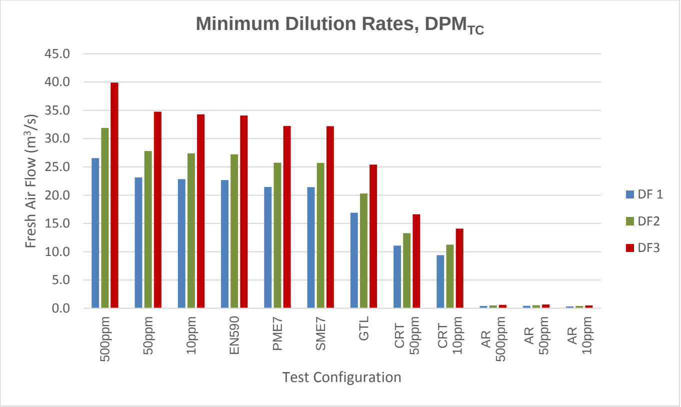


Figure 16: Fresh air dilution factors for emitted TPM

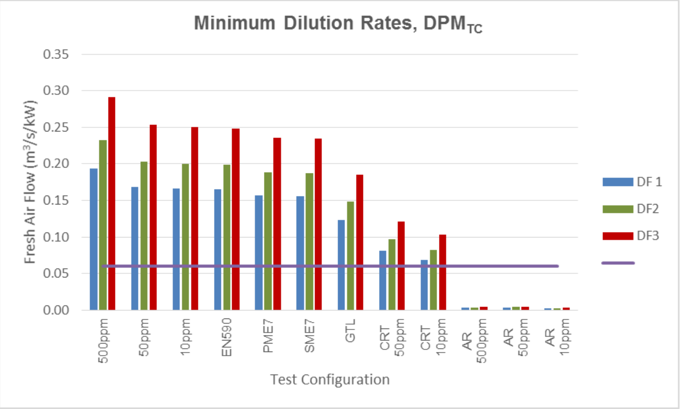


Figure 17: Normalised fresh air dilution factors for emitted TPM

In summary, dilution factors presented in this section show that for the Tier 1 engine tested, based on the specific operational cycle simulated and fuels used, adequate gas dilution may be achieved reasonably easily, particularly where cleaner burning fuels are used. However, results also show that the design dilution rate traditionally applied to diesel equipment is insufficient to ensure adherence to the proposed particulate matter OEL under these conditions.

These results further indicate that:

- The use of low sulphur fuels promotes cleaner exhaust both in terms of gases and particulates.
- The use of low sulphur fuels allows the use of catalysts in exhaust after-treatment systems that in turn reduce exhaust gas concentration.
- The concentration of emissions from an engine without a particulate filter requires high levels of fresh air dilution and precludes the re-use of air.
- The introduction of particulate filtration systems is essential in meeting the proposed DPM OELs.
- Engine deterioration, due to age and poor maintenance, impact significantly on the applicable fresh air dilution rates.
- Re-use of air between sections may only be possible if adequate fresh air dilution is applied – best results being achieved by the use of low sulphur fuels and adequate exhaust filtration.
- Although gas emissions require low fresh air dilution rates, the continual operation of equipment in main intakes may result in higher gas and particulate contamination at section entries that would have to be accounted in ensuring adequate air quality in the section.

Although the dilution factors indicated in Figures 16 and 17 are deemed to be achievable using appropriate particulate filtration, it must be remembered that, apart from the capital and operational cost of introducing such technology, the retrofitting of CRT and AR or equivalent particulate filters in existing equipment, specifically in the extra low profile (XLP) vehicles used in narrow reef mines may not be practically possible. A different solution may be necessary to ensure that such existing equipment will comply with proposed diesel exhaust particulate OELs.

It must be clear that these results are indicative and applicable to the type of engine and loading cycle used in the bench tests. Different engine technology or different loading cycles are likely to yield different results and demands on the mine’s ventilation system.

In addition, the application of very low fresh air dilution rates where diesel equipment is operated in practice, has to be managed in view of the resulting dry-bulb and wet-bulb temperatures and need to re-use such air further in the mine.

This indicates the need for careful and consistent assessment of diesel fleet performance based on regular, repeatable and representative tests performed on site. Possible consideration should be made in the use of emission based maintenance routines that may be used to “fingerprint” emissions from each vehicle over time and the data used to improve the effectiveness of selected ventilation strategies and assigned dilution quantities.

