Assessing stationary laboratory test methods for underground mining vehicles to determine their suitability in replicating real-world emissions

M.C. Wattrus
Sasol, South Africa

M. Biffi
Anglo American Operations, South Africa

C.J. Pretorius
CSIR, South Africa

D. Jacobs
Deutz Dieselpower, South Africa

ABSTRACT: Fuel, engine and after-treatment technologies are powerful levers to reduce diesel particulate matter emissions, however these benefits can only be guaranteed through routine maintenance and equipment monitoring. Portable emissions measurement equipment can be an effective solution to address the latter point. An investigation into the required equipment and in-field test methods was conducted in this study.

1 INTRODUCTION

Fuel, engine and after-treatment technologies are powerful levers to reduce diesel particulate matter (DPM) emissions, however these benefits can only be guaranteed through routine maintenance and equipment monitoring. Portable emissions measurement equipment can be an effective solution to verify that maintenance work has been completed adequately and that equipment is operating within acceptable parameters.

An investigation into the required equipment and in-field test methods was conducted as the basis of this study. Stationary in-field vehicle emission tests were reproduced in a controlled engine test cell to establish the repeatability and suitability of these methods. These stationary tests were compared against real-world data recorded during a load-haul-dump (LHD) vehicle underground operational cycle in order to devise the most appropriate stationary test for in-field vehicle condition monitoring.

The study concludes with an assessment of two portable DPM emission analysers, where their accuracy and linearity were checked against an automotive laboratory-grade emission analyser over one of the stationary tests.

2 OBJECTIVE

The objective was to investigate the suitability of various stationary in-field vehicle emission tests in reproducing performance observed during real-world underground vehicle operation. The most representative test was used to evaluate the performance of two portable diesel particulate matter emission analysers.

3 DETERMINING SUITABLE TEST POINTS

The first step was to evaluate the real-world operation regime of a LHD vehicle in order to select the most representative test that would replicate this regime for the purpose of in-field vehicle condition monitoring.

3.1 *Underground LHD operation*

The starting point for this investigation was to record the operating duty cycle typical of a LHD vehicle in a South African underground mine. From this dataset, operation was classified into segments for each of the vehicle’s functions, namely load, haul (full and empty), and dump (see Figure 1 below).

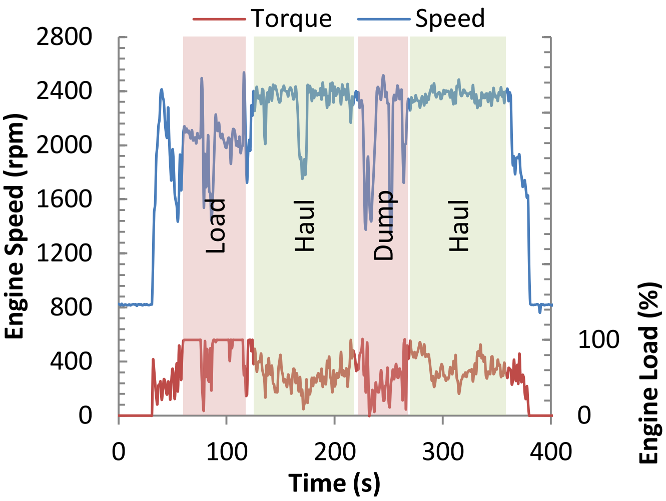

Figure 1. Engine speed (rpm) and load (%) profile of an underground LHD vehicle

"Load" is characterized by high engine load and medium engine speed segments, whereas "Haul" is characterized by medium engine load and high engine speed segments. The "load" and "haul" segments were averaged to obtain representative engine operating points for comparison against in-field vehicle test points that can be carried out while the vehicle is stationary. These will be compared in the following section.

3.2 *Stationary in-field vehicle tests*

Due to LHD vehicle constraints, the engine can only be reproducibly loaded in a limited number of steady-state conditions, namely: idle, high idle, and full stall. Transient testing is possible while the vehicle is stationary by rapidly increasing engine speed with the gearbox disengaged, the so called free-acceleration or snap-acceleration test. These operating points are elaborated below.

Idle conditions are achieved with the accelerator pedal in a neutral position and no gear engaged. Idle speed was around 820 rpm for the test engine.

