ASSESS THE FEASIBILITY OF REDUCING DIESEL PARTICULATE MATTER (DPM) EXPOSURE THROUGH REPLACEMENT AND/OR CONVERSION OF ALL TIER 0 WITH TIER 2 OR TIER 3 ENGINES TO BE ABLE TO USE LOW SULPHUR DIESEL FUEL AND THE EFFECTIVE MAINTENANCE OF DIESEL MACHINES

Milestone Report:
# 8 – Final Report

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Research agency: Enterprises at the University of Pretoria
Project number: CoE 150602
Date: 2 April 2019
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<tr>
<td>$</td>
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<td>%</td>
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<td>°</td>
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<td>ACGIH</td>
<td>US Conference of Government. Industrial Hygienists</td>
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<td>ADT</td>
<td>Articulated Dump Truck</td>
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<td>AIOH</td>
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<td>ANFO</td>
<td>Ammonium Nitrate Fuel Oil</td>
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<td>CO</td>
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<td>JNCI</td>
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<tr>
<td>kW</td>
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<td>merSETA</td>
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<td>N₂</td>
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<td>SIB</td>
<td>Stay in Business</td>
</tr>
<tr>
<td>SSP</td>
<td>Sector Skills Plan</td>
</tr>
<tr>
<td>STEM</td>
<td>Science, Technology, Engineering and Mathematics</td>
</tr>
<tr>
<td>TC</td>
<td>Total Carbon</td>
</tr>
<tr>
<td>ULSDF</td>
<td>Ultra Low Sulphur Diesel Fuel</td>
</tr>
<tr>
<td>US</td>
<td>United States of America</td>
</tr>
</tbody>
</table>
## LIST OF ABBREVIATIONS (continued)

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>UV</td>
<td>Utility Vehicle</td>
</tr>
<tr>
<td>VAT</td>
<td>Value Added Tax</td>
</tr>
<tr>
<td>VOC</td>
<td>Volatile Organic Compounds</td>
</tr>
<tr>
<td>WHO</td>
<td>World Health Organisation</td>
</tr>
<tr>
<td>WSP</td>
<td>Workplace Skills Plan</td>
</tr>
<tr>
<td>Y</td>
<td>Year</td>
</tr>
<tr>
<td>ZAR</td>
<td>South African Rand</td>
</tr>
<tr>
<td>μg</td>
<td>Microgram</td>
</tr>
<tr>
<td>μm</td>
<td>Micrometre</td>
</tr>
</tbody>
</table>
5 OVERALL PROJECT SUMMARY

The overall project summary is shown in Table 1.

Table 1: Overall Project Summary

<table>
<thead>
<tr>
<th>What was planned for the Milestone?</th>
<th>Was it achieved?</th>
<th>Any deviations?</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Milestone 1</strong> Project initiation</td>
<td>✓</td>
<td>none</td>
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<tr>
<td><strong>Milestone 2</strong> Literature Review on the factors that impact the feasibility of a transition when replacing/converting Tier 0 diesel machines to Tier 2 or Tier 3 diesel engines within the South African Mining Industry (SAMI).</td>
<td>✓</td>
<td>none</td>
</tr>
<tr>
<td><strong>Milestone 3</strong> Develop a guideline for a transition to lower DPM emissions in the underground mining operations in South Africa</td>
<td>✓</td>
<td>none</td>
</tr>
<tr>
<td><strong>Milestone 4</strong> Develop a guideline for effective maintenance on diesel machines in the SAMI that would assist in reducing and controlling DPM emissions</td>
<td>✓</td>
<td>none</td>
</tr>
<tr>
<td><strong>Milestone 5</strong> Analysis on local capacity for: engine conversion, manufacturing of the components, and LSD supply</td>
<td>✓</td>
<td>none</td>
</tr>
<tr>
<td><strong>Milestone 6</strong> Analysis on skills requirements for diesel equipment maintenance in the SAMI with the development of recommendations for upskilling and/or reskilling to support the maintenance skill requirements</td>
<td>✓</td>
<td>none</td>
</tr>
<tr>
<td><strong>Milestone 7</strong> Draft Final Report (submission)</td>
<td>✓</td>
<td>none</td>
</tr>
<tr>
<td><strong>Milestone 8</strong> Final Report (approval)</td>
<td>✓</td>
<td>none</td>
</tr>
</tbody>
</table>
6 EXECUTIVE SUMMARY

The objective of this project was to develop a guideline, supported with practical suggestions, on how a DPM Emission Control Program can be implemented. The proposed DPM Emission Control Guideline follows a progressive approach by implementing different measures for DPM emission reduction based on the best cost vs. benefit measures with which to start. This leads into measures that are more intensive and dependent on the needs applicable to a given mining operation (a summary of the guideline is given on the next page). Various supporting and enabling functions, including a proposed guideline for effective diesel engine maintenance, are also highlighted. These need to be in place in order to implement the proposed steps of the DPM Emission Control Guideline successfully and sustainably.

It should be noted that this report does not provide a “one size fits all” solution or plan to develop a solution. It highlights the different control measures that may be taken and aims to guide the users to assess and identify the optimal combination of measures that would best suit their operation. Toward this end, various suggestions are provided that would assist with effective implementation of the proposed steps as well as an overview of the potential challenges and opportunities that are associated with each of the proposed control measures.

Adding to this, the report further discusses in detail various challenges, opportunities and substantiating information to consider in line with and in support of the proposed guideline. The information contained within the report should be studied in detail and used as baseline to develop the necessary frameworks for a feasibility analysis, risk assessment, and trade-off analysis prior to attempting the implementation of any DPM emission control initiative.
<table>
<thead>
<tr>
<th>No.</th>
<th>Step Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Implement Diesel Fuel Supply Chain Management</td>
<td>Ensure that good quality diesel is used within the diesel machines. Poor quality diesel will result in engine failures, higher operating cost, high diesel usage and higher emission levels. Implementing retrofit devices or installing newer technology engines for emission reduction also require good quality diesel. Without the successful implementation of this step, this guideline (or any other similar initiative) will not be able to realise the desired results.</td>
</tr>
<tr>
<td>2</td>
<td>Conduct Fleet Assessment &amp; Determine the Gap</td>
<td>In order to identify what controls are required for a DPM emission level reduction program, it is crucial to assess the condition of the diesel equipment fleet and the gap that needs to be bridged. This means compiling a complete data sheet of all the diesel machines (i.e. information on machine type, engine make and model, engine hours, Tier level, expected engine life, major overhauls done, time since/to rebuild, total engine replacement date, etc.). Thereafter an individual assessment of each machine should be done (through exhaust gas analyses) to determine the current condition in terms of DPM emission levels. This will allow an operation to define what its existing baseline is for DPM emission levels that will allow the gap to be determined toward the desired DPM emission level status. This identified gap will drive the decision-making in terms of what measures to implement as per the following steps of the guideline.</td>
</tr>
<tr>
<td>3</td>
<td>Repair Engines to achieve OEM Baseline Specification</td>
<td>If the assessment from Step 2 identifies an engine that operates outside of OEM specification, then such an engine should be repaired. This will bring various benefits, namely improved operation, engine life, diesel consumption and improved emission levels. It will also assist with providing a more predictable emission level baseline for the diesel fleet, which will make planning for and control of emission levels more efficient (note this does not only include DPM, but also other harmful emissions). During this process, also clean the fuel tank and fuel lines and check the cooling system and radiator before starting the engine again.</td>
</tr>
<tr>
<td>4</td>
<td>Implement Retrofit Solutions</td>
<td>Once the current diesel fleet and corresponding emission level status has been determined, one of the potential approaches to reducing DPM emission levels may be through the installation of emission reducing retrofit systems/solutions. This approach should be assessed on a case-by-case basis since there are various challenges and limitations involved with retrofit installation, as well as potential intensive maintenance and change management requirements. However, when possible, this may provide a worthwhile solution over complete engine replacement as it will be at a lower capital expenditure. Implementing retrofit solutions may also be considered as a temporary solution before engine replacement at a later more feasible and/or practical time (e.g., when the engines are due for replacement at the end of their operating lives). Retrofit solutions may also serve as the ultimate control measure since some of these solutions will provide far greater DPM emission level reductions that implementing newer technology engines alone.</td>
</tr>
<tr>
<td>5</td>
<td>Replace Diesel Engine with Lower Emission Technology Engine</td>
<td>Replacing older technology diesel engines with newer technology engines, which adhere to higher Tier/Stage levels for DPM emission regulations, is another solution to reduce DPM emission levels. This solution should again be assessed based on site-specific scenarios. It may, for example, prove to be feasible to replace a full fleet’s engines to obtain the associated benefits from the newer technology, such as improved diesel consumption etc. However, it may be determined that it would be best to only replace the engines with new engines when the older engines are due for a rebuild, or, when they are due for replacement at the end of the total operating life. OEM consultation is strongly advised to ensure that compatible engine models are chosen for the machines in operation. Configuration and compatibility challenges limit the choice of engine modules.</td>
</tr>
<tr>
<td>No.</td>
<td>Step Name</td>
<td>Description</td>
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<tr>
<td>6</td>
<td>Implement Other Emission Controls</td>
<td>Various other engineering, management and administrative control measures may also be implemented to either support and add onto other control measures (e.g. solutions from steps 1 to 5), or, to temporarily reduce DPM emission levels prior to, or while, a permanent and sustainable solution(s) is being planned or executed. The most common control measure is through adequate ventilation. Increasing ventilation will dilute DPM emissions, but this comes at a high cost. Administrative controls may be implemented to reduce exposure time, such as managing operator change-over times (removing mid-shift changeovers). Fleet management controls may, for example, include reducing exposure down-stream of diesel equipment.</td>
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<tr>
<td>7</td>
<td>Implement Other Non-Diesel Alternatives</td>
<td>Ultimately, the best way to reduce and eliminate DPM exposure is to remove diesel engines and use non-diesel alternatives instead. The feasibility assessment of this approach is subject to various impacting factors, both from a financial and practical perspective. Non-diesel (e.g. electric, battery, or gas driven engines) may provide other benefits than merely emission reductions, but they also have their own challenges, limitations and drawbacks. An operation-specific assessment is advised.</td>
</tr>
</tbody>
</table>


7 OVERALL PROJECT AIMS AND OBJECTIVES

The overall project aims, and objectives are shown in Table 2.

Table 2: Overall Project Aims and Objectives

<table>
<thead>
<tr>
<th>What are the expected research outcomes</th>
<th>How will the research outcomes improve health and safety in South African Mining Industry?</th>
<th>How should the research outcomes be implemented?</th>
<th>Name the Champion Mine(s) that will be used in this research</th>
</tr>
</thead>
<tbody>
<tr>
<td>▪ A report on the feasibility of previous transitions of Tier 0 diesel machines to Tier 2 or Tier 3 diesel engines, along with opportunities and challenges encountered and how these could be or were addressed. ▪ Information on the factors that impact the transition to better technology engines. ▪ A guideline on how to achieve the desired transition for the South African Mining Industry that will allow reduced DPM emissions, along with proposed guidelines on how to overcome obstacles. ▪ A guideline on how to achieve enhanced maintenance that will reduce DPM emissions, along with opportunities and challenges faced and how these could potentially be overcome. ▪ A report on the local capacity and feasibility estimate to perform the required diesel engine replacement/conversion in South Africa, as well as to manufacture the required system components locally. ▪ Skills development recommendations to address the skills needs to perform the required maintenance on the newer technology diesel engines (to compliment the guideline for enhanced maintenance).</td>
<td>When the guideline is successfully implemented, mine employees will be exposed to lower concentrations of carcinogenic DPM emissions. This will result in a reduction in the associated occupational health diseases and other related health issues, leading to improvements in health and safety.</td>
<td>A shared understanding needs to be brought across to all the relevant stakeholders regarding the technological and socio-economic impact, opportunities and challenges that are associated with the project outcomes. This shared understanding regarding the reduction in exposure to DPM, as a result of the successful implementation of the abovementioned guidelines, will assist with the successful adoption in the workplace as well as with change management from leadership and management.</td>
<td>No single champion mine was used, although tests were done at mining operations as well as OEMs. A comprehensive list of stakeholders that were engaged with or worked with in some way is presented in Section 10.1.1.2</td>
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</table>
## 8 PROJECT SCHEDULE

**Figure 1: Project Gantt Chart**

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<td>2 Analysis of Transition</td>
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<tr>
<td>3 Guideline for Transition</td>
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<td>4 Guideline for Effective Maintenance</td>
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<td>5 Local Capacity Analysis</td>
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<tr>
<td>6 Skills Development Recommendations</td>
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<td>7 Draft Final Report (submission)</td>
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<td>8 Final Report (approval)</td>
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</table>

- **Achieved**: Green
- **Planned**: Black
9 PROJECT FINANCES

Table 3: Project Finances

<table>
<thead>
<tr>
<th>No.</th>
<th>Milestone</th>
<th>Milestone Timelines (mm/yy)</th>
<th>Start</th>
<th>End</th>
<th>HR Costs</th>
<th>Operating Costs</th>
<th>Sub-contractor costs</th>
<th>Capital costs</th>
<th>Total (ZAR) (excl. VAT)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Project initiation</td>
<td>08/17 08/17</td>
<td>159 925</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>159 925</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Analysis of Transition</td>
<td>08/17 02/18</td>
<td>196 975</td>
<td>44 000</td>
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<td>-</td>
<td>-</td>
<td>240 975</td>
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</tr>
<tr>
<td>3</td>
<td>Guideline for Transition</td>
<td>02/18 08/18</td>
<td>145 275</td>
<td>132 000</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>277 275</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Guideline for Effective Maintenance</td>
<td>11/17 06/18</td>
<td>80 906</td>
<td>-</td>
<td>184 800</td>
<td>-</td>
<td>-</td>
<td>265 706</td>
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</tr>
<tr>
<td>5</td>
<td>Local Capacity Analysis</td>
<td>06/18 11/18</td>
<td>106 031</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>106 031</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Skills Development Recommendations</td>
<td>04/18 10/18</td>
<td>9 450</td>
<td>300 000</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>309 450</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Draft final report (submission)</td>
<td>12/18 12/18</td>
<td>9 963</td>
<td>70 000</td>
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<td>-</td>
<td>79 963</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Final report (approval)</td>
<td>01/19 01/19</td>
<td>154 925</td>
<td>5 000</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>159 925</td>
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</tbody>
</table>

Total (ZAR) 863 450 75 000 660 800 - 1 599 250

Note that the amounts per milestone have been adjusted to achieve the specified percentage payments for the first (1) and last two milestones (7 and 8) (i.e. 10%, 5%, and 10% of project total respectively). As such, these amounts do not accurately reflect the working hours and operating costs for the bulk of the project work between Milestones 2 and 6.
10 MILESTONE RESULTS

The draft final report is presented across seven separate sections, in alignment with the project terms of reference and expected outcomes. The report layout is shown in Figure 2.

![Figure 2: Draft Final Report Results Overview](image)

10.1 INTRODUCTION

This report aims to provide a guideline for implementing a Diesel Particulate Matter (DPM) emission reduction program, to transition to reduce mine worker exposure to DPM. To support this guideline, substantiating information is also given to assist in performing site-specific feasibility assessments so as to improve the probability of implementing such a program effectively and in a sustainable manner.

The background that led to the project will be discussed in order to highlight the reason why DPM control is important. Following this, the current legislative environment is discussed along with the impact on the operating environment. Sources of DPM are then discussed briefly before an overview is given of the status of the diesel fleet in the mining industry in South Africa.

The fleet assessment, or the lack of accurate information, coupled with the identified trend of a natural and gradual transition to newer technology engines is then discussed. This provides the necessary background to the reasoning behind the progressive, stepwise approach that was taken to develop the proposed guideline on how to reduce DPM emission levels in underground mining operations. This guideline, and its enabling and supporting elements and factors (including identified skills gaps and recommended developments), is then discussed in detail (as summaries within the report, with greater detail included in appendices).

Finally, the local capacity analysis relating to DPM emission control applicable to the scope of this report is discussed before conclusions are drawn and recommendations are made, which results from the knowledge and insights obtained during the eighteen-month study.

10.1.1 Project Background

This section aims to give a thorough background in support of the need for the project as well as the resulting reasoning that shaped the approach to how the guidelines were developed.

10.1.1.1 Important Project Definitions

In terms of the project, it is important to understand several definitions clearly before considering the work that follows in this final report. These definitions are given in Table 4.
Table 4: Project Definitions

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rebuild</td>
<td>A diesel engine “rebuild” entails dismantling, cleaning and reconfiguring a used engine, followed by its reassembly. New engine parts may also be installed during this rebuild.</td>
</tr>
<tr>
<td>Engine Replacement / Repower</td>
<td>Replacement of one diesel engine with another. Typically replacing an older diesel engine with a new/newer technology diesel engine.</td>
</tr>
<tr>
<td>Conversion / Retrofit</td>
<td>The installation of harmful emission reducing technology (components, assemblies, systems etc.), in or on (typically older) diesel engines.</td>
</tr>
<tr>
<td>Engine Tier</td>
<td>The enforced emission level limits from United States (US) accepted standards.</td>
</tr>
<tr>
<td>Engine Stage</td>
<td>The enforced emission level limits from European (EU) accepted standards.</td>
</tr>
<tr>
<td>Diesel engine transition</td>
<td>Changing an engine, through replacement or conversion, from a given level of emission/exhaust to a reduced level. The given and reduced level is defined by different Tier/Stage emission standards and, as such, it is a transition towards a higher Tier/Stage rating.</td>
</tr>
</tbody>
</table>

10.1.1.2 Stakeholder Engagements

A critical success factor for the project was to obtain quality inputs from relevant stakeholders within the DPM “ecosystem”. Throughout the project, a number of stakeholders were consulted in order to obtain inputs for each of the main project deliverables. A list of the stakeholders consulted during the project is shown in Table 5.

Table 5: List of Stakeholders Consulted during the Project

<table>
<thead>
<tr>
<th>Stakeholder Group</th>
<th>Name</th>
</tr>
</thead>
</table>
| Mining Companies / Industry | • Anglo Platinum  
                          | • Sibanye-Stillwater  
                          | • South 32  
                          | • Royal Bafokeng  
                          | • African Rainbow Minerals  
                          | • Impala Platinum  
                          | • Sasol  
                          | • Minerals Council  |
|                   | • Bambanani  
                          | • Bathopele  
                          | • Beyers  
                          | • Burnstone  
                          | • Dwarsrivier  
                          | • Hackney  
                          | • Impala 14 shaft  
                          | • K6 shaft  
                          | • Kopanang  
                          | • Kroondal  
                          | • Kwezi  
                          | • Marapeng  
                          | • Modikwa  
                          | • Rasimone  
                          | • Simunye  |
Throughout this final report reference is made to the stakeholders listed in Table 5. In some cases, learnings from stakeholder engagements are not ascribed directly to individual stakeholders, but rather given as collective learnings. The reason for this is to offer a degree of anonymity to the stakeholders engaged.

10.1.2 Diesel Exhaust (DE) & Diesel Particulate Matter (DPM) Overview

Diesel-powered equipment is used on a large scale in all industries, including in numerous mining operations. The tail-pipe emissions from these engines contain gases and particles (CoM, 2012). The Environmental Protection Agency (EPA) of the US also classifies diesel engine exhaust (DE) as made up of a mixture of gases and particles (EPA, 2002). Guild et al (2001), however, lists a third main category under DE termed emissions. In this event, carbon monoxide (CO) and carbon dioxide (CO₂) are placed in the emissions category instead of in the gasses category (Guild et al, 2001). However, irrespective of definitions, DE contains specific components that pose serious health risks to humans.

Other examples for the gaseous components in DE further include nitrous fumes (NOₓ), sulphur fumes (SOₓ), and formaldehyde (HCHO), while the particulates refer to DPM as well as sulphur (Guild et al, 2001). DPM is the collective term for the un-burnt fuel particulates, which act as adsorption and condensation sites for a number of hydrocarbon vapours present in the fuel mixture or formed in the combustion chamber. These agglomerates typically have an aerodynamic diameter varying between 0.1µm and 1µm (CoM, 2012).
Based on its physical properties, DPM is classified as “respirable” matter and may be deposited in the lung’s alveoli. Furthermore, organizations such as the World Health Organisation (WHO), US EPA, National Institute for Occupational Safety (NIOH) of South Africa, International Agency for Research on Cancer (IARC), American Conference of Governmental Industrial Hygienists (ACGIH) and others have classified DPM as a “likely”, “suspected”, “probable” and “potential” carcinogen (CoM, 2012). In addition to what were previously suspected carcinogenetic effects, DPMs also cause irritation of the nose, eyes and respiratory tract, exacerbate asthma and may induce cardiovascular disorders (CoM, 2012).

Then, in June 2012 the WHO announced that diesel fumes are classified as a Category 1 carcinogen. This finally concluded the debate regarding various previous statements and suspicions surrounding the risk of inhaling DE and the cancerous consequences.

DPM poses a serious health risk, but. Addressing this issue should be taken seriously as DPM-based claims have the potential to reach the severity of other health related claims, such as those the industry has experienced with silicosis (Von Wielligh, 2018).

DPM consists of elemental carbon, organic carbon, ash and sulphuric compounds that, when inhaled, will penetrate deeply into regions of the human lung where gas exchange occurs, increasing the health risks for long term exposure (Bugarski et al, 2011). Phillips (2012), claimed that soot particles and the associated chemicals called Polynuclear Aromatic Hydrocarbons (PAHs) are the causes for lung cancer. DPM contains a large amount of PAHs and as such was classified as a carcinogen (Majewski, 2016). It is therefore clear that DPM has to be controlled, diluted and ultimately removed from underground mining environments to prevent unhealthy working circumstances (Guild et al, 2001).

In South Africa, underground mine workers are exposed to DPM due to the use of diesel equipment that produces DE. Diesel engines are used in different underground equipment and for multiple stages of a mining process. Large volumes of exhaust gasses are therefore produced in enclosed spaces underground. As such, the DPM exposure of mine workers in these environments is a serious threat to their health (Johnson, 2017).

South Africa has no legislation relating to limits for DPM exposure in underground mines (Van Niekerk et al, 2002 & CoM 2012). Due to this, the US and EU emission regulations are most commonly referred to for guidance since they are applied in mining operations globally. Regardless of specific regulation, the implementation of emission reduction- and/or control methods can reduce the risk of contracting lung cancer by preventing or minimising exposure to DPM particle inhalation.

While various options exist, during this project engine replacement focus was considering the replacement or conversion or Tier 0 diesel engines to a Tier 2 or Tier 3 emission standard. This would lead to reduced levels of DPM emissions, and, a corresponding level of DPM exposure for underground mine workers.
10.1.3 Health and Safety Aspects Related to DPM

In order to understand how to reduce negative health impacts associated with DPM, or DE emissions in general, it is important to understand the composition of both DE and DPM and why the components are harmful.

10.1.3.1 Diesel Engine Exhaust: Composition

DE is the term used for what is exhausted (expelled) from a diesel engine after combustion (while the engine operates). DE consists of a complex mixture of constituents in the form of either gas or particles. The gaseous components include carbon dioxide, oxygen, nitrogen, water vapour, carbon monoxide, nitrogen compounds, sulphur compounds, and numerous low-molecular-weight hydrocarbons. Among the gaseous hydrocarbon components of DE, that are individually known to be of toxicological relevance, are the aldehydes. These include formaldehyde, acetaldehyde, acrolein, benzene, 1,3-butadiene, and polycyclic aromatic hydrocarbons (PAHs) and nitro-PAHs (EPA, 2002).