5 CONCLUSIONS

After evaluating the effectiveness of seven fuels and two retrofitted diesel particulate filters to reduce diesel particulate matter emissions in a Tier 1 certified Deutz BF6M1013 engine that operates in an underground mine, the following conclusions can be drawn:

The fuel evaluations revealed that switching a mine from 500 ppm diesel to an ultra-low sulphur diesel (50 ppm or 10 ppm) reduced particulate matter emissions by approximately 10%. Adding 7% biodiesel (SME or PME) to ultra-low sulphur diesel reduced particulate matter emissions by a further 5%. GTL diesel offered the biggest DPM reduction of 28.4% from 500 ppm diesel levels.

GTL diesel upgraded the emission rating of the engine from Tier 1 to a partial Tier 3 rating (excluding nitrogen oxides emissions, which remained at Tier 1 despite a 17.9% reduction).

Lowering fuel sulphur from 500 ppm to 50 ppm reduced SO_2 emissions by 81.4%. Lowering fuel sulphur further down to 10 ppm, or less, effectively halved the SO_2 emissions of the 50 ppm diesel.

The exhaust after-treatment evaluation showed that the partial-flow SMF-CRT, when tested with 50 ppm diesel, achieved a particulate matter emissions reduction of 55.7% from the 500 ppm diesel base case (no after-treatment). 10 ppm diesel further reduced particulate matter emissions to 62.2% below the 500 ppm diesel base case; this represented a 14.7% reduction from the 50 ppm result. The SMF-CRT reduced carbon monoxide emissions by over 85%, but significantly increased nitrogen dioxide emissions.

The SMF-CRT upgraded the emission rating of the engine from Tier 1 to a partial Tier 3 rating (excluding nitrogen oxides emissions, which remained at Tier 1 despite around a 10% reduction).

The wall-flow SMF-AR reduced DPM emissions for all fuels (500 ppm, 50 ppm, and 10 ppm) by more than 98% from the 500 ppm diesel base case (no after-treatment). This system increased carbon monoxide emissions for all fuels (500 ppm, 50 ppm, and 10 ppm) by approximately 20% from the 500 ppm base case. NO_2 emissions were effectively eliminated—not NO emissions—with all fuels tested, when compared to operating the engine without after-treatment on 500 ppm diesel.

The SMF-AR upgraded the emission rating of the engine from Tier 1 to a partial Tier 4 rating (excluding nitrogen oxides emissions, which remained at Tier 1).

The use of low sulphur fuels and particulate filters in the exhaust train will enable the use of a lower specification diesel engine in mines without the introduction of excessively high air quantities. The ability of adapting existing equipment and upskilling technical personnel in the installation, use and maintenance of such equipment is key in achieving these results.

Considerable reductions in air quantities for sections where diesel-powered equipment is operated are dependent on the ability to limit pollutant levels as well as air temperature and humidity in the reject air stream – particularly where these are to be reused elsewhere in the mine.

6 RECOMMENDATIONS

Based on the findings in this report, the following are recommended:

Currently available ultra-low sulphur diesel should be considered to immediately and significantly reduce emissions in underground mines that are currently being supplied with 500 ppm diesel. This can be further improved in conjunction with retrofitted after-treatment technologies.

Customised fuel formulations that contain biodiesel and/or GTL diesel are avenues available to achieve even greater diesel particulate matter emission reductions, however commercial supply of large volumes is limited with these fuels, and fuel handling or blending requirements become onerous. It is recommended that a limited follow-up study is executed, where organic, metal-free combustion improver additives (original commercial additives only) are added to a commercially available fuel (50 ppm or 10 ppm diesel) to assess the potential of this technology. The optimised fuel could be delivered to underground mining customers with the additive package pre-blended.

The SMF-CRT represents a relatively low-cost, compact, bolt-on solution which offers significant diesel particulate matter, carbon monoxide, and total unburned hydrocarbons reductions. It is recommended to evaluate its performance in the test cell using an 8 hour shift simulation to verify if the exhaust temperatures are indeed high enough to sustain continuous soot oxidation on the filter material, and therefore prevent filter blockage. Service life endurance tests could also be considered.