High idle conditions are achieved by fully depressing the accelerator pedal while no gear is engaged. This allows the engine to ramp up to the maximum governed speed, which was set to 2500 rpm in the engine's electronic control unit (ECU). During the LHD in-field tests, it was noted that during this high idle condition there was a certain amount of load applied to the engine. The recorded ECU data revealed this to be around 30% engine load which resulted in a fuel flow rate of approximately 17 L/h. This load was generated in the torque converter that was coupled to the engine's crankshaft. This recorded data was reproduced in the test cell and labelled as the "high idle (torque converter)" condition. As not all vehicles will be fitted with a torque converter, another high idle test point was included in the evaluation where only a light load was applied during high idle (which should simulate an engine fitted with a manual gearbox that has the clutch fully disengaged). This case was labelled "high idle (manual)".

Full stall is achieved by fully depressing the accelerator pedal and subsequently applying the vehicle brakes. The engine starts to stall and slow from the high idle condition to a speed that allows sufficient torque to be produced to equal the resistance in the torque converter. During in-field testing the exact engine speed and load values were recorded during this condition. Reproducing this unique recording during the evaluation will provide an indication of the test point's reproducibility, and, therefore, suitability for in-field testing.

One of the most common in-field test methods for measuring vehicle exhaust smoke emissions (or particulate matter emissions) involves snap-acceleration testing (as described in SAE J1667); also known as the free-acceleration test, snap-idle test, or J1667 test. The method involves an operator moving the accelerator pedal to fully open as rapidly as possible, then holding it open for a set duration, and thereafter allowing the engine to return to idle for another set interval. This test is typically repeated to obtain an average of the peaks, and is preceded with a preliminary snap-acceleration to remove any loose soot from the exhaust system. This method relies on dynamic torque generated by rapid accelerations to high idle in order to load the engine.

The snap-acceleration test was originally developed for naturally aspirated diesel engines, but is problematic for the more common turbocharged diesel engine and electronic engine management systems that limit free acceleration. This is due to inconsistent development of boost pressure during rapid engine speed accelerations. Inconsistent boost pressure leads to inconsistent air-fuel ratios and subsequently inconsistent particulate matter emissions. Electronically controlled engines can limit the rate of engine acceleration—and therefore not be classified as free-acceleration—which would affect the peak DPM emission recorded. Despite the prevalence of this form of particulate matter emission testing, this test procedure is not recommended for condition monitoring and will be excluded from the in-field test assessment. Reports have shown that results from these tests do not correlate well with real-world emissions and run the danger of misclassifying gross polluters as relatively clean and low polluters as high emitters (Anyon et al. 2000).

The aforementioned steady-state tests were carried out on a suitably representative test engine in an engine test cell to assess their suitability for in-field testing. Test duration was 5 minutes for each condition, and each test was run three times to generate an average and standard deviation (presented as a percentage of the average).

A comparison of the engine speed and load recorded during the steady-state tests (excluding idle) with the real-world operating points for “load” and “haul” are presented in Table 1.

Table 1. Comparison of LHD operating points with test points

	Speed	Load
LHD operating points	rpm	%
Load	2077	89
Haul	2275	56
In-field test points		
High idle (torque converter)	2435	33
High idle (manual)	2486	11
Full stall	1941	91

It is apparent from the data in Table 1 that there was a good agreement between “Load” and “Full stall” conditions. Despite this favourable comparison, this test places significant strain on the vehicle’s brakes and drivetrain, and is not considered suitable for routine testing. This test point was, however, later included in the portable DPM emission analyser assessments for comparative purposes.

Of the two “high idle” test points, the “torque converter” variation showed a closer match to hauling conditions. Regardless of the drivetrain fitted to an LHD, both high idle points are considered highly suitable for routine in-field testing.

Given the closer match to hauling conditions, this paper will use the high idle (torque converter) test point for the assessment of two portable diesel particulate matter emission analysers in the following sections.

4 EXPERIMENTAL METHOD

This section provides details of the test engine and test fuel used as well as of the laboratory emissions measurement systems employed. These were used as a benchmark to evaluate the portable diesel particulate matter emission analysers in a controlled engine test cell environment.

4.1 *Test engine*

The LHD vehicle that was used to record the sample operational cycle was an Atlas Copco Scoop Tram 600 (ST600LP), which is a low profile LHD vehicle with a 6-tonne payload capacity, designed for South African platinum reef environments to a minimum of 1700 mm stoping width. This LHD is commonly fitted with a Deutz BF 6M 1013 E engine (Tier 1 emission level compliant). An identical engine was supplied by Deutz Dieselpower and used in the heavy-duty engine emission test cell at the Sasol Fuels Application Centre as the test engine for this study. The engine was originally new but was run-in by Deutz Dieselpower prior to testing. The basic details of the test engine are shown below in Table 2.