The particles present in DE (i.e., the DPM) are composed of a centre core of elemental carbon and adsorbed organic compounds, as well as small amounts of sulphate, nitrate, metals, and other trace elements. DPM consists of fine particles (<2.5 µm diameter), including a sub-group with a large number of ultrafine particles (<0.1 µm in diameter). Collectively, these particles have a large surface area which makes them an excellent medium for adsorbing organics. Furthermore, their small size makes them highly respirable and able to penetrate to the deep lung (EPA, 2002).

Note:

(i) Adsorb means: to take in or soak up (energy or a liquid or other substance) by chemical or physical action.

DE emissions vary significantly in chemical composition and particle sizes between different engine types (e.g. heavy-duty and light-duty), engine operating conditions (idle, accelerate, decelerate), and fuel formulations (high/low sulphur fuel). There are also differences in emissions between on-road and non-road diesel engines, mostly because the non-road engines to date generally use older technology (EPA, 2002).

DPM mass (normally expressed as µg DPM/m³) has historically been used as a surrogate measure of exposure for the whole DE. Although uncertainty exists as to whether DPM is the most appropriate parameter to correlate with human health effects, it is considered a reasonable choice until more definitive information about the mechanisms of toxicity or mode(s) of action of DE becomes available. In the ambient environment, human exposure to DE comes from both on-road and non-road engine exhaust (EPA, 2002). In underground mining operations, various types of diesel equipment contribute to DE, and by association DPM, exposure.

After DE emissions are released from the tailpipe, it undergoes dilution and chemical and physical transformations in the atmosphere. It is also dispersed and transported in and through the atmosphere. The atmospheric lifetime for some of these compounds in DE can then range from hours to days, highlighting the importance of adequate airflow in confined areas (e.g. underground areas or workshops). As such, DPM is directly emitted from diesel-powered engines (primary particulate matter) and can also be formed from the gaseous compounds emitted by diesel engines (secondary particulate matter), meaning DPM can refer to both primary emissions and secondary particles that are formed by atmospheric processes.
Primary diesel particles are considered fresh after being emitted and aged after undergoing oxidation, nitration, or other chemical and physical changes in the atmosphere (EPA, 2002).

10.1.3.2 Acute (Short-Term Exposure) Effects

On the basis of available human and animal evidence, the EPA of the US concluded that acute (short-term/episodic) exposure to DE can cause acute irritation (e.g. of the eye, throat, bronchial), neurophysiological symptoms (e.g. light-headedness, nausea), and respiratory symptoms (cough, phlegm). Furthermore, there is evidence for an immunologic effect, which is the exacerbation of allergic responses to known allergens and asthma-like symptoms (EPA, 2002).

10.1.3.3 Chronic (Long-Term Exposure) Effects

The first concerns for diesel emission exposure emerged in the middle 1900s. This encouraged the establishment of emission controls, improvements in technology and further investigation of the potential hazards associated with diesel exhaust emissions. In 1989 the International Agency for Research on Cancer classified diesel exhaust emissions as a probable carcinogen. This led to stricter DPM regulations and further advances in technology. (McClellan et al., 2012).

More recently, animal inhalation studies have shown a spectrum of dose-dependent inflammation and histopathological changes in the lung. This led to the conclusion by the EPA that DPM poses a chronic respiratory hazard to humans as well (EPA, 2002).

Phillips (2012), claimed that soot particles and PAHs in the DPM are the reasons for causing cancer. Phillips further stated that cancer can be caused through directly inhaling PAHs, or soot particles that are lodged inside the lungs over time, or a combination of the two. DPM was further also determined to contain one of the most powerful cancer-causing hydrocarbons known as benzo-a-pyrene, which is included in PAHs (Guild et al., 2001).

A case study published by the Journal of the National Cancer Institute (JNCI) reported on lung cancer caused by DE. The JNCI is a journal that publishes reviewed research on cancer and treatment from around the world and is funded by various institutions such as the National Cancer Institute and other health organisations worldwide. This study, published by the JNCI, included 12,315 workers from various non-metal mines. Included in this number were 198 recorded cancer deaths (Silverman et al., 2012).

The outcomes from this study are indicated in Table 6, which shows the odds ratio of cancer outcomes for various DE exposure levels containing Elemental Carbon (EC). A 15-year lagged period was used, which means that exposure was excluded 15 years before death (Silverman et al., 2012). An odds ratio of 1 means the exposure does not influence the outcome, while an odds ratio > 1 means exposure levels will be associated with higher odds of the outcome (Mans, 2017).

Table 6: Lung cancer odds ratio from DE exposure (Silverman et al., 2012).

<table>
<thead>
<tr>
<th>15 years lagged cumulative exposure levels (mg/m²-y)</th>
<th>Odds Ratio</th>
<th>Odds ratio (After smoking was removed from the model).</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.108</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>0.108 &lt; 0.445</td>
<td>2.11</td>
<td>1.94</td>
</tr>
<tr>
<td>0.445 &lt; 0.946</td>
<td>3.48</td>
<td>2.42</td>
</tr>
<tr>
<td>&gt; 0.946</td>
<td>5.9</td>
<td>3.75</td>
</tr>
</tbody>
</table>
The calculated odds ratios shown in Table 6 indicate that a person that is exposed to a cumulative DPM emission level of over 946 µg/m$^3$–y, lagged for a period of 15 years, is 4 to 6 times more likely to get lung cancer compared to someone who is not exposed to DPM (Silverman et al, 2012).

### 10.1.3.4 Diesel Engine Exhaust Regulations

To control and mitigate the negative effects from DE/DPM exposure, there have been various regulations implemented internationally. With reference to non-road diesel engines, the US and EU emission standards are most commonly referenced and applied internationally (NSW EPA, 2014).

DPM exposure in an underground mine can be measured by sampling EC or Total Carbon (TC). TC is the sum of EC and Organic Carbon (OC). Countries without an EC standard use TC measurement by applying a specific ratio to obtain the corresponding EC value. The ratio that is used to convert TC to EC or vice versa is mine specific and is determined from sample analysis (Janisko, 2010). EC and TC can be used to measure DPM, because DPM consists of over 80% TC (Noll et al, 2007).

Table 7 was adopted from (Nundlall, 2015 and Noll et al, 2015) and shows that the TC/EC ratios vary for different countries and also for their respective commodities. For this study, samples were taken to determine TC and EC content and the ratio was then calculated accordingly.

#### Table 7: TC/EC ratios for various countries (Nundlall, 2015 and Noll et al, 2015).

<table>
<thead>
<tr>
<th>Country</th>
<th>Commodity</th>
<th>TC/EC ratio range</th>
<th>Median</th>
</tr>
</thead>
<tbody>
<tr>
<td>SA</td>
<td>Platinum</td>
<td>1.2 – 5.8</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>Coal</td>
<td>1.25 – 2.13</td>
<td>1.44</td>
</tr>
<tr>
<td>US</td>
<td>Platinum</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Coal</td>
<td></td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>Other metals</td>
<td></td>
<td>1.53</td>
</tr>
<tr>
<td>Australia</td>
<td>Coal</td>
<td>1.1 – 1.5</td>
<td>1.3</td>
</tr>
</tbody>
</table>

#### 10.1.4 DPM Occupational Exposure Limits (OEL)

#### 10.1.4.1 International

Internationally, DPM emission is controlled via two standards, i.e. Occupational Health and Safety Standards and Tailpipe Emission Standards. Where diesel engines are used in confined spaces, their operation is regulated by occupational health standards in addition to tailpipe emissions (CoM, 2012).

Since EC and TC are used to estimate the amount of DPM exposure, using a ratio, OELs then typically specify regulations relating to EC or TC. For example, New South Wales (NSW) Department of Primary Industries (DPI) set a 0.1 mg/m$^3$ limit for EC limit in 2007. Followed by the NSW DPI was the Queensland Mines Inspectorate and Western Australia Department of Mines and Petroleum, adopting the recommended exposure limit of 0.1 mg/m$^3$ in 2013 (AIOH, 2013).

The US Mine Safety and Health Administration (MSHA) also reduced their OEL to 0.31 mg/m$^3$ EC in 2007, with another reduction to 0.12 mg/m$^3$ EC or 0.16 mg/m$^3$ TC in 2008. Germany has an exposure limit of 0.3 mg/m$^3$ for underground non-coal mines and 0.1 mg/m$^3$ for other mining operations (AIOH, 2013).
However, the acceptance of international OEL standards for South Africa has been a difficult process. Part of the reason being that South African TC/EC ratios differ from international ratios and for different commodity mines. Another reason for a slow, although progressive, acceptance may be due to a lack in fully understanding the problem.

The legislative DPM OELs for various countries and provinces, are shown in Table 8. This indicates the lack of an OEL for South Africa.

Table 8: DPM Exposure limits for various countries in 2012 (CANMET Mining, 2012).

<table>
<thead>
<tr>
<th>Country/Province</th>
<th>DPM exposure limit (mg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>British Colombia</td>
<td>1.5</td>
</tr>
<tr>
<td>Quebec</td>
<td>0.6</td>
</tr>
<tr>
<td>Saskatchewan</td>
<td>None</td>
</tr>
<tr>
<td>New Brunswick</td>
<td>1.5</td>
</tr>
<tr>
<td>Ontario</td>
<td>0.4</td>
</tr>
<tr>
<td>Nova Scotia</td>
<td>1.5</td>
</tr>
<tr>
<td>Yukon</td>
<td>1.5</td>
</tr>
<tr>
<td>USA</td>
<td>0.16 (Total Carbon)</td>
</tr>
<tr>
<td>Australia</td>
<td>0.1 (Elemental Carbon)</td>
</tr>
<tr>
<td>South Africa</td>
<td>None</td>
</tr>
</tbody>
</table>

In particular, the exposure limits for DPM in Australia, Canada, and the US are based on the measurement of particulate constituents (EC and TC) as shown in Table 9 (CoM, 2012).

Table 9: DPM OELs: Based on EC or TC content (CoM, 2012)

<table>
<thead>
<tr>
<th>Regulator/Agency</th>
<th>Exposure Guideline/Limit</th>
<th>Substance Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canada (Ontario province)</td>
<td>400 µg/m</td>
<td>Total Carbon</td>
</tr>
<tr>
<td>US MSHA</td>
<td>160 µg/m</td>
<td>Total Carbon</td>
</tr>
<tr>
<td>Australia</td>
<td>160 µg/m</td>
<td>Total Carbon</td>
</tr>
<tr>
<td></td>
<td>120 µg/m</td>
<td>Elemental Carbon</td>
</tr>
</tbody>
</table>

10.1.4.2 South African Mining Industry

The Group Environmental Engineers, a sub-committee of the Health Policy Committee, recognise that several International Agencies have imposed limits for DPM, but also that these limits have been developed in countries where (CoM, 2012):

- Higher quality diesel fuel with low sulphur content is used;
- Latest generation diesel engines are used;
- Maintenance staff are adequately trained and available for employment to work on these units; and,
- Exhaust purification systems are used extensively.

It can be argued that as no national OEL has been established a contributing factor for less than adequate control of DPM exists in South Africa when compared to other countries (e.g. in the US and Australia). One of the constraints, however, faced by the local mining industry in achieving internationally set OELs, is the poor quality of fuel that eventually gets used in operations, despite adequate quality being supplied by refineries. This in turn also limits the use of diesel engines with better fuel combustion that have reduced emissions (CoM, 2012; Carolin, 2010; Von Wielligh, 2018).
However, mining companies are obliged to conduct health and safety risk assessments in terms of Section 11 of the Mine Health and Safety Act (MHSA) (Act 29 of 1996) on all factors that could adversely affect the health and safety of the workforce (CoM, 2012). This requires the establishment of appropriate mitigation measures, with complete elimination being the ultimate end-goal as per a typical risk assessment methodology.

Where no local regulations exist, international best practice should be utilised. Original Equipment Manufacturers (OEMs) are also required to provide a full disclosure, in terms of Section 21 of the MHSA (Act 29 of 1996) of the health and safety impact of the equipment being sold to a mining company. They further need to advise on appropriate measures that can be taken to eliminate or reduce the associated risk (CoM, 2012).

**10.1.5 Diesel Equipment and Engines**

A diesel engine functions by igniting diesel fuel leading to combusting under high pressure and temperature conditions. The combustion results in the expansion of gasses that initiate the movement of engine pistons, converting chemical energy into mechanical energy (Cummins, 2017). Today, diesel engines are widely used in underground and surface mining operations. These engines can be used in a range of small to large equipment types.

**10.1.5.1 Mining Equipment: Surface**

While this project focuses on underground operations and the corresponding underground equipment, it should be noted that surface operations may, under certain circumstances, also induce detrimental DE exposure to employees. The majority of surface exposures occur in deep pits where temperature inversions are prevalent or in workshops where flow-through ventilation is limited, e.g. enclosed workshops where the doors are closed during winter. Other examples include where vehicles are idled for extensive periods in open workshops, e.g. during testing (Perkins, 2005).

It is important that these scenarios are identified and measures taken to limit and control exposure of employees. Basic controls may include allowing sufficient flow-through of air in workshops and considering engineering controls such as ventilated operator cabins.

**10.1.5.2 Mining Equipment: Underground**

Potential for exposure to DPM exists whenever workers are in close proximity to operating diesel equipment. Where diesel equipment is operating in confined areas (e.g. underground mines) there is a significant risk of exposure (CoM, 2012).

Underground mining equipment utilising diesel engines in South Africa may range from 15 to around 400kW, or even up to 600kW in some international operations (Von Wielligh, 2018). Table 10 shows some basic diesel-powered vehicles used in both hard rock and coal operations.
Table 10: Equipment utilising diesel engines in hard rock and coal mines (Adopted from: CANMET Mining, 2012; Dragt, 2005; Sandvik, 2017; and, Mining-Technology, 2017).

<table>
<thead>
<tr>
<th>Hard rock</th>
<th>Coal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load Haul and Dump machines (LHD)</td>
<td>Trackless drill rigs and roofbolters</td>
</tr>
<tr>
<td>Trackless drill rigs and roofbolters</td>
<td>Transportation vehicles</td>
</tr>
<tr>
<td>Dump trucks</td>
<td>Shotcrete (rare in South Africa)</td>
</tr>
<tr>
<td>Diesel locomotives</td>
<td>Diesel shuttle cars (rare if at all in South Africa)</td>
</tr>
<tr>
<td>Transportation / Personnel carriers vehicles</td>
<td>/ Personnel carriers</td>
</tr>
<tr>
<td>Utility vehicles</td>
<td>LHD</td>
</tr>
<tr>
<td>Explosives/emulsion truck</td>
<td>Light duty vehicles (LDV)</td>
</tr>
<tr>
<td>Shotcrete</td>
<td>Scoops</td>
</tr>
</tbody>
</table>

Research in Australia and Canada has indicated that exposure to diesel emissions from LDV’s in underground operations may in some circumstances exceed that from heavy duty mobile equipment (Perkins, 2005).

**10.1.5.3 Engines used in the Equipment**

The most common diesel engine configuration, used around the world, is the four-stroke cycle. It should, however, be noted that some two-stroke engines are still in operation but that they have less favourable emission levels compared to four-stroke engines. Most diesel engines in operation are also direct injection engines, which have better (up to 20% difference) in fuel economy and lower particulate emissions as compared to indirect injection diesel engines (Perkins, 2005).

The South African mining industry uses diesel engines from multiple OEMs, these typically include (Von Wielligh, 2018):

- Deutz;
- Caterpillar;
- Perkins;
- Kirloskar;
- John Deere;
- Motor and Turbine Union (MTU); and,
- Cummins;

MTU, for example, is a company which is part of the Rolls Royce power group that develops diesel engines and propulsion systems for multiple industry applications. MTU headquarters are located in Germany and delivers their products to various countries around the world, including South Africa. MTU diesel engines supplied for underground operations range from 75 kW to 429 kW and are used to power multiple vehicles such as drill rigs, LHD’s and articulated dump trucks (ADT’s) in South African mines (MTU, 2012).

Other OEM’s supplying diesel engines to South Africa include Cummins, which provides underground engines ranging from 37 kW to 567 kW (Cummins, 2017); and, Sandvik, which produces engine sizes for the following underground equipment (Sandvik, 2017):

- Drill rigs – up to 119 kW;
- Roofbolter – up to 170 kW;
LHD – up to 354 kW; and,

- Trucks – up to 567 kW.

While there is no clear defining line between light, medium and heavy-duty diesel engine applications, Perkins (2005) grouped them according to the applications for mining shown in Table 11.

**Table 11: Typical Diesel Equipment in Underground Mining (Perkins, 2005)**

<table>
<thead>
<tr>
<th>Power Range</th>
<th>Vehicle Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Duty</td>
<td>Personnel carriers, tractors, light service, forklifts, skid steers</td>
</tr>
<tr>
<td>22-67 kW (30-90 HP)</td>
<td></td>
</tr>
<tr>
<td>Medium Duty</td>
<td>Lube trucks, boom trucks, drill carriers, Ammonium Nitrate Fuel Oil (ANFO) loaders, scalers, LHDs (coal mines) power trams</td>
</tr>
<tr>
<td>67-127 kW (90-170 HP)</td>
<td></td>
</tr>
<tr>
<td>Heavy Duty</td>
<td>LHDs, haulage trucks, track locomotives (including smaller LHDs between 75-150 kW)</td>
</tr>
<tr>
<td>127-447 kW (170-600 HP)</td>
<td></td>
</tr>
</tbody>
</table>

### 10.1.5.4 Standards: Tier & Stage Ratings

A diesel engine may be classified by an engine Tier in terms of its certified standards for emission level limitations.

**Note:**

(i) In simple terms, a Tier rating is defined as a standard for emission levels for an engine.

The best known and most widely used standards for certifying diesel engines are from the EPA in the US, namely Tier 1 to 4, and from the EU, namely Stage I to IIIB. Currently, engines at Euro 6 are already in production in Europe, while Euro 7 standard engines are presently under development (Von Wielligh, 2018). This report uses Tier levels as frame of reference. Each Tier level of progression, i.e. higher Tier levels from 0 to 4, involves lower emission limits which are achieved through improved engine technology. Examples of these contributing technologies include electronic controls and fuel injection systems (Diesel Technology Forum, 2011).

Diesel engine manufacturers have been producing engines in varying power classifications to meet the proposed requirements within the set timelines. These requirements relate to the emission levels of NO\(_x\) and particulates. By studying the emission levels associated with each engine Tier (or Stage) of the engines, other countries (such as South Africa) can make their decisions on what engines and equipment to select and to be able to plan for improvements (Perkins, 2005).

A Tier 0 engine is classified as an engine which is mechanically controlled without any electronic emission controls. The DPM emission limits from this Tier standard is no longer sufficient in the US due to unacceptable levels of DPM production (Portvancouver, 2015). According to the California Environmental Protection Agencies’ Air Resources Board, a Tier 0 diesel engine may not be added to a vehicle fleet, in the US, since January 2014 (Air Resources Board, 2016).

Tier 1 engines were phased in from the years 1996 to 2000 and are defined as having in-cylinder control technologies aimed at primarily reducing NO\(_x\) emissions. These technologies include delayed fuel injection systems with upgraded fuel pumps and injector nozzles,
turbochargers, charge air coolers and smoke-puff limiters. These systems and controls are what limit and reduces the amount of emissions (Dallman and Menon, 2016). In the US, vehicles with Tier 1 engines may not be added to a large fleet (fleet with more than 5000 hp / 3725 kW) or medium fleet (a fleet with 2500-5000 hp / 1864-3725 kW) since 2014, but were allowed to be added to a small fleet (less or equal to 2500 hp / 1864 kW in total) up until 2016 (Air Resources Board, 2016).

Tier 2 engines were phased in from the between 2001 and 2006 and are classified as having continued emission control improvement. The fuel injection technology is improved and the use of electronic engine controls is implemented in larger engines (Dallman and Menon, 2016). The improvement of these systems reduces emission levels further than Tier 1 to accommodate lower emission standards, which were set out by the US EPA for Tier 2 engines (DieselNET, 2016). In the US, vehicles with Tier 2 engines may not be added to a large or medium fleet from 2018, but to a small fleet until 2023 (Air Resources Board, 2016).

Tier 3 engines were phased in from the year 2006 to 2008. These engines incorporate Exhaust Gas Recirculation (EGR) technology, which improves the control of NO\textsubscript{x} gasses. The technologies implemented in this stage are advanced electronic engine controls, turbochargers with variable geometry, and highly developed fuel injection systems. These engine controls improve the combustion process and so limit unwanted emissions (Dallman and Menon, 2016). The standards set out by the US EPA for this level of engine are the same as Tier 2 for DPM and CO pollutants. However, a decrease in Non-methane Hydrocarbons (NMHC) and NO\textsubscript{x} emissions, of approximately 40 %, was also prescribed for Tier 3 engines (Diesel Technology Forum, 2011). According to Environmental Technology (2015), NMHC is a gas that reduces air quality and causes respiratory distress in humans, animals and vegetation.

As such, older engines have a higher DPM emission than newer engines, the reason being that new engines have electronic ignitions systems and are turbocharged (Darling, 2011). Newer technology engines, which adhere to Tier 4 emission standards, are also commercially available. These engines fell outside the scope of this project. However, to provide additional information and give context to technological and emission control changes, Tier 4 engines will also be discussed briefly.

Tier 4 diesel engine standards were phased in by the US EPA from 2008 to 2015. The standard introduced a DPM reduction ranging from 0.03 g/kWh to 0.02 g/kWh for diesel engines up to 560 kW. A large reduction in NO\textsubscript{x}, down to 0.4 g/kWh, was introduced together with a hydrocarbon (HC) reduction, down to 0.19 g/kWh, for engines ranging from 56-560 kW (DieselNET, 2016). According to Jackson (2013), one of the main disadvantages is that Tier 4 emission reduction standards can increase new diesel engine prices by as much as 10%. Practical experience, however, has indicated that price increases for Tier 4 implementation can be substantially more than 10% (Von Wielligh, 2018). This is due to the increased number of after-treatment components (retrofitted technologies, as discussed later in this report) implemented on a new Tier 4 engine.

The associated maintenance and operating costs will also contribute to the increase in financial requirement. Table 12 indicates possible costs and savings associated with a Tier 4 engine. It should be noted that all costs indicated in this report are by no means accurate representations of current costs. Normal inflation- and exchange rate calculations do not necessarily provide adequate cost calculations when converting to current figures, since too many variables impact engine costs. The figures for costs (whether operating expenditure
(OPEX) or capital expenditure (CAPEX)) are provided for the purpose of illustration and to serve as a frame of reference for the given scenario or case study that is being described. No values given should be taken as accurate and no decisions should be made on these values alone.

Table 12: Tier 4 Costs and savings (Majewski, 2007 and NSW EPA, 2014).

<table>
<thead>
<tr>
<th>Tier 4</th>
<th>Description</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel savings</td>
<td>With selective catalytic reduction (SCR) and EGR fuel losses taken into consideration.</td>
<td>2.5 % improvement relative to Tier 3 consumption.</td>
</tr>
<tr>
<td>Diesel engine cost</td>
<td>Average cost of retrofit devices added to a Tier 3 (US$ 243/kW) to reflect a Tier 4F setup (Majewski, 2007).</td>
<td>US$ 380/hp or US$ 517/kW.</td>
</tr>
<tr>
<td>Maintenance costs</td>
<td>19 – 37 kW</td>
<td>0.4 % of Tier 4 engine cost/ year</td>
</tr>
<tr>
<td></td>
<td>37 – 560 kW</td>
<td>1.2 % of Tier 4 engine cost/ year</td>
</tr>
<tr>
<td></td>
<td>&gt; 560 kW</td>
<td>2.5 % of Tier 4 engine cost/ year</td>
</tr>
</tbody>
</table>

Tier 4 Final (4F) diesel emission standards have been implemented by multiple engine manufacturers globally. The conversion to reduced emission levels are in part due to retrofitting technologies that are added. These technologies vary from supplier to supplier, with Table 13 showing a few combinations of technologies adopted by the indicated suppliers (Mans, 2017).