Assess a passively regenerating DPF system that does not increase NO_2 above engine-out levels (such as a CRT combined with a NO_2 decomposition catalyst).

Consider the introduction of regular and consistent site-based engine emission testing to characterise the performance of and emission from all vehicles. This data may be used to assess the effectiveness of maintenance procedures and to optimise the allocation of fresh air while ensuring adequate air quality of all operational sites.

7 ACKNOWLEDGEMENTS

Acknowledgements below are given in no particular order.

The authors gratefully acknowledge Bathopele Mine for hosting me for two days to carry out the LHD duty cycle recording. This recording was pivotal to reproduce realistic engine operation in the test cell, and therefore generate relevant engine exhaust emission results.

Anglo American’s engineering team is also gratefully acknowledged for their guidance and facilitation roles throughout the project, as well as for arranging the fuel analysis at Intertek.

Appreciation is also extended to Deutz Dieselpower for supplying a run-in test engine and the two after-treatment systems. Their support in commissioning the engine, supplying CAN protocol information, assistance at Bathopele, and after-treatment commissioning was invaluable.

The supply of the SME and PME biodiesel from FalconMere is very much appreciated.

The diesel particulate filter supplier is gratefully acknowledged for the technical information shared with the author around their two after-treatment systems.

The assistance provided by the technical support team at the Sasol Fuels Application Centre during the engine setup and testing phase of the project is gratefully acknowledged. A vote of thanks is also extended to Sasol for offering up the use of the Sasol Fuels Application Centre heavy-duty engine test cell for the duration of this collaborative project, as well as the supply of all the test fuels.

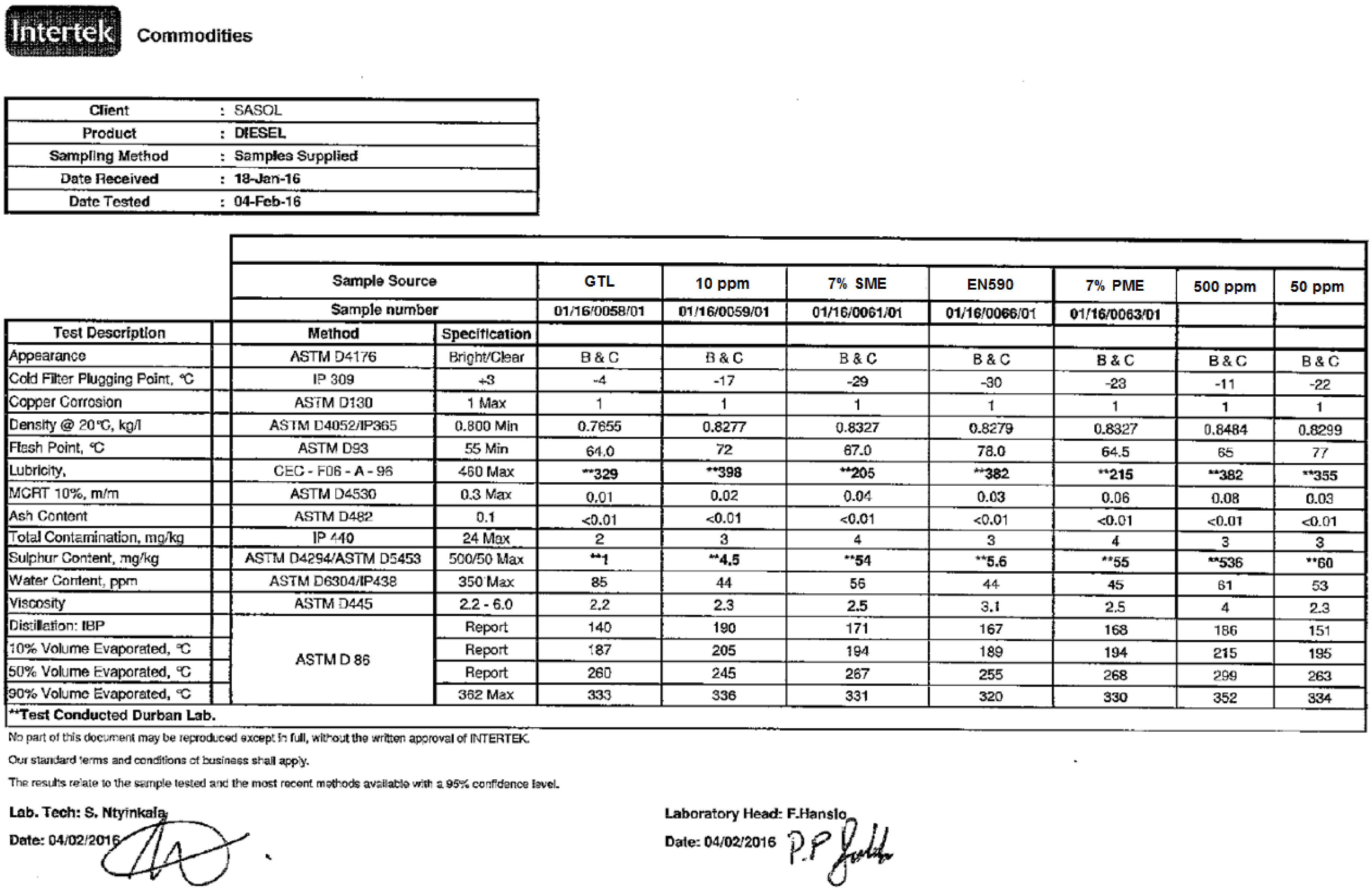
In general, the success of this extensive investigation into the reduction of emissions from diesel-powered equipment in underground mines was enabled by an industry wide collaboration, and would not have been possible without the professional, open, and committed interactions within the project team.