Table 2. Test engine.

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

Figure 2 shows the engine installed in the test cell at the Sasol Fuels Application Centre in Cape Town.

Figure 2. Deutz BF 6M 1013 E engine in a test cell at the Sasol Fuels Application Centre.

The test engine was retrofitted with a sintered-metal filter, continuously regenerating trap (SMF-CRT) diesel particulate filter (DPF) that was supplied by Deutz Dieselpower. It is important to highlight that this SMF-CRT, with its integrated diesel oxidation catalyst, will reduce DPM emissions by up to 60% thus lowering DPM exhaust concentrations into the lower end of most DPM emission analysers’ range.

4.2 *Test fuel*

A fully-synthetic South African ultra-low sulphur (ULS) diesel fuel that contains less than 10 ppm sulphur was used during testing (Sasol turbodiesel^{TM} ULS 10 ppm). This test fuel was sourced from a Sasol fuel retail site directly outside Sasol’s synthetic refinery in Secunda, and is SANS 342 compliant. The use of this fuel was necessary to prevent poisoning of the oxidation catalyst contained in the DPF.

4.3 *Laboratory Analytical Equipment*

In addition to the usual test cell instrumentation for measuring engine torque and speed, fuel consumption, pressures, temperatures, and air flow rates, the following instrumentation was employed during the tests:

- 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).
- 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).

4.4 *Portable emission analysers*

There is a wide range of portable emission analysers available on the market. The two instruments used for this test were chosen as examples of what is typically available, and were used to demonstrate how such instruments should be evaluated before use in the field.

The portable instruments were benchmarked against an automotive laboratory-grade soot sensor that is produced by AVL in Austria (AVL Micro Soot Sensor). This instrument conducts transient measurement of soot concentration, defined as elemental carbon concentration, using a photo-acoustic measurement principle; also known as a photo-acoustic soot sensor (PASS). With this measurement principle, the sample gas containing soot particulates is exposed to modulated light. The periodical warming and cooling and the resulting expansion and contraction of the carrier gas can be regarded as a sound wave. The changes in pressure from this sound wave are detected with a microphone and converted to an electronic signal proportional to the mass concentration of elemental carbon (EC).

The AVL Micro Soot Sensor measures in a range between 0.001 to 50 mg/m^3 with an accuracy of 1µg/m^3. When fitted with the dilution unit, the range is extended up to 1000 mg/m^3. The instrument is equipped with an advanced sampling system that enables sampling upstream and downstream of a DPF. It is therefore capable of handling exhaust back-pressures up to 2000 mbar, temperatures up to 1000°C, and pressure pulsations up to +/-1000 mbar. A photograph of the instrument is shown in Figure 3.

Figure 3. AVL Micro Soot Sensor.

Diesel particulate matter (DPM), as specified by US EPA procedures (US Code of Federal Regulations, Title 40, Part 89 - Control of emissions from new and in-use non-road compression-ignition engines), is determined by gravimetric analysis from a DPM sample obtained by filtering diluted diesel exhaust at a temperature of 47°C ± 5°C. Although relatively arbitrary, this procedure simulates, to a certain degree, diesel vehicle emissions into the atmosphere. DPM emissions measured using this procedure are typically expressed in grams of particulate matter per unit of mechanical energy delivered by the engine, such as g/kWh; this approach of normalising DPM with mechanical energy removes any variability between tests introduced by variable exhaust flow rates or engine power differences.

Given that gravimetric analysis, as described by the aforementioned EPA procedure, is the regulatory method for diesel particulate matter measurement of engine exhaust gas, a correlation is presented in Figure 4 between the AVL Micro Soot Sensor and the gravimetric analysis conducted on various fuels and DPFs. It must be noted that the AVL Micro Soot Sensor reports diesel particulate matter as EC, whereas gravimetric analysis reports total particulate matter. As such, all comparisons with the portable instruments were made using EC particulate emissions.