Table 13: Tier 4F emission treatment technologies (Benink, 2012).

<table>
<thead>
<tr>
<th>Supplier</th>
<th>Diesel Oxidation Catalyst (DOC)</th>
<th>Diesel Particulate Filter (DPF)</th>
<th>EGR</th>
<th>SCR</th>
</tr>
</thead>
<tbody>
<tr>
<td>John Deere</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Kohler</td>
<td>x</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Scania</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cummins</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Caterpillar</td>
<td>x</td>
<td>x</td>
<td></td>
<td>x</td>
</tr>
</tbody>
</table>

Table 13 shows that a Tier 4F engine may consist of multiple emission treatment technologies, which is why the price of such an engine will be higher than the lower Tiered engines (Benink, 2012). Tier 4 engines, are in some sense a Tier 3 diesel engine that has been retrofitted with multiple emission reduction technologies.

What should be noted, however, is that currently Tier 4 engines cannot be supported by the South African mining industry due to the quality of the diesel fuel used in industry. Tier 4 engines strictly require high quality ultra-low sulphur diesel fuel (ULSDF) (Von Wielligh, 2018).

### 10.1.6 Diesel Engine Fleet Estimation

In order to determine the number of engines that would require replacement or upgrading in South African mines (if a large-scale engine replacement program were to be promoted from Tier 0 engines to Tier 2 or 3), discussions were held with several mining companies as well as several OEMs.

As a general observation, some of the equipment information that was obtained from different mining companies and OEMs were considered accurate, whilst other information was either considered inaccurate, unavailable, or contradictory. Accurate information was obtained from OEMs with regards to new equipment that was supplied to industry. However, the information on older equipment or diesel engines was limited or contradicting depending on the source of
the information. The reason for this is that mining operations tend to rebuild, modify or repurpose some of their equipment, or outsource the work to a third party, to suit the dynamic needs of the mining environment. These records are scattered and often poorly kept, especially when handovers occur over many years, and the OEMs are rarely involved in such “after-market” modifications.

As such, it was concluded that no information is available, to a sufficient degree of accuracy that would provide a holistic indication of the status of the current diesel fleet operating in South Africa’s mining industry. To obtain this information, a fleet audit would be required of each individual mining operation.

However, the information that was obtained, that was deemed sufficient for representative purposes, on the diesel engine fleet estimation dataset is shown in Table 14 (operations are not named and are from various commodities).

**Table 14: Diesel Engine Fleet Estimation**

<table>
<thead>
<tr>
<th>Company/Mine</th>
<th>Number of Diesel Machines</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation A</td>
<td>173</td>
</tr>
<tr>
<td>Operation B</td>
<td>35</td>
</tr>
<tr>
<td>Operation C</td>
<td>20</td>
</tr>
<tr>
<td>Operation D</td>
<td>76</td>
</tr>
<tr>
<td>Operation E</td>
<td>44</td>
</tr>
<tr>
<td>Operation F</td>
<td>84</td>
</tr>
<tr>
<td>Operation G</td>
<td>62</td>
</tr>
<tr>
<td>Operation H</td>
<td>84</td>
</tr>
<tr>
<td>Operation I</td>
<td>350</td>
</tr>
<tr>
<td>Operation J</td>
<td>115</td>
</tr>
<tr>
<td>Operation K</td>
<td>337</td>
</tr>
<tr>
<td>Operation L</td>
<td>126</td>
</tr>
<tr>
<td>Operation M</td>
<td>56</td>
</tr>
<tr>
<td>Operation N</td>
<td>23</td>
</tr>
<tr>
<td>Operation O</td>
<td>28</td>
</tr>
<tr>
<td>Operation P</td>
<td>38</td>
</tr>
<tr>
<td>Operation Q</td>
<td>11</td>
</tr>
<tr>
<td>Operation R</td>
<td>9</td>
</tr>
<tr>
<td>Operation S</td>
<td>5</td>
</tr>
<tr>
<td>Operation T</td>
<td>8</td>
</tr>
<tr>
<td>Operation U</td>
<td>6</td>
</tr>
<tr>
<td>Operation V</td>
<td>1</td>
</tr>
</tbody>
</table>

**Preliminary Estimate** 1 691

From Table 14 it is important to note that the fleet numbers provided per mining operation may not be accurate representations of the actual fleet at the mining operations. As time passes, the information will become more inaccurate as the fleets are further modified.

Furthermore, the fleet information given was obtained from different sources (e.g. an OEM could only account for their machines at a given operation, and not for the entire diesel fleet within that operation as it often consists of different OEM products).

From the engagements with mining companies and OEM’s, the following was observed:

- Equipment often gets transferred between mines.
- In some cases, machines are scrapped without the OEM being informed.
- As long as the machines are under guarantee, the OEM’s know where they are deployed and what their condition is.
- In many cases, when the machines are out of the guarantee period, the mines prefer to do the maintenance and repairs themselves (or they make use of outsourced repair facilities). In such an event, the OEM does not have any record of the machines’ deployment or condition.

A list of the more popular underground machines was compiled, including the specifications of every machine. Due to the sheer size of the data set, this is not included in this report. The OEMs that supplied machine specifications (which can be provided upon request), are as follows:

- Aard mining
- Atlas Copco
- Bell
- Bobcat
- Caterpillar
- DOKING
- Fletcher
- GHH
- Manitou
- Maxim
- Sandvik
- RHAM
- Fermel

It was also established that on the coal mines in the Mpumalanga area, a large number of commercial light-duty vehicles (LDV) are converted for use underground. Due to the fact that these vehicles were bought from commercial suppliers, the vehicle OEM’s could not provide exact quantities. It was, however, established with a reasonable amount of certainty that the one of the coal mining companies utilise about 750 of these vehicles. The mines from this company also utilise about 300+ tractors pulling trailers underground.

During the discussions with the mining companies, it was also established that a large number of underground diesel locomotives are still in operation. The figures that could be obtained from one of the underground hard rock mining companies, was that they are still operating around 545 diesel locomotives underground. The number of electric/battery driven underground locos was given as 1 330 (this was assumed as a global figure). It was very difficult to determine whether the engines in the equipment in operation were Tier 0, Tier 1, Tier 2 or Tier 3.

Very good cooperation was experienced with RHAM, an OEM for underground machinery. They were able to provide the numbers of their machines in service as well as the Tier levels of the engines. These along with other OEM engagements indicated that roughly about 30%
of underground diesel engines are Tier 3 level, the rest being Tier 0 – 2, with the most being Tier 1.

During the discussions with the stakeholders, it was established that the mines face a situation where they have to cater for a variety of engines ranges, from Tier 0 to Tier 3. These vehicles are operating under very severe conditions underground and are usually maintained in underground workshops with limited workshop space and facilities.

An important factor that was identified during these engagements was that the majority of diesel engines currently in operation are not Tier 0, but Tier 1 or higher. This indicated a natural transition in industry to higher Tier levels and newer technology engines. As such, promoting a large-scale engine replacement program is not advised.
10.2 Potential Controls for DPM Emissions: Supporting Information

Considering the fact that the mining industry is already gradually transitioning to newer technology diesel engines with higher Tier ratings, and that the engines in operation are mostly Tier 1 or higher, it was determined that a more flexible DPM Emission Control Program alternative needed to be developed. Supporting this approach are the challenges associated with engine replacement, i.e. spatial (size and/or geometrical limitations/incompatibility) and/or technology (electronics, engine control modules, hydraulics, etc.) limitations or incompatibility, that limit the range of practical replacement options.

To develop a Guideline for a DPM Emission Control Program, various potential control measures were identified and their associated opportunities and challenges assessed. The supporting information for the identified potential controls has been divided into seven sections, namely:

- Diesel Fuel Quality;
- Diesel Fuel Supply Chain;
- Engine Technology;
- Engine Replacement;
- Engine Emission Level Conversion through Retro-fitting;
- Engineering, Management and Administrative;
- Existing Electronic Systems for Diesel Equipment Maintenance: and,
- Factors Affecting the Feasibility of a Transition to Reduced DPM Levels

The sections are discussed in detail below.

10.2.1 Diesel Fuel Quality

Fuel quality impacts the performance of equipment and materialises different side effects from its combustion. Diesel fuel undergoes a number of steps that influences the quality of the fuel during the refining process. Thereafter, other factors further influence the quality of the fuel in the diesel fuel supply chain, i.e. during handling, storage, testing and eventual use.

The factors to consider when reviewing the quality of a diesel fuel supply (or supplier) are (Perkins, 2005):

- **Cetane number**: This defines the “ignitability” of the fuel. A higher cetane number will improve ignition and reduce particulate emissions and noise.

- **Viscosity**: This refers to the resistance of a fluid to flow, where a higher viscosity indicates a higher resistance to flow. Viscosity affects the fuel injection system performance and metering. A narrower min/max span rating is preferable.

- **Cold behaviour**: Cold behaviour characteristics apply to winter fuels in colder geographical regions with a lower 90% distillation point. It is necessary to prevent clogging of waxes in the fuel, especially plugging in fuel filters.

- **Flash point**: Flashpoint is a critical point of consideration in safe handling and flammable concerns.

- **Lubricity**: The lubricating properties of diesel fuel are critical to the wear of components in the fuel injection system. Lubricity relates largely to the reduction in fuel
sulphur levels, where reduced sulphur content also reduces the lubricity of the fuel. It is, or can be, compensated for by additives in the refining process as well as modifications and engineering in fuel injection systems.

- **Sulphur**: Sulphur occurs naturally in diesel fuel (derived from fossil fuels) and relates to the quality of the fossil oil used in the refining process. The only real benefit of sulphur in diesel fuel is the lubricating property that reduces abrasion within the injection system. However, the presence of sulphur has a direct effect on exhaust emissions. In diesel fuel sulphur produces SO$_2$ gaseous and SO$_3$ sulphate particulate emissions. These in turn increase the production of particulate matter. Using low or ultra-low sulphur diesel (ULSD) fuel reduces these sulphur emissions as well as overall DPM emissions. It should also be noted that catalysed diesel particulate filter technologies can (and should, as per OEM requirements) be used with ULSD. Sulphur content varies considerably in typical market diesel fuels (Wattrus *et al*, 2016). Ensuring that the diesel used in operation actually adheres to the requirements is a large component in managing DPM emission levels.

### 10.2.1.1 Typical Diesel Fuels used in the SAMI

The South African Mining Industry (SAMI) uses diesel fuels of various qualities. The commercially available fuels in South Africa are 500 ppm, 50 ppm, 10 ppm, highly-paraffinic synthetic diesel (Sasol GTL), and some biofuels. The most widely used fuel in the commercial sector, due to cost, is 500 ppm sulphur diesel (Wattrus *et al*, 2016).

The quality, i.e. referring to the sulphur content, of diesel fuels varies internationally and is subject to regulations that are country specific. For example, in Russia there are three types of diesel available, known as the Euro 3, Euro 4 and Euro 5. The sulphur content is 350 ppm, 50 ppm and 10 ppm respectively. Previously the maximum sulphur content in Canada was 5000 – 500 ppm, but due to new regulations only 15 ppm is now produced. In the USA, a maximum sulphur content of 500 ppm is allowed with 15 ppm mostly used in the mining industry (CANMET Mining, 2012).

**10.2.1.1.1 High Sulphur: 500 ppm Diesel**

The definitions of what constitutes high, low and ultra-low sulphur diesel vary between countries. Here, fuels with higher than 50 ppm sulphur will be defined as a high sulphur diesel fuel. While the high sulphur diesel fuels found commercially in South Africa have varying degrees of actual sulphur content, it is generally referred to (and often bought as) 500 ppm (Von Wielligh, 2018). This kind of fuel is a crude-oil derived South African diesel containing 500 ppm sulphur (Wattrus *et al*, 2016).

**10.2.1.1.2 Low Sulphur: 500 to 50 ppm Diesel**

500 ppm to 50 ppm will be defined as low sulphur diesel (LSD) fuel for South African conditions. This is typically also a crude-oil derived South African diesel, but with 50 ppm sulphur content.

**10.2.1.1.3 Ultra-Low Sulphur: Below 50 ppm Diesel**

Below 50ppm will be defined as Ultra-Low Sulphur Diesel (ULSD) fuel for South African conditions. The ULSD available in South Africa is 10 ppm fuel. At the time of this study, 10ppm was available from Sasol, i.e. the Turbo Diesel TM Ultra Low Sulphur (ULS) 10 ppm. This is a
fully-synthetic diesel fuel that contains 10ppm or less sulphur and is SANS 342 compliant (Watrus et al, 2016).

10.2.1.2 Effect of Different Fuel Types [on DPM Emissions]

The sulphur content in the diesel used within diesel equipment directly impacts the level of DPM emissions. Lower sulphur fuels assist in lowering DPM emissions. Lower sulphur diesel is also a requisite for newer technology diesel engines. Using lower sulphur diesel fuels also adds to the effectiveness of retrofit technologies as an alternative way of engine conversion to higher Tier standards through reduced DPM emissions (Von Wielligh, 2018).

Specifically relating to retrofit technologies, the reason for using LSD or even ULSD fuels is to prevent catalyst poisoning. Catalyst poisoning is caused by contaminants in exhaust gasses, especially sulphur. The sulphur reduces the efficiency of a catalyst or halts its function completely (Kholod et al, 2015). Other benefits of LSD/ULSD with retrofit technologies include the reduction of DPM during combustion as well as reduced internal engine wear due to lower levels of acid, which is also a result of the sulphur content (Darlington, 1999).

Watrus et al (2016), conducted a study to quantify the extent of DPM emission level reductions for the various diesel fuels used in the South African mining industry. The study used 500 ppm diesel fuel as the baseline, which is the primary fuel type used in SA, and determined the following (Watrus et al, 2016):

- Switching from a 500 ppm diesel fuel to a 50 ppm or 10 ppm fuel resulted in an average DPM emission reduction of 10%;
- Switching from 500 ppm to Sasol GTL reduced DPM emissions by nearly 30%;
- Adding 7% Soy Methyl Ester (SME) or Palm oil Methyl Ester (PME) biofuels to a 500 ppm, 50 ppm or 10 ppm diesel fuel resulted in a 5% DPM reduction. Note, however, that with newer generation diesel engines, internal diesel injector deposits (IDID) can become a serious problem when using biofuels and as such should be evaluated in greater detail before implementation (Von Wielligh, 2018); and,
- It was further suggested that DPM emission reduction can be increased by as much as 40 % if Sasol GTL Diesel is mixed with biofuels.

The study further stated that commercial combustion additives are available, which are added to 500ppm to 10 ppm diesel fuel that resulted in improved combustion and a reduction in DPM emissions. Figure 3 indicates the measured levels of DPM emission reduction, in a 137 kW Tier 1 Diesel engine that initially used 500 ppm Diesel fuel. This engine was a Deutz BF 6M 1013 E engine, which is one of the most prevalent engines used in Platinum mines in South Africa. It is a Tier 1 level engine and usually used in LHDs (Watrus et al, 2016)
Figure 3 indicates that the Tier 1 engine’s DPM emissions were reduced by 28.4% when using Sasol GTL fuel, or at least by 10% when using the more commercially available ULSD fuels. Using LSD or ULSD clearly results in direct reductions of DPM emissions which would bring immediate benefit provided that all associated challenges can be overcome and that LSD/ULSD can be sourced sustainably.

The test results do not indicate the limit of what can be accomplished with a “fuel only solution”. There are other fuel formulations that will further reduce other harmful emissions. However, these formulations are typically not yet available commercially. Such formulations may have challenges for sustainable supply in the short- to medium-term, and have higher costs that may impact feasibility calculations. It is also possible that they may introduce other unwanted elements into the atmosphere, and/or introduce significant handling and operational challenges (Wattrus et al., 2016).

It seems unlikely that a transition to higher than Tier 2 standards will be achievable when considering only the use of currently available commercial diesel fuels as a single solution (Mans, 2017). Although, the use of the Sasol GTL diesel did manage to reduce the DPM emissions to below Tier 2 and Tier 3 limits (Wattrus et al, 2016).

Implementing newer technology engines, that adhere to higher Tier level requirements, or implementing retrofit technologies, will lead to greater reductions in DPM levels (as will be discussed in the following sections). Each of these alternatives have their own set of challenges and disadvantages as well. Employing one, or a combination, of the three primary methods mentioned of reducing DPM (lower sulphur fuel, newer engines, and retrofit technologies) should be considered on a case by case basis in order to determine the optimal solution.

**10.2.2 Diesel Fuel Supply Chain**

The storage and handling of diesel fuel is a key factor in maintaining the integrity of low and ultra-low sulphur diesel fuels. Several case studies exist that explain how diesel in underground fuel bays has been contaminated with dirt, garbage and water. This may be a result of containers that are left open, fill covers that are broken, bad testing protocols (e.g. dipping dirty rods into tanks to measure fuel levels), or poor management of the supply chain.
The latter may include various factors, some of which already start during procurement, e.g. when ULSD fuel is loaded into road tankers that have been used for another product and that were not sufficiently cleaned before loading the ULSD. This results in contamination, fuel mixing, and sometimes an increase in sulphur content (Perkins, 2005).

Contaminated diesel negatively affects performance as well as engine component life. It further also results in higher emissions (Perkins, 2005). It is therefore critical that good management practices are enforced throughout the diesel fuel supply chain to ensure that the fuel that gets used meets the required standards and that DPM emissions can be effectively estimated and therefore controlled more effectively. Management of the diesel supply chain should consider the following aspects:

- Variations in quality;
- Storage factors: methods and containers;
- Method of sampling;
- Maintenance, cleaning (good housekeeping) on storage and dispensing units.

See Section 10.5.3 for more information.

10.2.3 Engine Technology

Employing newer technology engines with higher Tier/Stage ratings and as such with reduced DPM and other associated emissions, improves the working environment by reducing potential exposure levels. Newer technology engines may also be coupled with retrofit devices to further decrease DPM emissions, however, studies have indicated that total and elemental carbon concentrations are significantly reduced with low emission engines alone. Nanoparticle emissions have also been found to be reduced, even by as much as 50%. In an on-site trial in 2002, conducted at the Cote Blanche underground salt mine in Louisiana USA, it was found that the levels of polycyclic aromatic hydrocarbons (PAHs) and biological activity (mutagenicity) associated with DPM also decreased by up to 90% with the implementation of lower emission engines (Perkins, 2005).

Almost all engine manufacturers employ waste gate turbochargers with their [newer] engines to limit the rpm of smaller turbos. Smaller turbos are installed to alleviate the effects from turbo lag, which is the delay between the delivery of the fuel and the corresponding charge air from the turbocharger that causes a puff of smoke and excessive emissions (Perkins, 2005).

10.2.4 Engine Replacement

Replacing an old diesel engine with a newer technology engine is one of the surest ways to reduce DPM emissions from diesel equipment operating in underground mines. The decision for engine replacement should consider the Tier/Stage ratings for which that the engine(s) is certified. As mentioned before, higher Tier/Stage ratings are associated with lower DPM (and other harmful exhaust) output. Engine manufacturers have invested in DPM reduction technologies and integrated it into newer generation engine models. These newer engines may also be more economical and reliable (Kholod et al, 2015). However, implementing newer technology engines does not come without challenges to consider.

Embarking on such a transition requires thorough analysis on the details surrounding the ‘how’, ‘what’, ‘when’ and ‘who’, with the ‘why’ being the end goal of improving working conditions through a reduced exposure to DPM. Towards this end, each operation will need
to perform a financial feasibility analysis to determine the optimal way to achieve a positive and sustainable transition and design the resulting implementation roadmap, i.e. detailed plan over a specific time period. Some of the identified factors to consider before implementing a new engine strategy are (Bradley, 2008):

- Engine vs. equipment compatibility;
- Commercial availability of engine size;
- Fuel requirement and availability thereof, e.g. LSD/ULSD;
- Maintenance requirements;
- Skills or upskilling requirements;
- Life of mine;
- Life of project for engine transition;
- Impact on health and safety; and,
- Re-sale options for equipment and engines.

Furthermore, some of the main factors that will impact a financial feasibility analysis include (Bradley, 2008):

- Engine replacement costs;
- Fuel consumption costs and changes in current/baseline consumption; and,
- The resulting maintenance and rebuild costs.

With the exception of replacement cost, the other costs mentioned are often overlooked, because they are not seen as having a cumulative effect on calculating the feasibility of the necessary transition (Bradley, 2008).

### 10.2.4.1 Replacement Options and Challenges

While there are various options for engine replacement, the focus of this project was on a transition of engines that are certified at a Tier 0 emission level, to a certified emission level at Tier 2 or Tier 3. For engine replacement as a standalone solution for such a transition, this means replacing older (Tier 0) diesel engines with newer (Tier 2 or Tier 3) diesel engines.

When selecting an engine for a particular application, whether to replace an engine in a piece of equipment or to do a rebuild, the most important consideration is the match of the engine output to the vehicle load requirements. Diesel engines perform at the best efficiency and lowest emissions when they operate between the peak power and peak torque band (green band) (Perkins, 2005). The more time an engine spends operating within this band, the cleaner, more efficient and longer it will run. As such, it is important to select an engine that will operate as much as possible within this range and minimise time at both less than peak power (freewheeling) and more than peak torque (lugging) (Perkins, 2005).

This requires decision-makers to study the power train and torque curve for the converter/transmission package as well as the load of the hydraulic system. All manufacturers have documentation available for engine power curves as do power train and hydraulic manufacturers (Perkins, 2005).
However, various studies highlight difficulty or even severe limitations with attempts to replace older diesel engines in the original older equipment with newer technology engines. For example, a conversion from a Tier 0 or Tier 1 to a Tier 2 engine had been noted to prove difficult due to the fact that a Tier 2 engine incorporates many additional emission controls. Tier 2 (and higher) engines also generally require the use of low or ultra-low sulphur diesel which should be considered during the feasibility trade-offs (Bradley, 2008). Esplin (2005), further stated that placing Tier 2 and Tier 3 diesel engines into equipment that was too old is not economically plausible, due to required changes and advances in chassis. He further stated that new equipment would have to be procured for a possible engine replacement, unless old equipment is totally rebuilt or able to cater for new engines. This has both financial and practical implications that need to be considered in detail.

### 10.2.5 Engine Emission Level Conversion through Retro-fitting

Retrofit technology (as a potential alternative for the conversion to higher Tier ratings apart from engine replacement) is the addition of a DPM emission reduction technology to a diesel engine. The technology, or system, is located in a specific region of the combustion or exhaust system to prevent DPM production before the exhaust fumes enter the atmosphere. Each retrofit solution has its own unique purpose and they can be combined to reduce not just DPM but other harmful gasses as well. Most retrofit solutions reduce DPM emissions by capturing and filtering particulate matter and/or converting unwanted gasses into less harmful gasses by means of a chemical reaction (Mans, 2017).

The selection of exhaust gas after-treatment solutions or systems that are suited for retrofitting onto mobile diesel equipment (e.g. LHDs), depends on various factors. For example, engine emission performance varies between manufacturers with operational cycles, fuels, oil, additive quality, and the engine emission certification level (e.g. Tier/Stage 1 to 4). As a result, after-treatment retrofit solutions need to be evaluated and selected on a case by case basis (Wattrus et al., 2016). The solutions discussed in the next sections serve to give an overview of potential alternatives in the drive towards reducing DPM in the mining industry and is by no means a guide towards a suitable and readily implementable solution for any given mining environment.

Furthermore, adding multiple devices to an engine must be carefully considered as it has practical as well as other feasibility implications. Some combinations that have been tested and found in literature will be discussed, but the exact implications of combining different and multiple retrofit solutions to a diesel engine in order to reduce harmful emissions falls outside the scope of this project.