8 REFERENCES

Henein, N. and Patterson, D. 1972. *Emissions From Combustion Engines And Their Control*, Ann Arbor Science Publishers Inc.

Heywood, John B. 1988. *Internal Combustion Engine Fundamentals*. Massachusetts: McGraw-Hill Book Company.

APPENDIX A



Intertek Commodities

Client	: SASOL
Product	: DIESEL
Sampling Method	: Samples Supplied
Date Received	: 18-Jan-16
Date Tested	: 04-Feb-16

	Sample Source		GTL	10 ppm	7% SME	EN590	7% PME	500 ppm	50 ppm
	Sample number		01/16/0058/01	01/16/0059/01	01/16/0061/01	01/16/0066/01	01/16/0063/01		
Test Description	**Method**	**Specification**							
Appearance	ASTM D4176	Bright/Clear	B & C	B & C	B & C	B & C	B & C	B & C	B & C
Cold Filter Plugging Point, °C	IP 309	+3	-4	-17	-29	-30	-23	-11	-22
Copper Corrosion	ASTM D130	1 Max	1	1	1	1	1	1	1
Density @ 20°C, kg/l	ASTM D4052/IP365	0.800 Min	0.7655	0.8277	0.8327	0.8279	0.8327	0.8484	0.8299
Flash Point, °C	ASTM D93	55 Min	64.0	72	67.0	78.0	64.5	65	77
Lubricity,	CEC - F06 - A - 96	460 Max	**329	**398	**205	**382	**215	**382	**355
MCRT 10%, m/m	ASTM D4530	0.3 Max	0.01	0.02	0.04	0.03	0.06	0.08	0.03
Ash Content	ASTM D482	0.1	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Total Contamination, mg/kg	IP 440	24 Max	2	3	4	3	4	3	3
Sulphur Content, mg/kg	ASTM D4294/ASTM D5453	500/50 Max	**1	**4.5	**54	**5.6	**55	**536	**60
Water Content, ppm	ASTM D6304/IP438	350 Max	85	44	56	44	45	61	53
Viscosity	ASTM D445	2.2 - 6.0	2.2	2.3	2.5	3.1	2.5	4	2.3
Distillation: IBP	ASTM D 86	Report	140	190	171	167	168	186	151
10% Volume Evaporated, °C		Report	187	205	194	189	194	215	195
50% Volume Evaporated, °C		Report	260	245	267	255	268	299	263
90% Volume Evaporated, °C		362 Max	333	336	331	320	330	352	334

**Test Conducted Durban Lab.

No part of this document may be reproduced except in full, without the written approval of INTERTEK.

Our standard terms and conditions of business shall apply.

The results relate to the sample tested and the most recent methods available with a 95% confidence level.

Lab. Tech: S. Ntyinkala
Date: 04/02/2016

Laboratory Head: F.Hanslo
Date: 04/02/2016