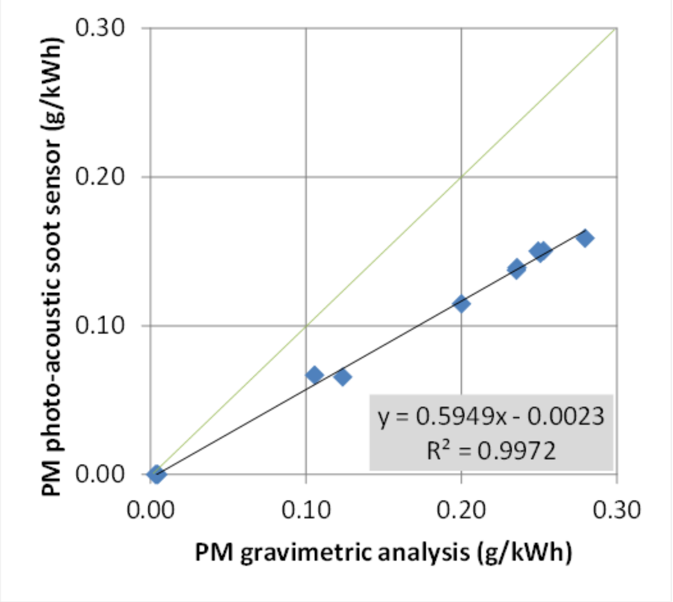

Figure 4. Correlation between AVL Micro Soot Sensor and gravimetric DPM analysis.

Overall, there was a very strong relationship between the photo-acoustic soot sensor and gravimetric analysis, where the coefficient of determination (R^2) was greater than 99%. Given that the AVL Micro Soot Sensor only reports elemental carbon, it was expected that there would not be a perfect correlation between the data (shown by the diagonal green line in Figure 4); the gradient of 0.5949 indicates EC is 59.49% of the total particulate matter (elemental carbon + organic carbon + ash + sulphates) for this engine. Moreover, the NIOSH 5040 analysis conducted on filters from the same engine tests indicated that EC was approximately 69% of total carbon (elemental carbon + organic carbon). Therefore, the difference between these two numbers was used to calculate the ash and sulphate portion (SO_4) of the diesel particulate matter (this combined portion equated to approximately 17% which is in agreement with literature: Kittleson 1998). Given the above, the AVL Micro Soot Sensor was considered a suitably accurate instrument to benchmark the portable emission analysers against.

The first portable analyser tested was the SAXON Junkalor DPM analyser which measures total particulate matter (TPM) using laser light-scattering technology. This measurement technology is preferred over traditional smoke meters as a poor correlation has been observed between fine diesel particulate matter emissions and smoke opacity in previous studies (Anyon et al. 2000). This instrument can measure up to a maximum TPM concentration of 300 mg/m^3 with an accuracy of ≤±10% of final value. Measured TPM was converted to EC using an experimentally determined EC to TPM ratio (shown in Figure 4) of 0.5949; this value was deemed satisfactory by SAXON Junkalor and their local partner in South Africa, Dispro Tech SA (Pty) Ltd. The equipment, shown in Figure 5, is designed to sample emissions from the exhaust tailpipe of a vehicle.