The retrofit technologies discussed here, except for Exhaust Gas Recirculation (EGR) systems, are installed in the exhaust section of a diesel engine. The technologies vary in functionality, effectiveness, challenges with implementation, and size. Size for example is to some extent typically related to the displacement size of the engine (Bradley, 2008). Meaning the larger the engine the larger the system needs to be as well, which may result in practical issues with available space to fit the technology.

Some of the technologies listed are purely designed to limit DPM emissions from diesel engines, such as Disposable Diesel Exhaust Filters (DDEFs), Diesel Oxidation Catalysts (DOCs) and Diesel Particulate Filters (DPFs). These devices mainly use catalysts and filters to capture, convert, and/or otherwise limit DPM emissions into the atmosphere. A catalyst is a substance used to convert harmful gasses such as hydrocarbons, carbon monoxide and
nitrous fumes into harmless gasses (McCartney, 1997). Another function of a catalyst is to reduce the oxidation temperature of DPM in DPFs (Bradley, 2008).

The other technologies listed, such as EGR systems, NO\textsubscript{x} Reduction Catalysts (NRCs), and Selective Catalytic Reduction (SCR) systems are control technologies with the primary focus of limiting the production of NO\textsubscript{x} fumes from diesel engine emissions. NO\textsubscript{x} gasses are poisonous and detrimental to human health. It reduces lung function, which causes breathing problems as well as damage to eyes and teeth. These gasses are visually represented by a suffocating smog (Wheels24, 2015). SCR and NRC devices utilise what is called a reductant together with a catalyst to reduce NO\textsubscript{x} emissions. A reductant is a chemical solution used in the reduction reaction of NO\textsubscript{x} (Bradley, 2008). For reducing both DPM and NO\textsubscript{x} gasses these control devices can be used in conjunction with DOCs and DPFs, which is why they are discussed in this report.

There is a large range of approved after-treatment retrofit technologies and suppliers. These can be found on the VERT® list (Vert, 2017), which is an association dedicated to the promotion of “Best Available Technology” for emission control. Other applicable sources to investigate regarding these lists are the US EPA Verified Technologies List for Clean Diesel, or the US Mine Safety and Health Administration (MSHA) website (Wattrus \textit{et al}, 2016). After-treatment systems that are not listed on one of these sources’ lists have not had their performance certified independently and should avoid or assessed with caution.

The main retrofit technologies (along with their opportunities/positives and challenges/negatives) are shown in Table 15.
## Table 15: Summary of Retrofit Technologies

<table>
<thead>
<tr>
<th>Technology</th>
<th>Description</th>
<th>Opportunities/Positives</th>
<th>Challenges/Negatives</th>
</tr>
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</table>
| Disposable Diesel Exhaust Filters (DDEF)    | The process involves fitting a canister to the exhaust system after the water filled conditioning tank, inserting a DDEF, and then operating the piece of equipment until the backpressure from the retained DPM on the filter exceeds predetermined limits or some other operational parameter (e.g. number of hours in service). DDEFS are effective in reducing DPM emissions, although the extent of which depends on various factors. It is still an alternative that may be considered in the interim in order to reduce employee exposure to DPM, but it does not provide a sustainable long-term solution. | - May reduce DPM emissions, although the extent of which seems uncertain as it is influenced by various factors.  
- Easy installation.  
- Relatively low maintenance requirements in total. | - Uncertain filter life, leading to uncertain estimations is consumable costs.  
- Trouble with filter washing and disposal.  
- Additional maintenance requirements need to be implemented and sustained.  
- Potential fire hazard. |
| Diesel Oxidation Catalysts (DOC)             | This device consists of a metallic container that looks like an exhaust muffler installed in the exhaust flow of a diesel engine. Inside the container is a metallic or ceramic core with flow channels. These channels are coated with a metal catalyst such as platinum. As the exhaust gasses flow through the DOC the catalyst removes harmful exhaust gasses by the oxidation of DPM, Volatile Organic Compounds (VOC) and CO. VOC’s are contained within emission vapours and may result in long term health effects such as damage to internal organs and the nervous system (US EPA, 2017). Refer to Appendix A: Deutz DOC Case Study | - May reduce DPM emissions by around 20%.  
- Reduces VOC and CO emissions.  
- Easy installation.  
- Could be coupled with other retro-fit technologies to reduce the addition of unwanted gasses and particles.  
- Comparatively low cost.  
- Permissible use of high sulphur content fuel. | - May increase DPM emissions when high Sulphur fuel is used, making it difficult to estimate overall DPM impact.  
- Increases NO₂ emissions.  
- Adding additional technologies makes the system complex, harder to maintain effectively and more difficult to install due to limitations in available space. |
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<th>Challenges/Negatives</th>
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| **Diesel Particulate Filters (DPF)**           | The function of a DPF is to capture DPM in a filter and incinerate most of the matter, with CO$_2$ and water being released as a result. This process is referred to as regeneration whereby a sufficient temperature is reached inside the DPF to ignite the built-up soot and combust it. If DPM is not combusted during this process the filter can become clogged and will result in an increase in engine backpressure, reducing engine life (Hammit, 2005). | ▪ Very effective at reducing DPM emissions.  
▪ Some systems are easy to implement / Low skill requirement.  
▪ Reduces HC and VOC emissions considerably. | ▪ Comparatively high cost.  
▪ Various practical requirements that limit applicable scenarios for implementation.  
▪ Complex system.  
▪ Highly maintenance and management intensive.  
▪ Produces other unwanted gasses.  
▪ Some systems require ULSDF which requires good management to ensure adequate fuel quality.  
▪ Could increase fuel consumption.  
▪ Active DPFs require ULSD fuel.  
▪ Requires threshold exhaust temperature. |
| **Exhaust Gas Recirculation (EGR)**           | An EGR system is an in-engine technology, as opposed the other retrofit technologies discussed that are installed on the exhaust system. It functions by recirculating the exhaust gasses back to the intake of the engine. The CO$_2$ gas, in the exhaust, reduces the required combustion temperature by absorbing heat and results in a reduction in the amount of NO$_x$ gas produced during combustion. Since NO$_x$ is harmful, an EGR system aids in the reduction of harmful exhaust gasses emitted in underground mining environments (Bradley, 2008). | ▪ Reduces NO$_x$.  
▪ When used with a DOC, the system reduces both DPM and NO$_x$ and as such counters negative aspects associated with only DOC installations.  
▪ Can be used with a DPF, to reduce both unwanted gasses and particle emissions. | ▪ An in-engine technology, meaning implementation is complex.  
▪ Maintenance is complex and very important.  
▪ Coupled with a DOC, the system will have the challenges associated with DOCs, except for increased NO$_x$ levels.  
▪ Coupled with a DPF, the system will have the challenges associated with DPFs  
▪ Increased replacement costs.  
▪ Increased fuel consumption.  
▪ Higher skill requirements for installation and maintenance.  
▪ High installation cost.  
▪ Currently, however, it has been found that EGR is likely to be phased out and replaced with water injection since EGR brings reliability and costly replacement issues (Von Wielligh, 2018). |
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</thead>
</table>
| NOx Reduction Catalyst (NRC) | This technology is located in the exhaust flow of a diesel engine. It uses a hydrocarbon reductant, as opposed to the urea solution used with SCRs and therefore does not require a urea tank installation (Bradley, 2008). The hydrocarbon, which can be diesel fuel, is used together with a hydrocarbon-optimised catalyst to reduce NO from the diesel engine emissions to molecular N₂ and water (Mans, 2017). | ▪ NOₓ emission reduction.  
▪ Can be used with a DOC or DPF to reduce both NOₓ and DPM.  
▪ Slightly less cost intensive as compared to an SCR system.  
▪ No urea tank required. | ▪ Maintenance is complex and very important.  
▪ Coupled with a DOC, the system will have the challenges associated with DOCs, except for increased NOₓ levels.  
▪ Coupled with a DPF, the system will have the challenges associated with DPFs  
▪ Increased replacement and consumable costs.  
▪ Increased fuel costs.  
▪ Higher skill requirements for installation and maintenance.  
▪ High installation cost. |
| Selective Catalytic Reduction (SCR) | SCR technology is fitted in the exhaust system, similar to an NRC, and injects what is called a reductant into the exhaust stream. A reductant (or urea solution) is used when the engine is active. Urea is an organic compound with a chemical formula known as CO (NH₂)₂. The standard reductant for mobile equipment is a urea-water solution with 32 % urea by weight (Bradley, 2008). | ▪ NOₓ emission reduction.  
▪ Can be used with a DOC or DPF to reduce both NOₓ and DPM. | ▪ Maintenance is complex and very important.  
▪ Coupled with a DOC, the system will have the challenges associated with DOCs, except for increased NOₓ levels.  
▪ Coupled with a DPF, the system will have the challenges associated with DPFs  
▪ High replacement costs.  
▪ Increased fuel costs and other consumable costs.  
▪ Higher skill requirements for installation and maintenance.  
▪ Requires urea tank for added reductant.  
▪ Requires threshold exhaust temperature. |
10.2.6 Engineering, Management and Administrative Controls

Over the past 15 years considerable research has taken place to develop suitable control technologies, especially for vehicles operating in confined areas (e.g. underground mining). Proven control technologies, apart from low/ultra-low sulphur diesel, low emission engines, and exhaust filtration systems, further include (CoM, 2012; Perkins, 2005; Mans, 2017; and, OHSA, 2012):

- Effective and efficiently designed ventilation;
- Real-time ventilation flow adjustment systems (connected to real-time monitoring sensors);
- Efficient engine maintenance;
- Air conditioned (filtered) operators’ cabins;
- Operating practices;
- Driver and workforce education;
- Sufficient employee and operator training;
- Positioning workers in upstream ventilated environments where possible;
- Using effective DPM monitoring (what gets measured gets done);
- Implementing/Transitioning to non-diesel equipment;
- Personal protective equipment; and,
- Focussed management and administrative practices. Examples include:
  - Limiting vehicle speeds;
  - Constraining vehicle idling time; and,
  - Controlling the number of vehicles operating in an underground area through efficient scheduling activities.

To provide more context on the various alternative controls mentioned above, a few of the points made are discussed further:

- Enclosed operator cabins can be a very effective control for reducing DPM exposure. Up to 80% reductions in exposure have been measured when cabs are air-conditioned and pressurised to maintain a comfortable operating temperature and ensure that positive pressure in the cab prevents contaminants from entering to where the operator is seated. This requires proper air filtration for the cab itself and the implementation of adequate maintenance practices. While this helps the operators, it is not a solution for other workers surrounding the equipment or working or travelling down-stream of the airflow (Perkins, 2005).

- Some of these solutions serve as short term improvements and must not form the basis of a DPM reduction transition or plan. If possible, these solutions may be considered additionally to engine conversion and replacement options to provide greater air quality and healthier work environments (Mans, 2017).

- It is also crucial to ensure sufficient control, dilution, extraction and filtration of DPM in workshops. Practices should be implemented and maintained that ensure workers are
not exposed to diesel exhaust at a dangerous level while working in [engineering] workshops.

- The use of electrically-powered vehicles in non-coal mines should be considered for new projects as an alternative to diesel units. Even partial replacement will contribute to significantly reducing DPM levels. It is, however, recognised that diesel machinery offers a greater degree of flexibility (particularly compared to equipment with trailing electrical cables) and that part of the fleet may need to remain diesel-powered (CoM, 2012).

- Diesel-powered equipment manufacturers and fuel suppliers must be requested to provide the latest generation engines and ultra-low emission fuels. These will be utilised pending availability and will require intensive, advanced training of maintenance personnel. Current and new equipment may further make use of exhaust after-treatment (catalysts and particulate filters) together with fuel additives if necessary (CoM, 2012). This highlights some of the control combination possibilities to be considered.

- In choosing this alternative, it must be noted that new generation engines being implemented into older generation machines may not be practically possible due to space and configuration mismatches (Von Wielligh, 2018).

- One factor to consider is the current misconception that newer technology engines are likely to be less powerful for the same engine size and are likely to run at comparatively higher temperatures. While potentially higher engine temperatures (which is currently a subject of debate as to whether newer technology engines actually operate at higher temperatures) will impact production planning and ventilation requirements, it should be noted that recent technology advances have indicated that the newer technology engines do not have less power compared to their older and similar engine size counterparts (Von Wielligh, 2018).

- In the longer term, the feasibility of using fuel-cell powered machinery should also be investigated as an additional opportunity for new projects (CoM, 2012).

- The possibility of using remotely-controlled or autonomous vehicles in conjunction with ventilation strategies that preclude the re-use of air downstream of these vehicles should also be investigated (CoM, 2012).

- Electronic speed control or automatic gearboxes for LDVs may also provide a means of overcoming some of the challenges with current retarding systems that are implemented, which uses the vehicle’s gearbox to enforce retardation. The latter puts the diesel engine in a lower gear, to slow the LDV down (often for safety reasons), which then increases the rpm at which the engine runs and results in higher DPM production.

- As a final line of defence against DPM exposure, the use of personal protective equipment (PPE) should also be considered where necessary. In this scenario, respiratory protection may assist in reducing DPM exposure, but it is by no means an adequate solution. As such, PPE is the last solution within the hierarchy of hazard controls and should only be considered as a temporary measure. Doing so should also be accompanied by a respiratory requirements program to ensure sufficient training, education and understanding to support the use of PPE (Perkins, 2005).
Lastly, the lessons learnt during BHP Billiton’s transformation to reduced DE exposure in their global operations, were highlighted by Perkins (2005) as follows:

- No one single solution exists;
- Control of DPM emissions requires a major commitment by all involved;
- Attention to detail is necessary to sustain control technologies;
- Low/lower emission engines should minimise the issue, but may not necessarily solve it as a single solution; and
- The benefits outweigh the costs through increased productivity. This conclusion was company specific and influenced by various variables, however, the increased worker health and happiness leading to improved productivity received a favourable focus in the report.

Of particular importance is that experience has shown that no one single solution exists. Individual mines need to explore which of the control technologies and other solutions best fit their circumstances and in what combination.

10.2.7 Existing Electronic Systems for Diesel Equipment Maintenance

It should be noted that an important component of engine maintenance is engine condition monitoring. This includes emission-, oil-, thermal-, and vibration analyses. Various monitoring systems and methods, electronic and otherwise, are available for these analyses that may be employed at the discretion of a mine.

There are also various electronic systems that can be installed that could assist an operation with predictive maintenance. These can be evaluated for potential implementation. Ultimately, however, effective maintenance starts with doing preventative maintenance prior to performing necessary maintenance in an optimal manner. To enable preventative maintenance, the requirement is to have efficient and accurate monitoring and analysis processes and systems in place to identify issues within an engine. After an issue has been identified, it is the technician’s responsibility to perform the necessary investigations to identify the cause and address it accordingly.

The existing electronic systems are summarised in Table 16.

**Table 16: Summary of Existing Electronic Systems for Diesel Equipment Maintenance**

<table>
<thead>
<tr>
<th>System</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expert Diagnostic</td>
<td>The expert diagnostic system (EDS), works by monitoring and analysing changes in relevant engine performance parameters. The encountered changes are then used for predictions of possible failures in future, as well as their cause. This then reduces the maintenance expenses and alerts the user of when maintenance is required. The EDS software allows the computer to function as a participant in decision-making, by using the installed files of knowledge and experience of expert on diesel equipment or any other field in question. The same way an expert would analyse and solve complex problems, the software does the same in a quicker and more precise way since the knowledge installed is from different experts (Krcum et al, 2004).</td>
</tr>
</tbody>
</table>
Data trend is a computerised system that is used to monitor the condition of the main engine and certain auxiliaries, as well as predict the future date of the recommended maintenance. In terms of its applicability, it can work as a stand-alone computer system and can also be installed as part of a computerised engine automation system (Sandtorv, year unknown).

Data trend allows for technical conditions of an equipment’s components to be assessed without dismantling them. Traditionally, it was required that a component be dismantled to check its condition. The advantage of the data trend is that it uses a systematic manipulation of data that is measured. The measured data (service values such as the efficiency of the compressors and the heat transfer coefficient) is used in the condition monitoring methodology not only to detect but also to correct the faults and inaccuracies in the system before they can become major problems.

System relies on the emission tests and engine data recorded to determine when/if and where there is a need for maintenance. It uses the following gas monitoring tools to estimate tailpipe DPM emissions:

**Electrochemical Sensors**

Electrochemical sensors are essentially fuel cells composed of noble metal electrodes in an electrolyte. The electrolyte is normally an aqueous solution of strong inorganic acids. When a gas is detected, the cell generates a small current proportional to the concentration of the gas (Delphian Corporation, 2018).

**Non-Dispersive Infrared (NDIR) Analysis**

NDIR detectors are the industry standard method of measuring the concentration of CO and CO\textsubscript{2}. (Cambustion Limited, 2018).

**Spectroscopy**

Gas chromatography mass spectroscopy is an instrumental technique, comprising a gas chromatograph (GC) coupled to a mass spectrometer (MS), by which complex mixtures of chemicals may be separated, identified, and quantified (University of Bristol, 2002).

Fourier transform infrared spectroscopy is a technique used to obtain an infrared spectrum of absorption or emission of a solid, liquid or gas particles.

### 10.2.8 Factors Affecting the Feasibility of a Transition to Reduced DPM Levels

When assessing the proposed guideline and supporting information from this report, in order to identify the optimal approach to reduce DPM emissions at a specific mining operation, it is important to bear the feasibility implications in mind. With every operation being unique, there is no single solution to DPM control. Therefore, it is important to ensure that the feasibility assessment is done responsibly in order decide between various alternatives. Toward this end, this section aims to highlight the main factors that were identified that affect such a feasibility analysis. These include, but may not be limited to:

- Capital costs;
- DPM reduction levels and impact on health and safety;
- Production of other harmful gasses as a result of the chosen strategy;
- Fuel consumption and cost;
- The commercial availability of DPM reduction technologies;
Duration of engine Tier transitions affecting production;
- Production halts;
- Possible reduction in ventilation requirements;
- Associated ventilation costs (typically around 20% of operating costs)
- Engine life;
- The number of economic diesel engine rebuilds left;
- Skill requirements;
- Retrofit and engine compatibility;
- Exhaust temperature requirements for specific retrofit technologies;
- “Old” equipment and engine replacement compatibility;
- The availability as well as the expected advantages and disadvantages of low and ultra-low sulphur diesel fuel in a mining operation;
- The level of maintenance required for the associated DPM reduction method, which ties in with the availability of a skilled workforce; and,
- The expected life of mine.

These are grouped and discussed under the following headings.

10.2.8.1 Capital Cost

The capital and operating cost of an engine replacement is one of the main factors that influences its feasibility. If the costs of reducing DPM exhaust fumes to acceptable and healthy levels are too great, then such a transition will fail. As such, a thorough feasibility analysis, to determine the optimal way in which to achieve improved air quality, is required. Capital cost refers to the financial amount that will be required for a transition. The two control methods with a required capital outlay are engine replacement and engine conversion through retrofitting.

10.2.8.2 Diesel engine replacement

Defining exact costs for diesel engines that adhere to the various Tier limits falls outside the scope of this study. Comparatively a Tier 1 engine was found to be 15-20% cheaper than a Tier 2 engine. According to Cummins Inc. (2014) the average price difference between a Tier 1 and Tier 2 engine, in the range from 750 kW to 2000 kW, is 18%. The cost difference between Tier 0 and Tier 1 seems negligible in most cases.

It was identified that a Tier 2 diesel engine is financially slightly more favourable as compared to a Tier 3 diesel engine. Since DPM emission level reduction is also the same for both Tiers, a Tier 2 engine seems to be the more feasible option. However, it must be noted that the reduction of other harmful gasses is not considered (which improves general air quality in addition to just the DPM levels). NO, for example, has an OEL of 5 ppm, so a reduction in NO emissions will result in other subsequent benefits beyond a reduction in DPM emissions. As such, it is advised that consideration be given to other harmful emission reductions in addition to DPM emissions, when considering newer technology engine replacements.
Another emissions reduction study done on a Canadian surface mine’s diesel fleet suggested that if a Tier 0 engine had to be upgraded to a higher Tiered engine using retrofitting during rebuilding, the rebuild cost could increase by up to 20% (Bradley, 2008).

Kholod et al (2015) argued that, rebuilding an old engine is approximately 70% of the price of a new engine. It should, however, be noted that OEMs are striving for complete engine replacement instead of rebuilding an engine. The concept of “Throw Away Engines”, meaning engines that need to be replaced and that cannot be rebuilt as per OEM requirements, are increasingly being implemented. This should be taken into account when making decisions for engine purchases (Von Wielligh, 2018).

Taking the above information into account, it can be argued that it is sensible to time engine replacements with the required rebuilding cycles within the useful operating/engine life. This may extend the timeline before older engines are replaced and in such an event other control measures, as discussed in this report, should be implemented until such time.

10.2.8.3 Engine Retrofitting / Exhaust After-treatment

Various retrofit technologies and systems exist, with wide ranging associated capital costs. What should be considered is that some of the retrofitting devices do not reduce DPM from the atmosphere, but only NOx gasses. These devices should therefore be used in combination with different products for the maximum potential reduction of harmful gas and particle emissions. As such, when analysing the practicality of retrofit installations as well as the associated costs, the full system requirements need to be investigated in detail beforehand.

10.2.8.4 Operating Cost Changes

Changes in operating costs that will be a result of a transition to reduced DPM exposure, will impact the feasibility analysis for such a transition, as well as the sustainability of keeping the transition in effect. The primary factors that influence operating costs (that requires analysis) are discussed in this section.

10.2.8.4.1 Fuel Requirements

Changes in fuel requirements as a result of implementing newer technology engines, installing retrofit exhaust after-treatment technologies, or as a means of improved management of the diesel fuel supply chain, will impact the overall associated operating costs. This primarily includes the use of LSD/ULSD fuel as per the focus of this project, but may at a later point in time include other alternative fuels.

The use of, and dependence on, LSD/ULSD may lead to (Mans, 2017):

- Changes in fuel cost;
- Additional additive consumables cost;
- Changes in fuel consumption;
- Additional requirements for fuel storage, logistics and management; and,
- Additional training on new maintenance and quality control;

Fuel Consumption

With fuel consumption being a large contributor to financial feasibility, it was decided to provide additional insight into potential fuel cost changes that may result from a transition. Kholod et al (2015), suggests that mining companies should take two main points into account when
attempting to repower (replace older diesel engines) their fleet. These are fuel economy savings and engine price increases. In addition to that, the availability and sustainability of fuel supply should also be investigated in the event where a change is made to a fuel that does not have the same commercial usage as what is currently used.

To illustrate potential fuel consumption changes, the differences in fuel consumption between Tier 0, 1, 2, and 3 engines, of different power and operating at various modes, is illustrated in Figure 4 and Figure 5. In these 3-dimensional graphs, “engine mode 1” represents the minimum load on the engine and “engine mode 10” represents the maximum load imposed on the engine during operation. I.e. mode 1 is the idling of the engine, where 2 to 10 are non-idling states of increasing intensity.

![Figure 4: Response surface for fuel use vs. HP and engine mode for Tier 0 (Lewis, 2009)](image)

![Figure 5: Response surface for fuel use vs. HP and engine mode for Tier 1, 2 and 3 (Lewis, 2009)](image)

Figure 5 was an average fuel use response surface taken from Tier 1, 2 and 3 engines and does not account for the differences in fuel usage between these different Tiers. What is, however, important to note from Figures 4 and 5 is that fuel usage increases as power and/or engine mode increases. With engine mode having a steeper gradient as opposed to power, meaning increasing engine mode (mode of operation) increases fuel consumption by the greatest amount. This further highlights the importance of operating within the operating envelope of a machine. The decrease in fuel consumption when replacing a Tier 0 engine with a Tier 1, 2 or 3 diesel engine can be seen as the decrease in gradient from Figure 4 to Figure 5, shown in gram per second.
Initially the US EPA suggested that a Tier 1 standard engine showed a three to five percent increase in fuel consumption compared to the Tier 0 engines. But, in recent years due to technological advancements higher Tier vehicles now largely have improved fuel efficiencies (Cummins Inc., 2014).