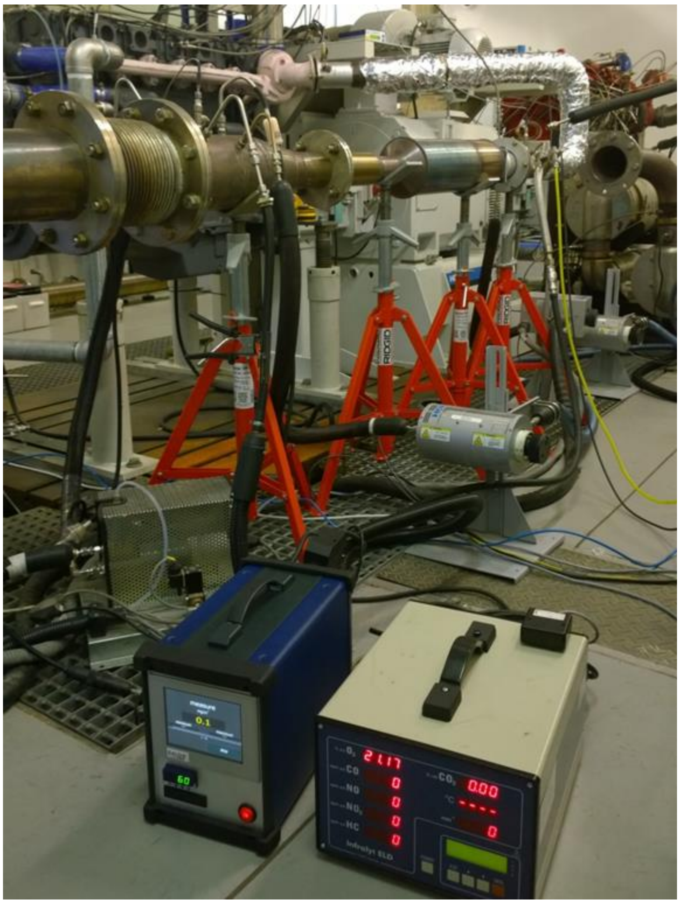

Figure 5. SAXON Junkalor DPM and exhaust gas analyser installed in the test cell.

The second instrument was the FLIR Airtec™ DPM series which uses an optical technique to quantify EC deposition on a sample filter gravimetrically. EC mass is then converted to EC concentration using the chosen volumetric flow. The instrument, shown in Figure 6, was originally designed to sample from the atmosphere for personal diesel particulate matter monitoring.

Figure 6. Airtec™ diesel particulate monitor.

Given the prevalence of these units in the underground mining industry, they potentially can be useful instruments for quick in-field tests on engines—provided they can be adapted to measure reliably from a vehicle's exhaust tailpipe where exhaust gas typically pulsates, contains water vapour, and has higher temperatures than ambient air.

5 RESULTS

The results from the high idle and full stall tests are presented below, where each data point represents an average of three tests. The error bars depict the standard deviation for each instrument to give the reader an appreciation of the repeatability between the three tests; horizontal error bars represent the AVL Micro Soot Sensor's repeatability, and the vertical error bars are for the portable instrument.

Figure 7 below presents the results from the tests assessing the SAXON Junkalor DPM analyser.

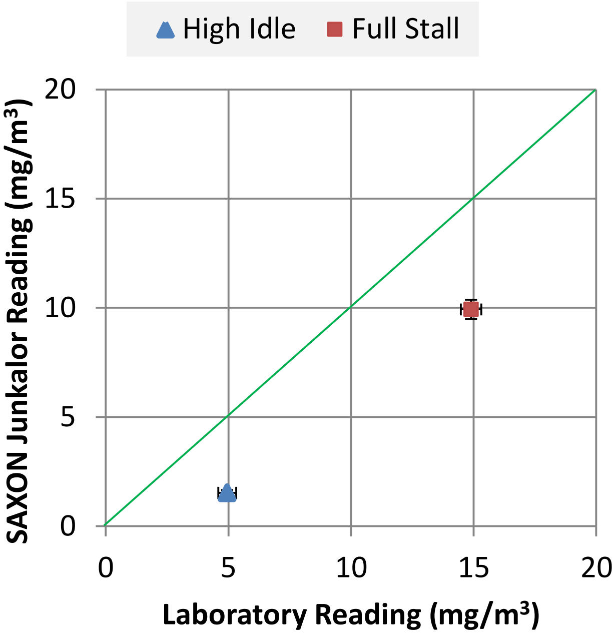

Figure 7. SAXON Junkalor DPM analyser comparison against the AVL Micro Soot Sensor.

The SAXON Junkalor DPM analyser showed a reasonable correlation with the laboratory analyser, but a considerable under-sensitivity was observed. Repeatability between the three tests for this instrument was good.

Figure 8 presents the results from the tests assessing the Airtec DPM analyser.

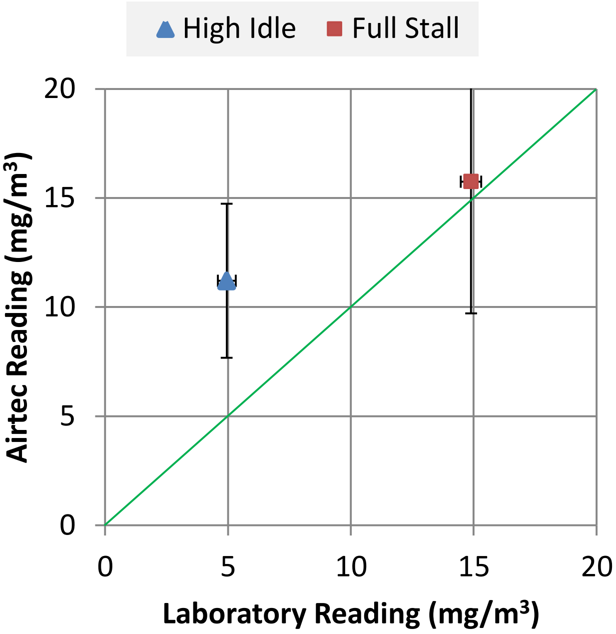

Figure 8. Airtec DPM analyser comparison against the AVL Micro Soot Sensor.

The Airtec DPM analyser showed a poor correlation with the laboratory analyser for the high idle point, whereas a good correlation was seen for the full stall point. Repeatability between the three tests for this instrument was poor for all test points.

6 DISCUSSION

One of the main challenges in conducting in-field engine condition monitoring through the use of exhaust emission trends, is to apply the same load to the engine repeatedly between periodic measurements to ensure that the engine is producing similar torque, exhaust flow rates, and engine speeds as the previous measurement. If any of these parameters change significantly between measurements, the exhaust pollutant concentration that has been recorded will not be valid.

Of the stationary in-field vehicle tests that were evaluated, high idle and full stall were deemed representative of typical load and haul LHD operations, respectively.

The engine testing confirmed that both these test conditions could be reproduced in a reliable manner, where the laboratory DPM analyser (AVL Micro Soot Sensor) could measure the DPM emissions with good repeatability.

When comparing portable emission analysers with the laboratory analysers, it must be borne in mind that the primary function of these portable instruments will be to conduct condition monitoring by generating trends that can be used to detect vehicle health problems. This implies that there is less dependence on accurate measurements for generating reliable trends. Essentially, an instrument exhibiting good linearity and repeatability would be considered fit for the purpose of measuring tailpipe emissions in the field.

The SAXON Junkalor DPM analyser measured the emissions with good repeatability, however the device was considerably under-sensitive when compared to the AVL Micro Soot Sensor. Considering the full scale range (300 mg/m^3) of the SAXON Junkalor DPM analyser, it is possible that measuring such low ranges was the cause for the inaccuracy.

The Airtec DPM performed poorly when sampling directly from an engine exhaust system. Although understandable considering what the equipment was originally designed for, with certain modifications to the sampling technique, it is conceivable that repeatability could be improved. Attention would have to be paid to reducing the pulsations in the exhaust stream with the use of a damping vessel. Ideally this damping vessel and sample pipe should be heated to prevent any condensation and subsequent loss of sample.

7 CONCLUSIONS

After evaluating the acceptability of stationary in-field vehicle emission tests in replicating real-world underground vehicle operation and evaluating the performance of two portable diesel particulate matter emission analysers, the following conclusions can be drawn:

Of the stationary in-field vehicle tests that were evaluated, high idle and full stall vehicle conditions were deemed representative of typical load and haul LHD operations, respectively. As such, they should be considered for use as a standardised stationary in-field vehicle emission tests.

SAXON Junkalor DPM analyser was determined suitable for stationary in-field vehicle emission tests.

The Airtec DPM analyser was shown to not be suitable for stationary in-field vehicle emission tests. Although understandable considering what the equipment was originally designed for, with certain modifications to the sampling technique, it is conceivable that repeatability could be improved.

It must be noted that these portable emission measurement systems are only intended for comparative testing of a vehicle's condition over its life and not accurate quantification of an exhaust composition. Once an engine has been identified as releasing high levels of DPM, it should be withdrawn from service and checked in a workshop.

Provided that the chosen portable emission measurement system is sourced from a reputable supplier, and is used with rigorously applied test procedures, this equipment and methodologies may be effective in identifying high polluters thereby achieving a sustained reduction in diesel particulate matter and gaseous emissions in underground mines.

It is recommended that when selecting a new portable emission measurement system, the assessment and comparison of such instruments should be done in the controlled environment of an engine testing laboratory.

8 ACKNOWLEDGEMENTS

Acknowledgements below are given in no particular order.

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

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

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

The authors also acknowledge Dispro Tech SA (Pty) Ltd and the CSIR for providing and operating their portable emission measurement systems during the benchmarking testing at the Sasol Fuels Application Centre.

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.

Gratitude is also expressed 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.

9 REFERENCES

Anyon, P., Brown, S., Pattison, D., Beville-Anderson, J., Wall, G. and Mowle, M., “In-Service Emissions Performance - Phase 2: Vehicle Testing," National Environment Protection Council, Adelaide, 2000.

Kittelson, D.B., “Engines and Nanoparticles: A Review”, J. Aerosol Sci., 29(5/6), 575-588, 1998