A study done in Russia, by Komatsu, imported trucks from the United States and Japan with Tier 2 engines with payload capacities of 90, 180 and 220 tons. The imported engine sizes of the trucks were 1500 kW, 1900 kW and 2900 kW for surface operations. Komatsu had previously supplied similar Tier 0 engines and could therefore assess the differences between the two Tiers of engines in terms of cost and efficiency. From the study, it was found that a Tier 2 engine was six percent more expensive than a Tier 0 engine. These Tier 2 engines, however, provided more power. With the Tier 2 engines having 875 kW of power compared to the Tier 0 engine with 783 kW. The transition from Tier 0 to Tier 2 diesel engines thus provided a power increase of 92 kW which affects the engine mode of operation and in turn improves fuel consumption (as can be confirmed from Figure 5) (Kholod et al, 2015).

The decrease in fuel consumption for this study, in the Murmansk region of Russia, was measured as an average of twelve percent (varying between 5-15% under different circumstances) when switching from Tier 0 to Tier 2 engines. This significantly improved operating costs for the engine fleet, since it was calculated that the BELAZ 75131 truck consumed 41.5 tons of diesel per month. This truck, with a payload of 130 tons, consumed approximately five hundred tons of fuel a year. This meant that 25 to 75 tons of fuel could be saved yearly per BELAZ truck. The price of fuel in the Murmansk region was US$ 778 per ton without VAT in 2014. The calculated cost saving for the BELAZ 75131 was therefore calculated as a saving of between US$ 20,000 and US$ 58,000 per vehicle per year (Kholod et al, 2015).

Another study done by Environment Canada (Bradley, 2008), suggested that the replacement of a Tier 0 engine with a Tier 2 engine may improve fuel economy by 5 -15% and looking specifically at a Tier 2 Komatsu engine by 4 - 12%, indicating small discrepancies between most engine makes. As such, this study confirmed that a replacement Tier 2 engine consumed less fuel than a Tier 0 [Komatsu] engine.

The technology in Tier 3 engines that adheres to Tier 3 emission standards (not limited to DPM emission levels), increases the fuel consumption between Tier 2 and Tier 3 engines. According to Deutz Dieselpower (2017), a Tier 3 TCD 2015 diesel engine for underground mobile equipment, ranging from 240 kW to 500 kW, has an average fuel consumption of 205 g/kWh. As compared to a Deutz Tier 2 BFM 1015 model engine, ranging from 195 kW to 440 kW, with an average fuel consumption of 207 g/kWh. Comparing the two engine models shows a minimal consumption improvement for a Tier 3 diesel engine. This consumption change between a Tier 2 and Tier 3 is therefore small enough to be neglected, depending on the accuracy requirement of a feasibility study.

Lastly, a study produced by the Patriot Coal Corporation illustrated the repowering of Komatsu 730-E haul trucks from Tier 1 engines to the MTU 4000 Tier 2 engines. The results indicated that the new Tier 2 engine produced 250 more hp (186 kW). The engines were also smaller with only 12 cylinders versus the 16 from the Tier 1. The 2250 horsepower Tier 2 engine then showed 20% improved fuel economy, it lasted 30,000 hours before an engine overhaul was required, and saved up to US$ 50,000 per year in operating costs (MTU, 2012).
It can therefore be concluded that improved fuel economy can be expected from Tier 2 engines as compared to Tier 0 or Tier 1 engines, which ultimately result in the reduction of operating costs. For several types of engines this reduction may off-set the capital cost of introducing new technology engines over a given time period.

10.2.8.4.2 Fuel Cost & Price Forecasting

Accurate calculations and forecasts of fuel prices will play a large role in determining the impact of fuel cost on the feasibility of a transition to reduced DPM emissions. Fuel cost, and a sustainable supply of the required fuel type and quality, will impact the method of transition implemented on a given mine.

10.2.8.4.3 Rebuild & Replacement Requirements

Maintenance of diesel engines, which includes performing the necessary rebuilds at the optimal intervals, can have multiple downstream affects. It is therefore an important factor to keep in mind when DPM reduction methodologies are selected.

Aside from fuel consumption and engine cost, another important factor to consider, when assessing the feasibility of engine replacement is the required after-sale service. This impacts the efficiency of maintenance, maintenance practices put in place, and particularly also performing the necessary engine rebuilds to ensure high engine availability. Good after-sale service ensures that an engine operates within acceptable operating costs and emission levels, until a new engine is financially more favourable (MTU, 2012).

As an engine ages it also produces increased DPM emissions. This is attributed to the combustion efficiency of an engine, which deteriorates over time. This rate of deterioration is further exacerbated by poor maintenance practices. Deterioration factors (DF) are allocated to diesel engine emission limits and determined by engine manufacturers, and are classified as follows (Wattrus et al, 2016):

- DF1 factor of 1;
- DF2 factor of 1.2; and,
- DF3 factor of 1.5.

A DF1 is defined as a new engine. DF2 and DF3 relate to the level of maintenance quality. A DF2 is defined as a well-maintained engine through its operating life and a DF3 defines a poorly maintained engine. If diesel engines are not well maintained, then they will exhibit increased harmful emissions (DPM included). In such an event, improved DPM emissions through diesel engine conversion will be offset through increased emissions from poorly maintained engines. It is therefore important to note what the impact of engine age and poor maintenance is on the quality of the exhaust stream, i.e. emission levels (Wattrus et al, 2016).

10.2.8.4.4 Ventilation Requirements

Decision-makers can, and do, consider international standards on engine certification along with more precise guidelines on mine ventilation recommendations. With South Africa currently lacking an occupational exposure limit (OEL) for DPM, and an approved process to certify engines for use in mines (Perkins, 2005), it is difficult to calculate exact changes in ventilation requirements based on potential changes in DPM emissions. This hinders effective financial evaluations as it impacts the assessment of potential ventilation requirement changes.
The most notable and widely referenced regulations are from the US Department of Labour’s Mine Safety and Health Authority (MSHA) and the Canadian Standards Association (CSA) CAN/CSA M424.2-90. The primary difference between the CSA and MSHA is that the CSA’s certifications include diesel particulate in the equation for calculating ventilation requirements, whereas the MSHA calculates ventilation requirements based on CO, CO$_2$, NO and NO$_2$. The MSHA certifies diesel engines for use in coal, metal and non-metal mines. The certification further includes the recommended ventilation rate, called a particulate index. Diesel particulates are included in the particulate index with the ventilation required to dilute particulate to 1 mg/m$^3$ from undiluted (raw tailpipe) exhaust (Perkins, 2005). This has a large impact on the overall ventilation requirements and increases associated (primarily electrical) costs.

While there may in some cases be various engine certifications available for a single engine model, Perkins (2005) suggested that instead of using only one, decision-makers should use all of them together. The MSHA and CSA provide much more precise ventilation prescriptions for each engine, as opposed to a pass-or-fail standard. When comparing the available ventilation prescriptions for similar size and technology engines, a final decision can be made regarding which would provide the cleaner and best option.

Factors to consider for the analysis of a transition to lower DPM emissions, when making decisions for air-flow requirements in order to determine the impact on an operation’s operating expenses resulting from ventilation, include (Wattrus et al, 2016):

- The type of fuel used;
- The condition of the engines in operation;
- The engine technology in operation;
- The loading cycles that are employed for the diesel equipment;
- The number of engines in operation and their emission output into the working environment to be ventilated;
- The type of exhaust after-treatment technology(ies) employed (if any);
- The impact of other unwanted emissions and gasses from the environment;
- The temperature and humidity of the air, the dry-bulb and wet-bulb effects; and,
- The dilution or mixing of down-stream air and its effects.

In the past ventilation had been the most straightforward method available to control exposure to [potentially] harmful emissions, gasses, and particulates. Yet as mining reaches increasing levels of complication, both in terms of operations and the dynamics of economics, it has become increasingly important to take a multi-faceted approach to solving problems. As such, the effect on ventilation requirements should be calculated in great detail for the needs of each operation or section by taking all the components into account that affect the transition toward reduced DPM exposure. Reduced ventilation requirements, as a result of lower DPM emissions, may significantly lower overall production costs and assist in achieving sustainable operation.

In ventilation intensive mines the ventilation cost can be as much as 40-50% of the electrical power consumed (De Souza, 2015). In South Africa, 20% is often a good estimate for ventilation’s contribution to operating expenses. As such, a reduction in ventilation...
requirements will therefore have a large and positive impact on the feasibility analysis of such an operation.

10.2.8.4.5 Maintenance Requirements

Maintenance of mobile diesel equipment in a mining operation should include a combination of preventive, predictive, planned and reactive activities. This rule of good maintenance is especially applicable to diesel engines. A good diesel emissions management plan will always be built around good engine maintenance applied to every unit within the mine. The role of good maintenance practices in the reduction of diesel particulate exposure cannot be over-emphasised. Fuel injection and air intake systems are particularly important to the control of emissions. However, many factors and components need to be taken into account which makes this a complex topic that falls outside the scope of this report (Perkins, 2005).

When maintenance is not carried out rigorously in an underground mine, then a large deterioration in emission levels can be expected. A comprehensive maintenance plan, based on an engine OEM’s advice, which is verified through routine in-field emission condition monitoring, is a crucial element in ensuring that appropriate underground air quality is maintained (Wattrus et al, 2016).

Failure to ensure that diesel engines and retrofit technologies are optimally maintained will also undo any improvement made through the implementation of retrofit technologies (Wattrus et al, 2016). Furthermore, maintenance practices extend beyond diesel engines and exhaust after-treatment retrofit technologies. It also includes adequate practices for fuel supply chain management and other controls put in place to reduce and manage DPM emissions levels. As such, both the feasibility analysis of a transition to lower DPM emissions and ensuring sustainability of the transition and subsequent program hinges on implementing sustainable and efficient maintenance plans.

10.2.8.5 Timeline and Timing for a Transition

10.2.8.5.1 Engine Life

Engine life refers to the number of operating hours for a specific engine. It provides an indication on how long the engine can remain in operation with confidence before operational issues may increase beyond a certain point of desirability. Engine life is an important factor to consider when evaluating diesel engine replacement and the instalment of retrofit technologies. The number of hours before an engine needs to be replaced is affected by the quality of routine maintenance, which in turn affects the duration between required engine rebuilds. These factors are therefore important, since Stay in Business (SIB) capital may be influenced by the engine life of the operating fleet (Bradley, 2008).

Engine life, and the required replacement of an engine, is primarily influenced by (Darling 2011 and NSW EPA, 2014):

- The amount of economical rebuilds left; and,
- The maintenance cost involved (which typically increases beyond economic desirability after a certain point in the engine’s operating life).

A case study evaluating black carbon emissions in Russia’s Murmansk region also indicated that Tier 2 engines did not only bring reduced levels of DPM emissions, but also had an increased life span. The Cummins QSK19 Tier 2 engine, for example, lasted 30% longer than the corresponding Tier 1 engine (Kholod et al, 2015). Adding to this, the QSK19 Tier 2 engine
also had the same fuel consumption, power, torque, and service intervals as the Tier 1 models (Cummins Inc., 2014).

As an engine ages an increase in emissions can be expected, but it should remain compliant for the duration of the engine’s useful life, to the Tier level emission requirements for which it is approved. According to the US Environmental Protection Agency (EPA), the useful life of a non-road engine with a power rating above 35 kW is 8000 hours or 10 years, whichever occur first (Watrus et al., 2016). This number should be taken in context for the type of equipment that uses the diesel engine, its mode of operation, and maintenance practices implemented. As such, useful engine life between rebuilds can vary, in reality, between 5 000 and 20 000 hours (Von Wielligh, 2018).

A Tier 0/1 to Tier 2 engine rebuild for haul trucks, ranging from 218 to 363 tonnes, should be done every 15 000 to 16 000 hours (Bradley, 2008). With the advances in technology and maintenance, these hours have been pushed up to between 22 000 and 30 000 hours between rebuilds (Von Wielligh, 2018). Table 17 serves to indicate the average engine life for mining diesel equipment as measured on an Australian mine. These averages were shown to be ranging from 2500–8000 hours. These numbers are also in line with the definitions for useful diesel engine life as given by the US EPA (NSW EPA, 2014). Another Australian study based on controlling DPM levels in underground metal mines, situated in Queensland, suggested that the maximum operating hours before a diesel engine requires a rebuild (not replacement) is every 4000 hours (Hedges, 2007).

Table 17: Average life span of diesel engines used in mining (NSW EPA, 2014)

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Engine rating class (kW)</th>
<th>Median life to rebuild (hours)</th>
<th>Useful life (hours)</th>
<th>Hours of operation (h/annum)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction &amp; mining engines</td>
<td>&lt;8</td>
<td>2500</td>
<td>3000</td>
<td>2500</td>
</tr>
<tr>
<td>Construction &amp; mining engines</td>
<td>8 – 19</td>
<td>2500</td>
<td>3000</td>
<td>2500</td>
</tr>
<tr>
<td>Construction &amp; mining engines</td>
<td>19 – 37</td>
<td>2500</td>
<td>5000</td>
<td>2500</td>
</tr>
<tr>
<td>Construction &amp; mining engines</td>
<td>37 – 56</td>
<td>4667</td>
<td>8000</td>
<td>2500</td>
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<tr>
<td>Construction &amp; mining engines</td>
<td>56 – 130</td>
<td>4150</td>
<td>8000</td>
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<tr>
<td>Construction &amp; mining engines</td>
<td>130 – 560</td>
<td>4667</td>
<td>8000</td>
<td>2500</td>
</tr>
<tr>
<td>Construction &amp; mining engines</td>
<td>&gt;560</td>
<td>7000</td>
<td>8000</td>
<td>2500</td>
</tr>
</tbody>
</table>

It should be noted that diesel engines may be in operation for much longer than the suggested time periods. The ranges only serve as a guideline for technical decision-making regarding diesel engine rebuild and replacement requirements (NSW EPA, 2014). Presently South African mines achieve better values, i.e. longer engine life (Von Wielligh, 2018), but it is unclear what the correlation is between this statement and the higher toleration for DPM/DE emissions.
10.2.8.5.2 Timing Engine Replacements and Retrofit Conversions

To provide context on the timeline and timing for engine replacements and retrofit conversions, consider the following:

▪ A case study at Modikwa Platinum Mine in South Africa, stated that a new series of MTU engines were being used in their underground drill rigs, LHD’s and smaller dump trucks. The two MTU 9000 series engines discussed were the MTU 4R 904 model capable of producing 129 kW and the MTU 6R 926 model producing 240 kW. MTU estimated that a diesel engine replacement would take between eight to twenty-four hours to complete and that if the necessary planning was not done in advance, replacement could be delayed for up to two weeks (MTU, 2012). This highlights the need for adequate planning, scheduling and management to ensure optimal outcomes.

▪ Retrofit Tier level conversion for a diesel engine during a rebuild will not noticeably affect the overall duration the truck is out of service. However, replacing the engine will increase the duration that the truck will be out of service by a week or more. This is due to the modifications to be made to the following (Bradley, 2008):
  ▪ Vehicle structure;
  ▪ Wiring harnesses;
  ▪ Engine air intake; and,
  ▪ Cooling systems.

▪ Diesel engines undergo one to two rebuilds over their economic life, after this period maintenance costs are usually higher than for a new engine (Darling, 2011).

▪ Both rebuilding and replacing an engine is something that has to be done during a machine’s operating lifetime. The amount of rebuilds before replacement will be affected by the quality of the maintenance performed on the engine, as well as the mode of operation of the engine. Timing a transition to newer technology engines, or implementing retrofit technologies can therefore be aligned with the required engine replacement cycles. As such, production stoppages can be avoided by taking a phased approach to replacing older technology engines. However, this does not mean that implementing newer technology engines will be feasible and practical as various other factors, as highlighted throughout this report, impact these assessments. Some examples being the amenability of newer technology engines to older equipment or other practical challenges associated with new or different technology engines that may cause equipment downtime.

10.2.8.6 Skill Requirements

Appropriately skilled artisans are essential to supporting effective maintenance practices. It has, however, been identified that the formal qualification alone does not provide sufficient skills development to realise effective maintenance practices. Operations need to determine the gaps to be bridged toward this end, for various soft and technical skills as discussed in Appendix F. To assess the feasibility implication, this upskilling and/or sourcing of the necessary skills should be accounted for in the feasibility model.

While some retrofit technologies may be installed successfully on older engines with low levels of required skills, technical personnel with high skill levels will typically be required to maintain both the equipment and the retrofit technology (Wattrus et al, 2016). It was further identified
that each retrofit / exhaust after-treatment product would require product-specific training on installation and maintenance.

To minimise engine down time and prevent unnecessary costs, a South African mining operation, Modikwa Platinum underground mine, appointed MTU service technicians to be on site for the duration of operations to check and maintain vehicles (MTU, 2012). Engine suppliers incorporate the latest technologies into their new engines to be as efficient, clean and dependable as possible. Some of these OEMs also provide additional services, such as maintenance and other administrative focussed services. An example is the Engine Control Module (ECM) utilised by new diesel engines that produces important engine data. The data is recorded over time and can be used to analyse statistics such as engine life and engine performance. The ECM can also indicate when a service is required and predicts maintenance intervals based on gathered information. The data can be downloaded by service technicians for optimal maintenance planning (MTU, 2012). Working with OEMs not only assists in developing and maintaining efficient maintenance and management practices, but could also assist in bridging skills gaps for doing on-site maintenance as well as for engine rebuilds and replacements.

10.2.8.7 Impact on Health and Safety

While the focus of this project was on reducing DPM emission levels, it should be noted that DPM is not the only harmful emission that results from the use of diesel engines in underground mining operations. Deciding which pollutant requires the highest priority for improved health and safety, between harmful emissions such as DPM, CO, NOₓ, and SO₂, can become a complex decision-making exercise. This decision needs to take multiple factors, as laid out in this report, into account in the associated feasibility analysis. As such, there is no “one size fits all” solution or even necessarily a prioritised pollutant focus as these are most likely site-specific.

The main aim, however, is to reduce potential worker exposure and to improve health and safety for mine workers and also adhere to potential regulations on OELs, which may then decide on which pollutants deserve higher priorities. With DPM being a carcinogen, limiting and controlling emissions to below prescribed levels is a necessity, regardless of financial feasibility for the required transition to an improved state. In this endeavour, the impact of improved health and safety as a result of a transition, as laid out in this report, is difficult to assign criteria to for a feasibility evaluation. Improved health and safety is a factor that outweighs most, or all, other factors in such an equation. Still, balancing the intensity derived from a transition to improved air quality, with the associated requirements of achieving it, is an exercise that will be very specific to each operation.

Previous studies showed a reduced exposure to EC (as a measure of DPM), resulted in a decreased odds ratio for obtaining cancer. A person that is exposed to a cumulative DPM emission level of over 946 µg/m³ per year, over a period of 15 years, is 4 to 6 times more likely to get lung cancer compared to someone who is not exposed to such DPM levels. A Queensland coal mine study showed a DPM reduction from 0.18 mg/m³ (EC) to 0.06 mg/m³ (EC), which translated to a DPM reduction of approximately 66 %. As a result, the odds ratio of developing cancer reduced from 2.11 to 1 (Mans, 2017). Such a positive impact on employee health cannot be measured in financial or other terms.
10.3 Enabling or Supporting Factors Toward the Successful Implementation of the Proposed Guidelines

To implement a feasible program that is designed to achieve reduced DPM emission levels in a sustainable manner, consideration should be given to all aspects that need to be in place to enable the desired transition and that would support the control program. Various factors were identified that affect or even determine the success of a DPM emission control program, i.e. the successful application of the proposed guidelines for DPM Emission Reduction and the supporting Effective Diesel Engine Maintenance. These factors, listed in Table 18, should be carefully considered and the operating environment assessed to identify existing gaps that need to be addressed.

Full discussion on factors is presented in Appendix D.

Table 18: Summary of Enabling/Supporting Factors of the Proposed Guidelines

<table>
<thead>
<tr>
<th>No.</th>
<th>Factor Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Appropriate culture, discipline and change management</td>
<td>Ensure that a culture is instilled that would support a sustainable DPM emission control program, through a change management process. Foster employee discipline that enables good housekeeping practices, maintenance practices, adherence to required high standards of work, and adherence to prescribed practices and procedures.</td>
</tr>
<tr>
<td>B</td>
<td>Appointment of a project champion with the appropriate team</td>
<td>Appoint a project champion to take full responsibility for the successful implementation of a DPM emission control program. This should preferably be a senior, competent, and enthusiastic person.</td>
</tr>
<tr>
<td>C</td>
<td>Appointment of a champion mine</td>
<td>Implementation of the MOSH Leading Practice Adoption System is recommended to identify a champion mine for initial implementation of the proposed guideline, followed by refinements based on key factors learned.</td>
</tr>
<tr>
<td>D</td>
<td>Contamination &amp; quality control</td>
<td>Ensure that efficient management of diesel fuel is in place to reduce (and ultimately eliminate) sources leading to diesel contamination (with dust, water, oil, or other substances). Similarly, ensure the same for other consumables (oils, water) to keep contaminants out of the engine as any contaminating material (from dust grains, water droplets, to larger particles) will have a detrimental effect on engine health and emission levels.</td>
</tr>
<tr>
<td>E</td>
<td>Adhering to required practices and procedures</td>
<td>Ensure that the prescribed practices and procedures, by an accredited or reputable body, is implemented and followed for sampling and monitoring of diesel fuel and exhaust gas analyses (refer to the final report for the SIM 150601 project for prescribed DPM emission testing practices and methodologies), as well as for conducting machine and engine maintenance (refer to the proposed guideline for effective maintenance practices in Section 10.4).</td>
</tr>
<tr>
<td>F</td>
<td>Conduct effective maintenance</td>
<td>It is critical to ensure that the diesel equipment fleet is maintained effectively to allow equipment/engines to operate within OEM specification. Ensuring that this supporting factor is in place will keep DPM emission levels within expected ranges, leading to improved efficiency when planning and implementing control measures. Consider the proposed Guideline on effective engine maintenance in Section 10.4.</td>
</tr>
<tr>
<td>No.</td>
<td>Factor Name</td>
<td>Description</td>
</tr>
<tr>
<td>-----</td>
<td>-----------------------------------------------------------------------------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>G</td>
<td>Machine operation to be within optimal operational envelope</td>
<td>Ensure that engine operate within the specific “operational envelope” for the given engine model. An engine should not idle for extensively long periods, nor should it be overloaded continuously in operation, to reduce negative impacts on engine health and resulting emission levels. Identify the root cause leading to engines not operating within the operational envelope and implement corrective measures (measures may range from addressing soft issues, to performing the necessary engine repairs).</td>
</tr>
</tbody>
</table>
| H   | Knowledge and understanding relating to DPM implications                    | Improve the knowledge and understanding of operators and technicians on the cause-and-effect relationships that impact DPM emission levels. Improve technician knowledge and understanding, e.g. on:  
  - Fault finding, root-cause analysis, cause-and-effect between machine performance and treatment and emission levels  
  - Filtration systems  
  - Cooling systems  
  - Diesel additives  
  - Testing practices  
  - Airflow blockages  
  See Appendix E for substantiating information to enhance the necessary knowledge relating to engine maintenance and health, in support of DPM emission control. |
| I   | Appropriate skills, training and knowledge                                  | Ensure that the necessary skills are in place by training technicians/mechanics appropriately to conduct effective maintenance on the engine models in operation. Technicians need to be suitably qualified through formal qualification, as well as with OEM or mine specific training to address identified gaps in expertise (e.g. with retrofit device installation or maintenance, soft skills / communication, fault-finding, or with computer literacy, etc.). See Appendix F for detail on applicable skills and identified gaps to be addressed. |
| J   | Information provided by the machine operator                               | Implement an effective information feedback system between machine operators and technicians (or the broader maintenance staff). Operators should have sufficient understanding of how to do basic fault analysis, and the means to report on deviations from the baseline standard of engine operation. |
| K   | Collaboration with OEMs                                                     | Collaborate with the OEMs for decision-making on engine replacement and/or after-treatment (retrofitted) solution options and alternatives. Collaborate with the OEMs to ensure that effective maintenance practices are implemented and maintained and that the necessary skills and training are in place. |
| L   | Continuous Testing                                                         | Perform an exhaust gas analysis on any diesel engine that received major work (maintenance, replacement, rebuild, etc.), to ensure compliance to expected emission levels and perform the necessary fault finding if required to repair the engine to specification, before releasing it back into production. |
| M   | Use of Approved Workshops                                                  | Use OEM approved workshops, with appropriately skilled technicians, for engine replacements/refurbishments. Such workshops should support dynamometer tests, exhaust gas analyses, fuel tank and fuel line cleaning, contamination control, and good housekeeping practices. |
10.4 A PROPOSED GUIDELINE: TOWARD EFFECTIVE DIESEL ENGINE MAINTENANCE

10.4.1 Introduction

Similar to the proposed guideline on reducing DPM emission levels, it should be noted that this proposed guideline shares the dependency on enabling and supporting factors that have to be in place to ensure that the guideline may be implemented effectively and sustainably. Of particular importance or relevance are Factor Numbers A, D, E, H, I, J, K, L, M and N from Table 18 in Section 10.3.

10.4.2 Stepwise Approach

The proposed guideline for effective diesel engine maintenance is summarised in Table 19 in a stepwise manner. Each step follows on the previous step in a cyclical manner corresponding to the OEM prescribed maintenance schedules.

Table 19: Proposed Guideline: Effective Diesel Engine Maintenance

<table>
<thead>
<tr>
<th>No.</th>
<th>Step Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Implement OEM Prescribed</td>
<td>The maintenance practices and procedures prescribed by OEMs for their various machine and engine models ensure effective and optimal maintenance and resulting benefits. It is critical to ensure that these practices and procedures are followed and adhered to throughout the life of the machine and/or engine to keep it within or as close as practically possible to operating within OEM specification. Different factors often lead to deviation from these practices and procedures (such as poor discipline, lack of cause-and-effect understanding, lack of required practical knowledge, poor communication, lack of necessary skills, etc.), which is why it is important to ensure that the required enabling and supporting factors are in place.</td>
</tr>
<tr>
<td></td>
<td>Maintenance Practices and Procedures</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Perform Exhaust Gas Analysis</td>
<td>Continuous testing is necessary to determine the state of the diesel engines and identify when an engine is operating outside of OEM specification. Such engines will release unwanted emissions at levels that cannot be accurately anticipated and planned for, rendering a DPM Emission Control Program ineffective.</td>
</tr>
<tr>
<td>3</td>
<td>Repair/Refurbish Engines to Achieve OEM Baseline Specification</td>
<td>Exhaust gas analyses will identify engines operating outside of OEM specification. This may happen in spite of the continued utilisation of OEM prescribed maintenance practices and procedures since various factors impact engine life in harsh underground conditions (mode of operation, excessive heat, poor ventilation, extended idling periods, etc.). Engines that are identified to be operating outside of specification should be repaired/refurbished to again achieve the OEM baseline specification. This will ensure that a known baseline for emission levels (e.g. corresponding to the actual engine Tier level) can be worked with, which is necessary for analysing the gap as per Step 2 of the proposed guideline for reducing DPM emission levels.</td>
</tr>
</tbody>
</table>
10.5 A Proposed Guideline: Toward Reduced DPM Emission Levels

10.5.1 Introduction

This suggested guideline was developed based on the outcomes from the literature research findings, subsequent investigations and testing to date, and from the direct engagements with industry stakeholders over the duration of the project. It is supported through the sharing of practical experience in an attempt to achieve solutions that could be implemented in an effective and sustainable manner. The guideline aims to assist mining operations by providing a practical approach to implementing practical solutions toward reducing DPM emission levels.

10.5.2 Progressive Approach

The guideline aims to provide a progressive approach toward reducing DPM emissions. This approach focuses on first addressing the highest impact focal points that come at the lowest comparative cost, before progressing toward more complex and costly measures for DPM control. Furthermore, the proposed steps also aim to get the necessary requirements in place to ensure a DPM control (emission reduction) program is sustainable.

Depending on what the emission baseline is for a specific operation, it may be that DPM emission levels are sufficiently addressed to reach levels below a given/proposed threshold (or below the proposed upcoming OEL’s), before reaching the final steps of this guideline (i.e. engine retrofit installation or engine replacement). However, it may also be necessary for the majority of, or all, of the steps (shy of implementing diesel alternatives) to take place in order to reduce an operation’s DPM emission levels sufficiently.

These decisions will depend on various factors specific to a given mining operation. These factors will depend on operation-specific scenarios and it is advised that this guideline should be implemented at the discretion of each operation, following the necessary site-specific risk assessments.

The suggested stepwise guideline will also assist in understanding the problem and its severity while working toward obtaining optimal results through the most efficient and feasible approach. The steps in the guideline are summarised in Table 20:

Table 20: Proposed Guideline: DPM Emission Control

<table>
<thead>
<tr>
<th>No.</th>
<th>Step Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Implement Diesel Fuel Supply Chain Management</td>
<td>Ensure that good quality diesel is used within the diesel machines. Poor quality diesel will result in engine failures, higher operating cost, high diesel usage and higher emission levels. Implementing retrofit devices or installing newer technology engines for emission reduction also require good quality diesel. Without the successful implementation of this step, this guideline (or any other similar initiative) will not be able to realise the desired results.</td>
</tr>
<tr>
<td>No.</td>
<td>Step Name</td>
<td>Description</td>
</tr>
<tr>
<td>-----</td>
<td>-----------------------------------------------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>2</td>
<td>Conduct Fleet Assessment &amp; Determine the Gap</td>
<td>In order to identify what controls are required for a DPM emission reduction program, it is crucial to assess the condition of the diesel equipment fleet and the gap that needs to be bridged. This means compiling a complete data sheet of all the diesel machines (i.e. information on machine type, engine make and model, engine hours, Tier level, expected engine life, major overhauls done, time since/to rebuild, total engine replacement date, etc.). Thereafter an individual assessment of each machine should be done (through exhaust gas analyses) to determine the current condition in terms of harmful emission levels. This will allow an operation to define what its existing baseline is for DPM emission levels that will allow the gap to be determined toward the desired emission level status. This identified gap will drive the decision-making in terms of what measures to implement as per the following steps of the guideline.</td>
</tr>
<tr>
<td>3</td>
<td>Repair Engines to achieve OEM Baseline Specification</td>
<td>If the assessment from Step 2 identifies an engine that operates outside of OEM specification, then such an engine should be repaired. This will bring various benefits, namely improved operation, engine life, diesel consumption and improved emission levels. It will also assist with providing a more predictable emission level baseline for the diesel fleet, which will make planning for and control of emission levels more efficient (note this does not only include DPM, but also other harmful emissions). During this process, also clean the fuel tank and fuel lines and check the cooling system and radiator before starting the engine again.</td>
</tr>
<tr>
<td>4</td>
<td>Implement Retrofit Solutions</td>
<td>Once the current diesel fleet and corresponding emission level status has been determined, one of the potential approaches to reducing DPM emissions may be through the installation of emission reducing retrofit systems/solutions. This approach should be assessed on a case-by-case basis since there are various challenges and limitations involved with retrofit installation, as well as potential intensive maintenance and change management requirements. However, when possible, this may provide a worthwhile solution over complete engine replacement as it will be at a lower capital expenditure. Implementing retrofit solutions may also be considered as a temporary solution before engine replacement at a later more feasible and/or practical time (e.g., when the engines are due for replacement at the end of their operating lives). Retrofit solutions may also serve as the ultimate control measure since some of these solutions will provide far greater DPM emission reductions that implementing newer technology engines alone.</td>
</tr>
<tr>
<td>5</td>
<td>Replace Diesel Engine with Lower Emission Technology Engine</td>
<td>Replacing older technology diesel engines with newer technology engines, which adhere to higher Tier/Stage levels for DPM emission regulations, is another solution to reduce DPM emissions. This solution should again be assessed based on site-specific scenarios. It may, for example, prove to be feasible to replace a full fleet's engines to obtain the associated benefits from the newer technology, such as improved diesel consumption etc. However, it may be determined that it would be best to only replace the engines with new engines when the older engines are due for a rebuild, or, when they are due for replacement at the end of the total operating life. OEM consultation is strongly advised to ensure that compatible engine models are chosen for the machines in operation. Configuration and compatibility challenges limit the choice of engine modules.</td>
</tr>
<tr>
<td>6</td>
<td>Implement Other Emission Controls</td>
<td>Various other engineering, management and administrative control measures may also be implemented to either support and add onto other control measures (e.g. solutions from steps 1 to 5), or, to temporarily reduce DPM emission levels prior to, or while, a permanent and sustainable solution(s) is being planned or executed. The most common control measure is through adequate ventilation. Increasing ventilation will dilute DPM emissions, but this comes at a high cost. Administrative controls may be implemented to reduce exposure time, such as managing operator change-over times (removing mid-shift changeovers). Fleet management controls may, for example, include reducing exposure down-stream of diesel equipment.</td>
</tr>
<tr>
<td>No.</td>
<td>Step Name</td>
<td>Description</td>
</tr>
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<td>-----</td>
<td>---------------------------------------------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>7</td>
<td>Implement Other Non-Diesel Alternatives</td>
<td>Ultimately, the best way to reduce and eliminate DPM exposure is to remove diesel engines and use non-diesel alternatives instead. The feasibility assessment of this approach is subject to various impacting factors, both from a financial and practical perspective. Non-diesel (e.g. electric, battery, or gas driven engines) may provide other benefits than merely emission reductions, but they also have their own challenges, limitations and drawbacks. An operation-specific assessment is again advised.</td>
</tr>
</tbody>
</table>

A detailed explanation of the seven steps in the proposed guideline (summarised above) will follow. Additionally, an attempt was made to produce a shorter version of the following explanation in Appendix B. The purpose of Appendix B is to serve as a standalone section that may be printed in a booklet format for easier reference and on-site use. It should be stressed that the champion, i.e. person responsible for implementing a DPM Control Program, would need to understand and have access to the content within this report (particularly also the information in Appendix D and E), in order to effectively implement any recommendations made within Appendix B.
10.5.3 Step 1: Implement Diesel Fuel Supply Chain Management (SCM)

10.5.3.1 Description & Overview of Step

In the context of this guideline, SCM refers to the entire chain from diesel procurement through to usage, i.e. from purchase to transport, storage, handling, monitoring, down to the ultimate dispensing of the diesel into the diesel tank for combustion by the diesel engine in operation. Each of these phases should have adequate quality management practices and procedures in place in order to ensure that the diesel that gets used in operation is of sufficient quality.

In the context of DPM emission control, diesel quality refers to the sulphur content of the diesel as well as the presence of other unwanted substances or particles. Lower sulphur content (in ppm), within the diesel produces lower DPM content in the exhaust emissions from the diesel engine. It is therefore advised to use LSDF with a 50 ppm sulphur content, or where possible and available to use ULSDF with a sulphur content below 50 ppm such as the 10 ppm available in South Africa from Sasol. Other types of diesel are also available that may be assessed for their potential use and potential consequences on emission levels and engine health etc. Figure 6 provides an overview of test results on a Tier 1 engine by Wattrus et al (2016), indicating the percentage DPM emission reduction obtained by only using different diesel types.

![Figure 6: Diesel fuel effect on DPM emission levels (measured % reduction), with 500ppm as the baseline at a 0% reduction (PME = Palm oil Methyl Ester; SME = Soy Methyl Ester; GTL = Sasol GTL fuel) (Mans, 2017).](image)

Based on the above it should be clearly noted that using LSDF/ULSDF, and ensuring that the quality of the diesel used in the engines is indeed as it should be, would already produce a positive impact in reducing DPM emission levels. Switching from 500 ppm to 50 ppm or lower led to roughly 10% reduced DPM emission levels, while the difference between 50 and 10 ppm was found to be negligible for these test conditions. Similarly, other harmful emissions are also reduced when using lower sulphur diesel.

Adding to this, Error! Reference source not found. displays test results from an anonymous mine where a decrease in diesel consumption resulted from the use of a higher quality diesel
fuel (as shown by the indicated ISO cleanliness ratings\(^1\) in the graph). The reason for this stems from the fact that the increase in cleanliness rating results in a decreased number of larger particles in the diesel. Larger particles clog the diesel filters of the machines at a faster rate, while the smaller particles (4-6 micron) lead to injector damage which results in increased diesel consumption due to irregular spray pattern.

![Graph showing L/hr burn rate and quality of diesel fuel over a sample period in 2018 (courtesy SupaFuel)](image)

**Figure 7:** Litre/hour burn rate and quality of diesel fuel over a sample period in 2018 (courtesy SupaFuel)

To monitor and control diesel quality, throughout the supply chain, it is advised that the diesel purchased and used should comply with SANS 342:2006\(^2\) and an ISO Cleanliness rating of 18/13/12\(^3\). Any samples taken throughout the supply chain or through random sampling on the mine should also comply with these standards. If a sample does not comply with these quality criteria then the cause of the contamination should be identified and rectified to eliminate its downstream effects.

Ultimately, however, the diesel in the fuel tank of the diesel machine should meet the quality criteria provided in SANS 342-2016\(^4\). This is not limited only to the bulk tanks but should include the final point of discharge and end-use.

Apart from a direct impact on DPM emission levels and on diesel consumption, implementing effective supply chain management to ensure that the required quality for diesel is maintained will also improve engine health. Common problems that result from poor diesel quality, linked to injector malfunction and a resulting increase in DPM emissions, include:

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1. ISO Cleanliness Rating/Code is used to quantify particulate contamination levels per milliliter of fluid and is expressed in 3 numbers (e.g. 19/17/12), where each number represents a contaminant level code for the correlating particle size. This code includes all particles of the specified size and larger.
2. SANS 342:2006 reference [link](#)
3. ISO Cleanliness Code 4406:1999
4. SANS 342-2016 reference [link](#)
- Water contamination – Water has no lubricity properties. Water in diesel acts as an abrasive substance that damages diesel injectors. Whenever even a micro droplet of water enters the needle passage, the result is cold seizure and scuffing. This scuffing causes the needle to become sticky in its operation, which adversely affects the spray pattern and causes higher DPM emissions in the exhaust. This is often a result from poor filtration at the bulk tank or in the line up to the dispenser. Other causes may include diesel tank lids that are not closed properly, or not put back in place at all, or water entering through the diesel tank vent on the machine when cleaned with a high-pressure cleaning system.

- Contamination of the diesel – Similar to water, other particles (especially fine mineral and silica particles in dust) that enter the diesel will have a damaging effect on the diesel injectors and ultimately cause increased emission levels as well as reduced engine performance and health. Dust particles can however also enter various other parts of an engine (through the air intake or through contaminated oil) if good housekeeping practices (to minimise the probability of dust contamination) are not employed. This could damage the engine in different areas and lead to detrimental consequences in engine health and emission levels. When oil is added to diesel, it causes deposit build-up in the injectors from the additive package within the oil itself.

- Lubricity of the diesel – Poor quality diesel is normally associated with reduced lubricity that increases wear within the engine, leading to reduced engine health and poorer emission levels. Most operations and suppliers do however make use of additives to address this issue (if present).

Implementing effective SCM practices (as shown in Table 21) will reduce the probability of these issues occurring. However, by sampling the diesel directly in the diesel tanks of the machines, as part of the quality assurance within the SCM, the root cause of a problem may be traced back and rectified.

In summary, using good quality diesel, that is also LSDF/ULSDF instead of high Sulphur content diesel, will lead to significant improvements in DPM emission levels, diesel consumption and engine health. Implementing this step successfully is also a requirement in order to implement the subsequent steps of this guideline effectively.

### 10.5.3.2 Potential Challenges and Opportunities

The table below summarises the identified opportunities and challenges associated with this step of the proposed guideline.

<table>
<thead>
<tr>
<th>Potential Challenges</th>
<th>Potential Opportunities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lacking knowledge of diesel quality specifications.</td>
<td>Good quality diesel will likely lead to lower diesel consumption.</td>
</tr>
<tr>
<td>Poor working relationship with diesel supplier(s).</td>
<td>Good quality diesel will potentially lead to lower maintenance cost.</td>
</tr>
<tr>
<td>Management insisting on purchasing lower cost diesel alternatives without performing the necessary quality assessments.</td>
<td>Good quality diesel will potentially lead to increased engine life and a higher machine availability.</td>
</tr>
<tr>
<td>Old infrastructure (diesel tanks, diesel bowsers, pipes and pipelines, utility vehicles, etc.) contaminating the diesel.</td>
<td>Good quality diesel will potentially reduce the risk of a catastrophic engine failure.</td>
</tr>
</tbody>
</table>
Potential Challenges | Potential Opportunities
--- | ---
Lacking training and skills for personnel dispensing the diesel. | Consistently using good quality diesel will have a positive impact on overall operating costs.
Additional skills and training requirements for SCM and quality assurance. | Using lower Sulphur content diesel will reduce DPM emission levels considerably.
Sub-optimal diesel filtration on the diesel machine itself. | Using LSDF/ULSDF allows the use of newer technology engines with higher Tier ratings.
Reduced diesel lubricity leading to increased wear on components. | Using LSDF/ULSDF improves the effectiveness of retrofit emission control technologies.
Potentially higher cost for LSDF/ULSDF from certified providers. | 
Potentially limited and unsustainable supply of ULSD (<15ppm). | 
Potential to get leaking diesel pump seals in older engines when using LSDF/ULSDF. | 
Changes in additive requirements may occur which would add additional costs. | 
Global companies often have contracts in place with service providers in a global context. In terms of diesel suppliers, this may bring challenges for local desired changes in a given product (e.g. switching to 10-ppm diesel but the company has a contract in place with a different diesel supplier for 50-500ppm globally). | 

10.5.3.3 Effective Implementation

The following outlines the suggestions to ensure effective implementation of this step:

- Procure and use only LSDF/ULSDF (50 ppm or lower Sulphur content diesel).
- Purchase diesel from a reputable and certified provider.
- Ensure diesel transport to site is done by a reputable service.
- Leverage on collaborative relationships with the diesel suppliers to ensure that quality diesel is supplied.
- Implement quality management procedures throughout the diesel SCM process to ensure that diesel of the correct quality is dispensed into the diesel tanks.
- Implement quality management procedures to ensure that contamination sources are eliminated and managed. This includes procedures associated with bulk tank filtration, Utility Vehicles (UVs) with clean tanks and correct filtration, clean dispensers, clean diesel tanks on the machines, properly sealing diesel caps, etc.
- Ensure that the necessary training and skills are in place to support effective SCM.
- Ensure that the necessary skills, practices and procedures are in place to perform the required quality assurance.
- Implement a filtration system on key points within the diesel supply chain, e.g. kidney systems (some of the current potential suppliers of filtration systems include Donaldson, iCerMax, Parker Store, SupaFuel, etc.).
- Implement monitoring systems, to monitor for contamination, water content, or diesel specifications as per ISO (ISO Cleanliness Code 4406:1999) and SANS (SANS...
342:2006) standards. This must be supported with the correct procedures governing monitoring.

- Conduct regular maintenance, cleaning (good housekeeping) of storage and dispensing units.
- Assess, choose and use applicable (and prescribed by the OEM) additive solutions/packages.
- Management commitment to quality diesel supply over a pure cost focus.
- Where possible, use only similar diesel types on an engine under all conditions (even if sent off-site).

### 10.5.4 Step 2: Conduct Fleet Assessment & Determine the Gap

#### 10.5.4.1 Description & Overview of Step

Following a successful implementation of SCM and diesel quality assurance, the next steps for DPM emission control should be planned. However, planning can only start when the correct information is available for decisions. Toward this end, it is necessary to complete a gap analysis to identify what action steps to take and to plan the successful execution thereof. This gap refers to the difference between the desired end-goal for DPM emission levels and the current emission levels from individual equipment within the diesel fleet in operation.

It is necessary to perform a full assessment of the diesel fleet as well as an analysis on the emission levels of each individual diesel engine. The outcomes from these assessments will assist with planning the transition toward achieving the desired emission levels, as well as to ensure sustainable emission control. These outcomes will also support effective maintenance practices, which form the required foundation for any sustainable DPM control program. The information required from the fleet assessment should include:

- Machine type, the OEM, and the machine model.
- Engine OEM/make and model.
- Engine and equipment/machine serial number.
- Year of engine manufacture.
- Engine Tier level and expected emission levels as per specifications.
- Current engine operating hours.
- Whether it is the original engine or whether the engine has been repaired/refurbished.
- If the engine has been repaired/refurbished/overhauled, what exactly was done and when (date and how many operating hours ago).
- Time (number of operating hours and expected date) until a required engine rebuild.
- Total expected engine life left (operating hours and expected end of life date) and date of next expected engine replacement.
- Total expected machine life left (operating hours and expected end of life date).
- Measured levels of emissions (in the context of this project, particularly DPM levels).

The information needs to be captured in a live database that is continuously updating the baseline for the fleet and its resulting DPM emission status.
The measurement and monitoring of the DPM emission levels per individual engine should be conducted during regular service intervals (typically every 2-3 weeks) in order to perform engine fault analyses and to ensure that DPM control measures in place are up to date. DPM sampling and monitoring should be done according to prescribed methodologies by an accredited body to ensure that accurate measurements are obtained.

The outcomes from these full assessments, including having determined the existing emission baseline, will then serve the following purposes:

1. Measure engine performance, health and emission levels according to OEM prescribed specifications. This will determine whether an engine is operating outside of specification or not. The machines can then be grouped based on requirements, such as operating within specifications - not in need of attention, in need of minor adjustments, in need of major repair/refurbishment, or in need of engine replacement. This will identify which engines to focus on in order to achieve operation within specification. The primary aim of this is to ensure that DPM emission levels are within the expected ranges for every engine, which will make planning for DPM control more effective.

2. Determine the gap to be bridged toward the desired DPM emission levels. This identified gap should be used for the decision-making in terms of what measures and action steps to implement as per the following steps of the guideline.

10.5.4.2 Potential Challenges and Opportunities

The table below summarises the identified opportunities and challenges associated with this step of the proposed guideline.

Table 22: Step 2 – Conduct Fleet Assessment: Summary of Potential Challenges and Opportunities

<table>
<thead>
<tr>
<th>Potential Challenges</th>
<th>Potential Opportunities</th>
</tr>
</thead>
<tbody>
<tr>
<td>All the required information not being available or difficult to gather.</td>
<td>Assistance from an OEM with required information and procedures.</td>
</tr>
<tr>
<td>Additional costs for regular assessments &amp; emission monitoring.</td>
<td>Rectification of engines to operate within OEM specification may improve engine &amp; machine health and operating life.</td>
</tr>
<tr>
<td>Additional personnel, capable of performing the necessary tasks, may be required.</td>
<td>Rectification of engines to operate within OEM specification may improve diesel consumption.</td>
</tr>
<tr>
<td>Lack of understanding of, or access to, a suitable DPM emission testing methodology.</td>
<td>Proper assessments will allow more effective and accurate targeting and planning for a DPM emission reduction initiative/program.</td>
</tr>
<tr>
<td>Misdiagnosis of engine faults and causes.</td>
<td></td>
</tr>
</tbody>
</table>

10.5.4.3 Effective Implementation

The following outlines the suggestions to ensure effective implementation of this step:

- Follow prescribed procedures or methodologies during the fleet and emission assessments.
- Acquire the support from the OEMs to obtain information on the engine operation and improved understanding of engine operation and impact on emission levels.
10.5.5 Step 3: Repair Engines To Achieve OEM Baseline Specification

10.5.5.1 Description & Overview of Step

Engines that are found, from the outcomes of Step 2, to operate outside of OEM specification (i.e. hard starting, smoking, higher fuel consumption than a similar machine, higher oil consumption, erratic idling, noisy tappets, etc.) should be repaired as required. This step is important for the following reasons:

1. Engines operating outside of OEM specification produce higher emission levels than what should be reasonably expected, based on the engine’s standard. Therefore, having all diesel engines operate within specification will both reduce DPM emission levels (if the baseline was worse than prescribed specification), and will allow more effective planning for emission control based on an accurately determinable fleet baseline.

2. Engines operating outside of OEM specification also have poorer operation, health, diesel consumption and expected operating life. All of these factors contribute not only to an increase in harmful emissions, but also to an increase in operating and maintenance costs. Therefore, having all diesel engines operate within specification will bring financial benefit.

3. Engines operating outside of OEM specification also cause retrofit technologies, such as DPM filters, to block up faster which causes increased maintenance requirements and reduced benefit from such technologies.

For these reasons, it is advised to ensure that the current diesel engines operate within prescribed specification before implementing any of the following steps of this guideline. Once this has been achieved, tests have indicated that the baseline for emission levels in an operation is significantly reduced. This also reduces the gap to be bridged by subsequent action steps in a DPM emission control program, leading to reduced costs for such an initiative as well as improved benefits obtained from the existing diesel fleet.

10.5.5.2 Potential Challenges and Opportunities

The table below summarises the identified opportunities and challenges associated with this step of the proposed guideline.

Table 23: Step 3 – Repair Engines to OEM Specifications: Summary of Potential Challenges and Opportunities

<table>
<thead>
<tr>
<th>Potential Challenges</th>
<th>Potential Opportunities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adequately trained technicians/artisans to correctly diagnose the root cause of excessive emissions.</td>
<td>Rectification of engines to operate within OEM specification may already significantly improve DPM emissions.</td>
</tr>
<tr>
<td>An external company refurbishing/repairing the engines may not have the correct expertise/dynamometer/emission testing equipment etc.</td>
<td>Potential to reduce operating and maintenance costs.</td>
</tr>
<tr>
<td>No service indicators after the inlet filter.</td>
<td>May reduce ventilation demand resulting from lower emission levels, leading to reduced operating cost.</td>
</tr>
<tr>
<td>Poor ventilation at the face may cause overheating of the engine. This causes incomplete combustion, leading to a smoking engine (i.e. higher emission levels).</td>
<td>May provide a better baseline to address in terms of reducing DPM emission levels.</td>
</tr>
</tbody>
</table>
10.5.5.3 Effective Implementation

The following outlines the suggestions to ensure effective implementation of this step:

- To ensure that engines operate at OEM specification for prolonged periods, apply the proposed Guideline for Effective Diesel Engine Maintenance (Section 10.4).
- Ensure that the necessary skills are in place to perform the required repairs optimally.
- Good fault-finding skills are required to identify the root causes that need to be addressed in order to repair an engine effectively and at the lowest cost possible.
- If an external company is used for the engine repairs, ensure that it is reputable and accredited by the OEM as an engine rebuilder (who also has the necessary tools, e.g. dynamometer, emission analysers, etc.)
- Obtain information of reputable suppliers/service providers to assist with this step from other mining operations or from the OEMs.
- Employ the appropriate practices and procedures to ensure that OEM warranties are not jeopardised.
- Start with the worst machines/engines, this will achieve the highest impact on DPM reduction within the shortest time.
- Start on a small scale even if a large number of repairs are necessary to ensure quality work and avoid unnecessary reworks.
- Ensure that the ventilation and temperature at the working face underground is not detrimental to engine/machine health.

10.5.6 Step 4: Implement Retrofit Solutions

10.5.6.1 Description & Overview of Step

One of the solutions to be considered is the implementation of emission reducing retrofit technologies/solutions. There are various retrofit solutions available and an operation is advised to consider all alternatives based on fleet requirements and on the specific DPM emission gap for that operation.

Implementing such a solution may sufficiently reduce DPM levels without performing an engine replacement. The additional implementation, following an engine replacement, of a retrofit solution can further reduce emissions closing the DPM gap that should be addressed. Retrofit solutions require that the engine should be in good operating condition, i.e. operating within OEM specification as advised in Step 3. If this is not true for the engine then the retrofitted solution will block much faster, leading to it losing its efficiency for emission reduction and requiring more intensive and regular maintenance that will influence cost and equipment availability.

Some retrofit solutions are, in general, maintenance intensive. If maintenance is not done effectively, regularly and according to standard this solution may not prove sustainable or cost effective. There are solutions (particularly some DPF’s) that are easy to maintain. An example of a DPF product is from Deutz Diesel Power and this can simply be cleaned by hosing the filter out with water. Cleaning of these retrofit solutions should be done according to prescribed
procedures in order to avoid releasing the captured DPM without proper control measures, causing excessive exposure within another environment.

For DPFs, in particular, there have been major advancement in technology and efficiency over the last few years making this a potentially viable solution. There are challenges associated with the implementation of after treatment / retrofitted technology to consider, such as compatibility with the machine or engine and with worker adoption. Cases have been noted by stakeholders where operators remove retrofitted devices (such as a filter) during operation and then replace it at the end of the shift.

One of tests performed indicated a drastic reduction in DPM emissions when an Exhaust After-Treatment (EAT) solution was installed/retrofitted onto a Tier 2 diesel engine on a dynamometer (Deutz Diesel Power, 2018). The results, shown in Error! Reference source not found., indicated that extremely low DPM emissions exited the retrofitted system on the exhaust for both idling and loaded conditions. Note that these results were obtained on the reduced emission levels from a Tier 2 engine, meaning that the EAT solution provided a far superior emission reduction over that obtained from merely implementing the newer technology engine alone.
10.5.6.2 Potential Challenges and Opportunities

The table below summarises the identified opportunities and challenges associated with this step of the proposed guideline.

**Table 24: Step 4 – Implement Retrofit Solutions: Summary of Potential Challenges and Opportunities**

<table>
<thead>
<tr>
<th>Potential Challenges</th>
<th>Potential Opportunities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Additional capital cost required.</td>
<td>After treatment (retrofitted) solutions on the exhaust reduce or even completely capture the excessive smoke/soot released upon engine startup.</td>
</tr>
<tr>
<td>Many, especially the older, equipment/machines have limited engine space that may not allow installation of a retrofit solution.</td>
<td>Some retrofit (after treatment) systems/solutions are easy to maintain.</td>
</tr>
<tr>
<td>Engines with a mechanical diesel pump will only have a warning indicator if the DPM backpressure rises to the maximum limit. This makes it challenging to determine whether maintenance (e.g. filter cleaning) is due without a physical inspection.</td>
<td>Potential for major DPM emission reduction if used and maintained properly.</td>
</tr>
<tr>
<td>Electronically controlled fuel systems can cut the engine if the retrofit technology is not operating as per design, e.g. if the DPF is blocked.</td>
<td>Potential alternative to engine replacement.</td>
</tr>
<tr>
<td>Expertise to evaluate and select optimal products/solutions may be lacking.</td>
<td></td>
</tr>
<tr>
<td>The skills to install retrofit solutions, especially on a large scale, may be lacking.</td>
<td></td>
</tr>
<tr>
<td>Managing the backpressure of DPFs by the operators/technicians may be difficult.</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 8:** Testing under idle and load conditions on the impact of an EAT solution on DPM emission levels (courtesy Deutz Diesel Power, 2018)
### Potential Challenges

<table>
<thead>
<tr>
<th>Potential Challenges</th>
<th>Potential Opportunities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ensuring that the appropriate maintenance/cleaning takes place may prove difficult, which would greatly hinder effectiveness.</td>
<td>Some retrofit (after treatment) systems/solutions are maintenance intensive (i.e. costly and impacting on equipment availability).</td>
</tr>
<tr>
<td>Requires that the engine operate within OEM specification for optimal functionality.</td>
<td></td>
</tr>
<tr>
<td>Worker adoption/acceptance and deliberate sabotage or removal.</td>
<td></td>
</tr>
<tr>
<td>Large-scale supply of specific retrofit /after-treatment systems may be difficult.</td>
<td></td>
</tr>
<tr>
<td>Often requires that an engine first be repaired before installation can take place.</td>
<td></td>
</tr>
</tbody>
</table>

### 10.5.6.3 Effective Implementation

The following outlines the suggestions to ensure effective implementation of this step:

- Perform retrofit evaluation and selection in collaboration with experts and/or with the machine and engine OEM.
- Ensure the correct maintenance practices and procedures are in place and being followed.
- Evaluate the cost vs. benefit of implementing retrofit solutions as opposed to, as well as in addition to, the replacement of engines with newer technology engines.
- Implement solutions on a small scale at first to trial implementations in terms of impact and sustainability as well as to develop the necessary skills and manage change as required.
- Plan the implementation of this step carefully in collaboration with the OEM(s).
- Ensure the operators understand how the technology works and what it is for.
- Ensure regular discussions with both operators and technicians take place to identify issues that may hinder the effective and sustainable adoption of a retrofit technology.
- It is advised to only implement this step if Steps 1 to 3 have been implemented successfully.

### 10.5.7 Step 5: Replace Diesel Engines with Lower Emission Technology Engines

### 10.5.7.1 Description & Overview of Step

Another approach to reducing DPM emission levels is to replace older technology engines (particularly Tier 0 or Tier 1 rating) with newer technology engines that adhere to Tier 2 or higher emission standards. Higher Tier rated engines have a lower baseline for emission levels. This will significantly reduce the emission baseline and require a much smaller gap to be bridged through other control measures.
It is important to note that Tier 2 and Tier 3 standards provide for the same DPM emission limits, while Tier 3 engines also provide reduced levels for other harmful emissions. Some OEMs promote their Tier 2 engines while other OEMs instead promote their Tier 3 engines for implementation. Tier 4 engines are often not promoted in the South African mining industry since the diesel used in operation is often too low quality for these engines to use. However, if Tier 4 engines are used it is important to ensure that Step 1 of this guideline is followed as deviations will result in even more severe consequences. Operations should also make use of the additional additive, as prescribed by the OEM, for the internal cleaning of injectors and high-pressure pumps. The cleaning additive removes the IDID that develop in these engines.

Some engines (depending on brand and model) can only be replaced by certain other model engines, leading to restricted “choice” in terms of Tier ratings or engine models. For example, newer engines may not be amenable to older equipment due to space and configuration limitations. Unintelligent/non-electronic equipment are particularly difficult to replace with new electronically controlled engines due to the absence of electrical harnessing, space for the ECM or space for the exhaust filtration system for higher Tier engines. Replacing intelligent (electronically controlled) engines with other (newer) intelligent engines can also be difficult since the entire harnessing and ECM should be replaced as well to ensure compatibility with the machine.

On some of the older machines, often only a Tier 2 engine can be used to replace a Tier 0 or Tier 1 engine. On newer machines, it may be possible to replace older engines with a Tier 3 engine, if there is sufficient space for the exhaust filtration system as well as the required ECM and electrical harnessing. A Tier 3 engine supplied without an exhaust filtration system may then require a retrofit EAT system.

As such, it is critically important for an operation to communicate and collaborate closely with their preferred service providers (OEMs) in order to conduct a thorough assessment of which option(s) would be best suited for specific equipment and the required emission outcome.

Newer technology engines do not necessarily provide increased machine availability due to the engines being more sophisticated, electronic, and in need of higher levels of maintenance. Machine availability is a function of the effectiveness of the maintenance regime. Maintenance intensity and requirements in turn also differ between engine types and models (also age). As such, a statement cannot be made on the relationship between older and newer technology engines without considering the levels of maintenance required. It can be concluded that if effective maintenance practices are in place, then the assessment of newer engines should not be penalised on the basis of potentially lower availability.

Replacing older engines with newer engines requires careful evaluation. There are various factors and constraints related to machine and engine compatibility that requires consideration. On older machines with mechanical engines the required electronics (wiring and control modules etc.) are not in place and they have to be installed along with a newer technology engine, making it more complex and difficult to ensure suitability to the machine (assuming sufficient space is available for installation). On newer machines with electronically managed engines, there may be compatibility challenges due to machines and engines not being manufactured to ensure compatibility. Different electronics and software often mean that replacing engines is not a plug-and-play solution.
10.5.7.2 Potential Challenges and Opportunities

The table below summarises the identified opportunities and challenges associated with this step of the proposed guideline.

Table 25: Step 5 – Replace Engines: Summary of Potential Challenges and Opportunities

<table>
<thead>
<tr>
<th>Potential Challenges</th>
<th>Potential Opportunities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Older equipment may not be amenable to have new technology engines installed within</td>
<td>Reduced ventilation requirements resulting from reduced emission and heat outputs.</td>
</tr>
<tr>
<td>them due to compatibility and/or space issues.</td>
<td></td>
</tr>
<tr>
<td>Newer technology engines may experience operational interruptions (increased</td>
<td>Reduced diesel consumption from newer engines.</td>
</tr>
<tr>
<td>maintenance, breakdowns, reduced availability, total failures, etc.) if good quality</td>
<td></td>
</tr>
<tr>
<td>diesel is not used to fuel them.</td>
<td></td>
</tr>
<tr>
<td>Older equipment with mechanical engines, may require a total machine upgrade</td>
<td>Reduced requirements for emission controls and a smaller gap to bridge through these</td>
</tr>
<tr>
<td>including engine control modules and electrical harnesses etc.</td>
<td>control measures.</td>
</tr>
<tr>
<td>It may be necessary in some cases to do an engine replacement underground, which has</td>
<td>Renewed engine-operating life.</td>
</tr>
<tr>
<td>potential challenges with logistics.</td>
<td></td>
</tr>
<tr>
<td>It may be necessary for some machines to have their engines rebuild at the OEM's</td>
<td>Developing a replacement kit to take to a mining operation for onsite replacements is</td>
</tr>
<tr>
<td>site, which will have logistical challenges and production impacts.</td>
<td>possible.</td>
</tr>
<tr>
<td>OEMs need to plan and develop capacity if large-scale engine replacements are</td>
<td></td>
</tr>
<tr>
<td>required, leading to potential time constraints.</td>
<td></td>
</tr>
<tr>
<td>It is often more difficult to replace one electronically controlled engine (newer</td>
<td></td>
</tr>
<tr>
<td>technology engine) with another due to incompatibility between electronics and</td>
<td></td>
</tr>
<tr>
<td>software.</td>
<td></td>
</tr>
<tr>
<td>Engine replacement sometimes causes machines or engines to operate outside of</td>
<td></td>
</tr>
<tr>
<td>specification.</td>
<td></td>
</tr>
<tr>
<td>High capital outlay required.</td>
<td></td>
</tr>
</tbody>
</table>

10.5.7.3 Effective Implementation

The following outlines the suggestions to ensure effective implementation of this step:

- Decision-making should be based on cost benefit analysis to quantify financial benefits. Key factors to consider during such an analysis are the life of mine, operating life left of the fleet and of each of the engines, impact on operating costs, additional supporting requirements, the cost of alternative solutions vs. their impact and whether they can sustainably be maintained, etc.

- Do not replace engines unless required and based on the individual machine/equipment gap analysis. Various other DPM control measures (as explained within this guideline) need to be considered as part of the final solution. However, it
should be clearly understood whether an alternative measure is a short-term solution or a sustainable solution. Non-sustainable solutions require replacement with sustainable solutions as per the measures proposed in this guideline.

- Plan to replace engines when they are due for a replacement or when an engine is due for a rebuild/refurbishment that is in line with the engine’s operating lifecycle.

- Consider total equipment life and replacement of the equipment instead of an engine replacement (when feasible).

- Evaluate the new engine and existing equipment compatibility. Obtain advice and recommendations from the OEM(s).

- In particular, consider the match of the engine output to the vehicle load requirements. Diesel engines perform at their best efficiency and lowest emissions when they operate between the peak power and torque band (i.e. within the operational window as prescribed by the OEM).

- Evaluate the supplier (engine OEM) and ensure that credible suppliers are used with good after sales services.

- Assess the commercial availability of the engine and sustainability of parts supply.

- Evaluate the maintenance and rebuild costs and requirements of a new engine.

- Evaluate the necessary skills or upskilling requirements for a new engine.

- Consider the life of project and cost for a transition to newer engines within a fleet or portion of a fleet.

- Assess the impact on health and safety that will result from engine replacement.

- Evaluate potential resale options for equipment and engines (the old and the new in terms of replacement schedule).

- Collaborate closely with the OEMs to ensure that replacement, especially on a large scale, is planned and executed effectively.

- Consider which OEMs to engage with for a replacement process. Often it is best to engage with the OEMs of the equipment for which the engine should be replaced, since they work in close collaboration with the engine OEM of their choice.

- It is advised to only implement this step if Steps 1 to 3 have been implemented successfully.

**10.5.8 Step 6: Implement Other Emission Controls**

10.5.8.1 Description & Overview of Step

Apart from the control measures discussed above, there are alternative mitigation measures that can be implemented prior to embarking on the chosen optimal DPM emission control program. These mitigation measures should be considered through the various levels of risk controls specific to the operation. In most cases, these controls are a means of mitigating the effects from DPM exposure and ultimately another more sufficient and sustainable control method should be put in place. However, even after successful implementation of a DPM control program, these mitigation measures may still be employed to support good practice for improved air quality.
Over the past 15 years, considerable research has taken place to develop suitable control technologies, especially for vehicles operating in confined areas (e.g. underground mining). Proven control technologies and practices, apart from what has already been covered, further include (CoM, 2012; Perkins, 2005; Mans, 2017; and, OHSA, 2012):

- Effective and efficiently designed and planned ventilation;
- Real-time ventilation flow adjustment systems (connected to real-time monitoring sensors);
- Air conditioned (filtered) operators’ cabins to reduce operator emission exposure;
- Operating practices and fleet management / dispatch;
- Driver and workforce education;
- Sufficient employee and operator training and awareness;
- Positioning workers in upstream ventilated environments where possible;
- Using effective DPM monitoring (what gets measured gets done);
- Gradually implementing/transitioning to non-diesel equipment;
- Personal protective equipment; and,
- Focussed management and administrative practices. Examples include:
  - Limiting vehicle speeds (Note that for speed limitations it is not advisable to attain this through the prevention of higher gear usage. The practice of forcing equipment to only operate in lower gears causes the engine to operate at excessive engine speeds, which increases engine wear as well as DPM emission output. Speed control is best done electronically);
  - Constraining vehicle idling time; and,
  - Controlling the number of vehicles operating in an underground area through efficient scheduling activities.

10.5.9 Step 7: Implement Other Non-Diesel Alternatives

10.5.9.1 Description & Overview of Step

Investigating non-diesel alternatives (electrical-, battery, gas-powered, hybrids, etc.) fell outside the scope of this project. However, some of these alternatives may provide a beneficial solution in terms of harmful emission reduction as well as lower equipment-based operating costs. Such alternatives have to be considered on a case-by-case basis as the criteria for evaluation and selection depends on the specific needs of an individual operation.

From the engagements with the OEMs, it was found that the majority believe that electric or battery-electric equipment/machines are the future. It is the opinion of the authors that such equipment should require consideration through careful evaluation. Studies done by the OEMs indicated that electric/battery equipment will not only eliminate the current harmful emissions from diesel engines, but will also result in a material reduction in ventilation and cooling requirements which make up a large component of operating costs especially in deep level operations (Reynders, 2018). Electrically driven equipment is also likely to be far less maintenance intensive and have a lower probability of breakdown. Maintenance requirements will, however, differ with more intensive and higher-level skills being required.
A feasibility analysis is advised on electric/battery vehicles to determine the viability of implementation as compared to alternatives. Factors to consider include, but are not limited to:

- The current timelines and lifecycles of existing diesel fleets;
- The alternative DPM control program and the costs and implementation lifecycle(s) thereof; and,
- Potential technology implementation constraints.
10.6 Local Capacity Analysis

Local capacity was analysed for the following three aspects:

- Convert/replace lower tier diesel engines with higher tier diesel engines;
- Locally manufacture DPM-reducing retrofit/after-treatment components; and
- Supply low sulphur (50ppm) and ultra-low sulphur (10ppm) diesel fuel to mines.

Throughout the course of this study, the above topics were partially addressed/answered, or key aspects relating to the local capacity to perform these activities were discussed. For the local capacity analysis, further stakeholder engagements were conducted with six more of the local original equipment manufacturers (OEM), engine manufacturers and retrofit/after-treatment component manufacturers. Due to the sensitivity and subjectivity (in some cases) of the information obtained, the names of the consulted stakeholders are not included in this report.

The engagements with the stakeholders were guided by eight predetermined questions that assisted the team in determining whether local capacity exists in South Africa (or could exist in the near future). The questions posed to the stakeholders can be seen in Appendix C.

It is important to note that although the engagement sessions with the stakeholders were based on the eight questions, they were not constrained to them. Furthermore, these engagements were in addition to earlier stakeholder engagements, done over the duration of the project. These additional engagements were done to close any potential remaining information gaps.

The results of the additional stakeholder engagements, as well as the learnings from previous engagements are summarised in bullet points under the following local capacity analysis subsections:

1. Engine Replacement/Conversion;
2. Retrofit/After-Treatment Components; and,
3. Low Sulphur Diesel Fuel.

10.6.1 Engine Replacement/Conversion

- It was found that generally, either the OEM is responsible for maintenance on the equipment and the engine, or skilled artisans/mechanics on the mine are responsible (trained, in most cases, by the OEM and/or the engine manufacturer).

- In terms of replacing or converting an engine, vehicle OEMs would perform and take responsibility for the replacement/conversion. Quality checks from the engine manufacturers could then be performed after the OEM has done the replacement/conversion.

- All of the OEMs indicated that they have the capacity and would be able to satisfy the demand, as long as the approach is synchronised to the normal engine lifecycle (e.g. instead of overhauling or rebuilding an engine, it is replaced with a newer one).

- In terms of the required skills, the OEMs indicated that they train the majority of their skilled artisans and mechanics to the required skill levels themselves (if the persons are not already at that level) and would be able to adequately ramp up this capacity if the demand for it was there.
All of the OEMs engaged indicated that they would be willing to offer value propositions with detailed engine replacement/conversion strategies to their clients if required.

The engine manufacturers indicated that they would be able to supply the engines in the required quantities, as long as the demand is satisfied over time, and not all at once. If planned properly, it would be possible to satisfy the demand but over a planned ramp-up period.

It is important to note that none of the equipment OEMs or engine manufacturers were of the opinion that replacement/conversions of old Tier 0/1 engines with newer Tier 3 (or Tier 4) is the best strategy or solution to reduce DPM emissions. In fact, the resounding feedback was that it would, in many cases, introduce great unnecessary complexity going forward (in terms of operating and maintaining the machines after the replacements/conversions), and that other approaches exist that would better address the DPM emission issue.

Replacement or conversion may not be practically possible in certain cases, due to space and configuration mismatches. Determining whether replacements/conversion will be practically possible will have to be done on a case by case (or engine by engine) basis.

One of the OEMs noted that their existing systems/machines fitted with Tier 2 engines are air-cooled. Tier 3 requires a water-cooled solution, which would make the replacement/upgrade more complex. The Tier 3 water-cooled engine that the specific OEM uses is much cheaper than the Tier 2 air-cooled engines however, the OEM believes that the conversion would be more expensive and cancel out any financial benefits associated with the cheaper initial engine cost.

The challenge of space within the machine was re-iterated by all of the stakeholders that were engaged with.

One of the OEMs noted that a key challenge/consideration in replacing old engines with new ones is the aftermarket service providers. These service providers can still supply Tier 0 repairs, parts, engines and services, which means that they can still keep old engines “alive” for those mining companies and individual mines who cannot afford a replacement/conversion. These service providers would thus be made obsolete through forced replacements and/or conversions.

One of the engine manufacturers pointed out that in terms of design, generally the equipment is designed to be fit-for-purpose for a specific engine. To change the engine means that the machine will be sub-optimal somewhere else. Thus, a machine that was designed for a higher Tier engine will always perform better than a machine that has been converted or upgraded.

From the questions that were posed to the stakeholders during the engagements, as well as the work done in during this project, it was deduced that the capacity to perform engine replacements and/or conversions of engines would be feasible if the following conditions are met:

- The demand for the replacements and/or conversions exists and the value proposition by the OEMs and engine manufacturers are financially viable for them;
The engine replacement and/or conversion is technically and practically possible; and

- The replacements and/or conversions are scheduled to align with the normal engine lifecycle.

None of the OEMs or engine manufacturers indicated that skills (or a lack thereof) to do the replacements and/or conversions would be a challenge. However, the general consensus was that the issue would come in after the replacements/conversions, where they believed that a lack of skills could lead to sub-par maintenance on the new non-mechanical engines (and increased complexities due to conversions).

### 10.6.2 Retrofit/After-Treatment Components

- Retrofit/after-treatment systems can be very costly. One of the diesel engine manufacturers noted that in their experience, after-treatment systems can cost up to two thirds of the price of a brand new engine. Further to this, one of the DPF manufacturers noted that the single biggest reason for them not “closing” a sale was the cost of their filters.

- One of the retrofit manufacturers (specifically a manufacturer of DPFs) noted that it is important to consider the lifecycle of disposable material-based DPFs (for soft rock applications) – they need to be disposed of once they reach the end of their rated lifetimes. This needs to be done through incineration, which means that they need to be removed from the direct mining environment and incinerated elsewhere. The same retrofit manufacturer noted that with their regenerative DPFs (for hard rock applications), the filters also need to be taken out of the direct mining environment to be regenerated at certain intervals. In both cases, infrastructure for regeneration or incineration would need to be established at the mine to serve this purpose, or the manufacturer would have to address the need through some type of other value-offering.

- Maintenance of the retrofit/after-treatment systems is critical. One of the engine manufacturers noted that in their experience, the adequate cleaning of DPFs is a major issue. They mentioned numerous case studies where this issue led to filters being removed on machines at the start of a shift, and then put back at the end of the shift (in order to avoid the tedious task of cleaning the filter).

- One of the engine manufacturers stated that in their experience through using a number of retrofit/after-treatment systems, that they do not always work as well as they should in practice – and that a relatively large discrepancy exists between theoretical performance and actual performance.

- Retrofit/after-treatment systems introduce more complexity. One of the engine manufacturers noted that the more after treatment and retrofit parts are added on to an engine/machine, the more complexity gets introduced into the system.

- One of the engine manufacturers noted that their Tier 3 engines require fuel of less than 50ppm for retrofits/after-treatment systems to function properly. Another engine manufacturer quoted a theoretically ideal figure of 15ppm for after treatment to function properly, as well as a low ash content in the fuel. In essence, these engine manufacturers believed that after treatment is only really applicable for ULSD, where
close attention needs to be paid to the correct oil being used and the correct oil change intervals being adhered to.

- One of the engine manufacturers noted that the maximum exhaust pipe pressure of a machine is critical to understand in terms of selecting, installing and maintaining retrofit products, and if it is not monitored and addressed accordingly, an engine could be lost.

- Effectiveness decreases with age. One of the engine manufacturers noted that in their experience, DPFs effectiveness decrease constantly with age, and requires an increase in maintenance intensity and shorter intervals. If not maintained properly, a DPF can have substantial negative impacts on the engine itself. This specific engine manufacturer stated that they may not extend warranties if certain after-treatment products are used.

- The retrofit/after-treatment companies that were consulted during the stakeholder engagements indicated that they currently import all of their products and do not manufacture in South Africa. They were, however, of the belief that they would be able to satisfy the potential demand through their international import capacity. It must be noted that this view was expressed by the consulted companies and this may not necessarily be the case for the entire retrofit/after-treatment industry. It is currently difficult to estimate the exact scope of the potential retrofit industry since there are still various technologies and solutions that are emerging and no dominant design(s) have been established that will shape the industry’s focus and direction.

- One of the DPF manufacturers noted that they currently manufacture their material filters for soft rock applications overseas, and import them for use in South Africa. In terms of their regenerative filters for hard rock applications the same would apply, but they noted that they currently do not sell these to any South African mines due to a complete lack of demand. The manufacturer indicated that they would be willing to gear up to manufacture the material filters locally if the demand was there. In the case of the regenerative filters, the South African representatives of the company were unsure whether this would be possible.

- Similar future intent was displayed by one of the OEMs and one of the engine manufacturers that was consulted. As with the DPF manufacturing company, the OEMs indicated that they currently import any required retrofit components, but that they may be willing to invest in a local retrofit manufacturing company if the demand is there. The specific engine manufacturer indicated that they may also be interested in manufacturing DPFs if the business opportunity existed.

- In terms of the first aspect of the local capacity analysis, the answer is no – currently there is not sufficient local capacity to manufacture the retrofit/after-treatment components and systems in South Africa. With that said, it appears that the intent is there to create local capacity, on the condition that a tangible and viable business case exists for those investing effort and resources into establishing the capacity.

- The second aspect of whether capacity exists to properly install the components and systems is largely dependent on the first aspect. In a situation where a machine is retrofitted with, for example, a DPF, it is the OEM that will take responsibility for this installation (and supported by the engine manufacturer, as was the case with the engine replacements and/or conversions). When asked during engagements whether they would be able to procure/develop the skills to perform these retrofits, the OEMs
indicated with confidence that they would be able to upskill their employees/representatives to perform the installations adequately. The engine manufacturers indicated that if the demand for retrofit/after-treatment was created, they would work closely with the OEMs and retrofit component manufacturers to ensure that installations were done adequately and that engine warranties would then still be valid.

In summary, the local capacity to manufacture, supply and install retrofit/after-treatment components and systems does not currently exist. However, if regulations and/or favourable market conditions create tangible business opportunities, the local capacity could be developed.

10.6.3 Low Sulphur Diesel Fuel

- The issue of cost was re-iterated by all stakeholders that were engaged with specifically on this topic – they believed that this would be the largest reason for resistance against ULSD or LSD by the mines. Taking into account the relatively small potential reduction in DPM emissions and trading it off against the challenges and difficulties associated with the switch to LSD or ULSD, this specific DPM-reducing intervention appears to present more disadvantages than advantages.

- Discussions with Total SA and Sasol showed that the above sentiment is shared. They indicated that although LSD and ULSD would provide benefits as far as exhaust pollution is concerned, the availability (of ULSD) and cost (of both) would presently be a large problem.

- In terms of the local capacity of fuel manufacturers to supply all mines with LSD and/or ULSD, the fuel manufacturers agree that the South African fuel industry as a whole has the capacity to supply all mines with 50ppm LSD, but not 10ppm ULSD. This view was shared by all of the OEMs and diesel engine manufacturers that were engaged with during the stakeholder engagements.

- The reason for the inability to supply 10ppm ULSD comes down to demand and supply – the current demand is such that it does not justify investments from these companies into additional manufacturing infrastructure that would allow them to increase their supply. In theory, if a business case exists where it would be financially viable for these companies to pursue the route of increasing the supply of 10ppm ULSD to satisfy a demand from the mines, it could be possible.

- However, the main intent of this project needs to be remembered – reducing DPM emissions. The local capacity is there to supply all mines with 50ppm LSD. The differences in DPM reductions between using 10ppm ULSD and 50ppm LSD are limited. Thus, from the perspective of reducing DPM emissions, there is no need to increase local supply capacity for 10ppm ULSD when the capacity for 50ppm exists.
11 MILESTONE CONCLUSIONS

From the results contained within this report and the knowledge obtained throughout the duration of the project, the following can be concluded:

11.1 DPM EMISSION CONTROL

- The proposed DPM Emission Control Guideline (Section 10.5) aims to provide practical solutions to reducing DPM emission levels.
- The guideline takes the financial constraints of the mining industry into account and attempts to provide a means that would not exacerbate this constraint.
- To achieve the objective of lower exhaust emissions, a progressive stepwise approach was developed that starts with the lowest cost vs. highest impact solutions and mitigation measures.
- This progressive approach recommends that Steps 1 to 3 (from Section 10.5) be implemented prior to implementing the subsequent steps. This involves implementing diesel fuel supply chain management (Step 1), to ensure that sufficient quality diesel is used in the equipment; conducting a fleet assessment (Step 2), to determine the DPM emission gap to address and which equipment require repairs; and repairing the equipment to achieve OEM specification (Step 3), to ensure that engines operate according to expectations.
- Operations have been identified that already employ the proposed engine management approach (Step 3), through the conducting of exhaust gas analysis to identify engine faults. It was stated that these operations benefit from improved engine availability as well as reduced emission levels from this practice alone.
- Experience has shown that no one single solution exists. Therefore, individual mines need to explore which of the control measures and other solutions, listed in Steps 4 to 7, best fit their circumstances and in what combination.
- Combining control measures from Step 4 to 7 should be assessed on the needs of an individual operation, based on the outcomes from Step 2’s gap analysis.
- The implementation of a given, or combination of, DPM emission (or exposure) control methods have multiple possible challenges and opportunities that have to be considered before implementation is attempted.
- This report highlighted a number of these opportunities and challenges that are associated with the various control methods discussed (steps within the guideline). These factors should be considered for a feasibility analysis when evaluating the optimal way to approach a transition toward reduced DPM exposure in underground mining.
- Since the primary focus for the scope of this study was engine replacement and retrofitting of exhaust after-treatment technologies, it should be noted that both of these options have limitations in terms of spatial and/or technological compatibility with existing diesel machines.
- Retrofit technologies may greatly assist in reducing DPM exposure (provided that they are properly maintained), however, it may not be practically possible to implement such technologies on the diesel equipment used in mining due to space and configuration limitations. This is particularly the case for narrow-reef operations where low and ultra-low-
profile equipment have size and space limitations that may not allow the installation of such technologies.

- Implementing retrofit technologies requires the introduction of adequate maintenance practices to ensure successful and sustained DPM control.

- The deterioration of diesel engines, as a result of aging and poor maintenance, also has a significant impact on the applicable fresh air dilution rate requirements as a result of increased emissions. This highlights a necessity for adequate maintenance of diesel equipment and engines in general. Good maintenance is also fundamental for the sustained control of DPM emissions and associated exposure.

- Careful and consistent assessment is needed of a diesel fleet’s performance through regular, repeatable and representative testing on site, to determine the real levels of DPM emissions and the real impact of implemented controls. Over time, these controls and other practices can be fine-tuned for improved results, such as more precisely designed ventilation strategies and dilution quantities.

- Furthermore, the concentration of emissions from an engine that exhausts DPM significantly above acceptable levels, requires high levels of fresh air dilution and precludes the reuse of air.

- Other opportunities were identified to support reduced DPM emission levels. The first being that using low sulphur diesel (LSD) or ultra-low sulphur diesel (ULSD) fuels can produce an immediate DPM emission reduction.

- The use of LSD / ULSD fuels promotes cleaner engine exhaust, both in terms of gasses and particles, and allows the use of catalysts in exhaust after-treatment technologies/systems that in turn reduce exhaust gas concentration.

- LSD is also an OEM requirement for most retrofit technologies and also for the newer technology diesel engines being implemented.

- Using LSD / ULSD is, however, not limited by engine technology or Tier rating. As such, any diesel engine can use these fuels to achieve immediate (although often insufficient) improved DPM levels.

- One of the primary challenges with using appropriate fuels (LSD/ULSD) is getting the correct fuel quality into operation. A number of challenges were highlighted starting from the supply chain, to the storage, discharge and use of diesel that contaminates the fuel and eventually leads to poor quality being used that causes excessive emission levels.

- Various other engineering, management and administrative controls can be implemented to assist in reducing DPM exposure. These control methods are complementary to the primary controls discussed in this report.

- Although gas emissions may require low fresh air dilution rates, the continual operation of equipment in intake airways and the direction of travel with respect to airflow direction may result in higher gas and particulate contamination at section entries. This has to be accounted for to ensure adequate air quality within the section itself.

- Reducing DPM emissions also brings a substantial opportunity to reduce overall airflow requirements as well as the potential reduction in cooling and refrigeration requirements in hot mines (diesel engines are also a major source of heat). This will have a large impact on operating costs and should be investigated.
Non-diesel, particularly electric and battery-electric, vehicles are recommended to be included in any feasibility analysis as a potential solution, due to the advances in technology (especially in battery technology). Underground locos, which are one of the primary culprits for excessive emission levels, have some of the greatest potential for electrification.

The ultimate goal is reducing DPM emissions, which has a significant health impact. This health impact should receive a critical focus in any feasibility study relating to reducing DPM emissions and exposure.

11.2 Effective Maintenance

Current prescribed maintenance practices and procedures for the different technology engines (different Tier levels), as provided by the OEMs, are sufficient in providing effective engine maintenance.

The challenge found is that mine personnel often do not perform maintenance according to these prescribed standards, which leads to engine degradation that keeps the engine from operating according to standard. This includes the engine’s emission levels.

If diesel engines can be maintained according to the prescribed maintenance standard, then the engines will operate within the specified emission levels. This would make planning for and control of emissions (DPM) easier since the DPM levels can be estimated more accurately.

It is suggested that all diesel equipment should be routinely subjected to exhaust gas analyses. These tests should be performed under load, to get a representative sample of what transpires in the operating environment.

Whenever an engine fails the exhaust gas analysis, it should be sent for repair or adjustment. This will ensure that all engines operating underground will at least be to OEM specification. None of these engines should produce visible smoke at all. The DPM values might however be unacceptably high, in spite of no smoke being visible.

The DPM emission levels from diesel engines that operate outside of OEM specification can be controlled/minimised through other means as per the Steps indicated in the DPM Emission Control Guideline (Section 10.5). However, for a sustainable emission control program, it is recommended to perform effective maintenance practices that would keep engines within OEM operating specification as far as possible.

It is recommended that exhaust gas monitoring/analyses be carried on all machines (including modern Tier 4 engines) as this is the only way to ensure that the systems are operating effectively and that the pollution due to exhaust gasses are within acceptable limits.

It should be noted that OEMs are continuously improving their products. It is therefore necessary for continual assessments to compare site-specific needs to the latest available technological solutions.

This report does not aim to promote any specific OEMs, but names along with recent developments, were provided for trade-off analysis references and to highlight continuous improvement developments.
11.3 LOCAL CAPACITY ANALYSIS

- In terms of replacing and/or converting diesel engines, the capacity exists (or will exist, if required) to perform the replacement and conversions on machines that have been determined to be feasible for replacement/conversion. This will be done by the respective OEMs, and supported by the engine manufacturers.

- Local capacity does not currently exist in terms of retrofit/after-treatment component manufacturing in South Africa. This is primarily due to the current lack of demand for these products. However, local capacity could be established over time if the demand is created. Establishing this local capacity will require considerable investment, thus the business case/s need to be compelling enough to motivate financial investment.

- In terms of the supply of LSD and ULSD, the capacity exists amongst fuel manufacturers in South Africa to supply all of the mines with 50ppm diesel, but not 10ppm diesel.

- Focus in future should also be placed on non-diesel alternatives that would ultimately eliminate the DPM issue from South African mines in the long run, and rather building local capacity for these. The vast majority of OEMs and engine manufacturers who were consulted during the engagements are of the belief that the future is not diesel-driven. Certain non-diesel alternatives from the OEMs and engine manufacturers are currently being trialled, tested and used at mine sites in South Africa and internationally (as well as in other industries), with great success. These could be the ultimate solution to eliminating all DPM emissions from mines in South Africa.

11.4 SKILLS GAP AND DEVELOPMENT RECOMMENDATIONS

- A person conducting maintenance should have some form of formal qualification (artisan qualification such as Diesel Mechanic or Fitter) to allow this person to correctly and effectively undertake maintenance practices.

- The current formal qualifications in place are sufficient to qualify individuals to undertake effective maintenance from a knowledge viewpoint. However, further attention should be given to electrical and electronic skills due to changing technology and the requirements of higher tier level engines.

- Formal qualifications also require better quality practical components to prepare apprentices to be successful in the workplace and equip them with basic technical skills.

- A culture of continuous improvement, employee engagement, learning and change management is essential to create an environment conducive to positive maintenance practices.

- A gap has been identified in basic education and in soft and technical skills. The primary factors to address through further development are:
  - Technical skills that are essential to effective maintenance, that have been indicated as lacking, are fault-finding, contamination control, problem-solving, quality control and computer literacy.
Soft skills are also essential to employee success. The skills that have been found to be lacking are communication, teamwork, leadership, supervisory and motivation.
12 MILESTONE RECOMMENDATIONS

From the results contained within this report and the knowledge obtained throughout the duration of the project, the following can be recommended:

12.1 DPM EMISSION CONTROL

- The results of this study can be used as an overview of the factors affecting the feasibility of a transition toward reduced DPM exposure, associated with Tier 2/3 emission limits. This transition refers, primarily, to the replacement of older diesel engines with newer technology engines or alternative Tier level conversion through retrofit technologies.

- The results, as identified from various case studies, further also indicate what previous transitions, from Tier 0 to Tier 2/3 emission level standards, have found in terms of the feasibility of implementing such a transition. These feasibility factors were discussed both in terms of practical implementation as well as financial feasibility as both influence the possibility of achieving a successful and sustainable transition.

- The research in this report can be used as a frame of reference for designing the framework of a feasibility analysis, to account for site-specific needs, when evaluating the requirements and the control method(s) to be implemented to achieve a similar transition to reduce the DPM exposure of mine workers.

- It is advised that the proposed guideline for DPM emission control should be used at the discretion of each operation, following the necessary site-specific risk assessments.

- The proposed control measures and steps toward achieving reduced DPM emission levels should then be assessed to determine which combinations would be suited for a given operation.

- A study is recommended into the development of a feasibility analysis framework for decision-making on electric/battery-electric equipment.

12.2 EFFECTIVE MAINTENANCE

- Ensure that maintenance on diesel engines is done according to the practices and procedures prescribed by OEMs in order to maintain engines according to standard.

- Ensure the necessary skills and expertise is employed for effective engine maintenance according to prescribed standards by OEMs.

- Monitor engines and test emissions to evaluate engine status and perform investigations to address issues if the results indicate non-standard operating parameters.

- Improve the knowledge and understanding of personnel on effective diesel engine maintenance.

12.3 LOCAL CAPACITY ANALYSIS

- A detailed market analyses should be conducted if any initiatives of local capacity building or local manufacturing are to be pursued in earnest in future. It is further recommended that investigations into diesel alternatives should be conducted from a
local capacity perspective, in order to establish their feasibility as an overall replacement for all diesel equipment in the SAMI.

12.4 **SKILLS GAP AND DEVELOPMENT RECOMMENDATIONS**

- Further investigate and define the roles of the OEM and the mining companies in the undertaking of maintenance, replacement and retrofitting of diesel engines. Understanding these responsibilities will provide a clear context for what skills are needed by which stakeholder.

- An in-depth skills audit of the mining industry may be required to understand the skill levels of the employees responsible for the operating and maintenance of the diesel engines, as well as what is required to ensure effective reduction of DPM emissions (including replacement or conversion skills requirements). Determining this gap will enable the provision of a comprehensive training plan.

- Conduct an HR audit of the mining industry’s HR practices (employee value proposition) based on the first point for the control and management of the trainee in terms of the correct working methods relating to the maintenance, replacement and retrofitting of diesel engines. This creates a culture of quality work and better employee performance, leading to better care and operation of the machines.

- Investigate the feasibility of an integrated platform whereby all stakeholders within the industry (including government bodies and enablers) are able to jointly discuss, research and resolve current and future skills needs. In particular, industry should lobby government, through the Minerals Council, to address the poor basic education standards.

- During the investigations throughout the project it was clear that the Human Factor plays an important part in the reduction of DPM emissions. The mining industry is currently, and for the near foreseeable future, dependent on diesel engines and therefore it is recommended that a change management programme be initiated to ensure that all employees working with or involved in the maintenance of these engines understand the importance and impact of effective maintenance processes.
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14 APPENDIX A: DEUTZ DOC CASE STUDY

During the project, discussions were held with Deutz, where they presented their continuous regenerating technology (CRT) system. Theirs system is a wall flow filter with a DOC section on the filter system. Figure 9 illustrates the particulars of the system.

![Diagram of Deutz CRT Wall-flow Filter "Closed System"](image)

**Figure 9: Deutz CRT® Wall-flow Filter “Closed System” – Exhaust gas temperature 250°C to 450°C (courtesy Deutz)**

The DPM filter section does not require daily inspections, and the filter element can operate for at least 1 000 hours, before the element is easily removed and cleaned by means of a high-pressure water cleaner. The element is then refitted and can operate for another 1 000 hours. The components are shown in Figure 10, with a dirty and a clean element, as well as a photo showing the cleaning process.

![Image of filter elements before and after cleaning](image)

**Figure 10: Filter Before and After Cleaning (courtesy Deutz)**

A test on one of the dynamometers of Deutz was witnessed by project team members, where a normal Tier 1 air-cooled Deutz engine was put on the dynamometer and firstly tested with a
normal exhaust without any filtration. The gas analysis was done by Disprotech during all the tests. The test was undertaken on 21 May 2018. After the test, without any filtration or exhaust gas treatment, the diesel particular filter was fitted to the engine and the test was repeated at full load and at idle, with the gas going through the filtering system.

Figure 11 shows the engine, a brand new Deutz F6L914 with the DPM Filter and test equipment in position. Figure 12, Figure 13 and Figure 14 illustrate the improvement in the gas quality after the filter, in relation to the gas quality without the filter. The new engine without a DPM filter gave a DPM reading of 14.5 mg/m³, while the fitting of the filter brought the DPM level down to 0.1 mg/m³. The difference between idle and loaded conditions is also shown.

![Figure 11: (a) Test Cell; (b) Measuring Instruments](image)

![Figure 12: Engine Test on DDP Dynamometer (Deutz F6L914) (courtesy Deutz Dieselpower)](image)
The test results show a drastic reduction in DPM occurred with the use of the filter. At full load, the DPM value without exhaust gas treatment was 14.5 mg/m$^3$. With the exhaust gas filtering system fitted, the DPM value dropped to a value of 0.1 mg/m$^3$. Deutz then advised that they are carrying out tests at a mine in Limpopo, where these filters are in service for a period of 1 000 hours. The pressure drop over the filter is still within the allowable limits of the engine manufacturer Deutz and no attention whatsoever is required by the cleaning system.
After the service of about 1 000 hours, the DPM filter element was taken out and washed with a high-pressure water cleaner or blown clean with compressed air. The filter element was then reinstalled and was ready for another 1 000 hours of service.

The test results after 1 000 hours in service, at various degrees of operation/load, within the mine are shown in Figure 15, Figure 16, and Figure 17.

**Figure 15: In-field Test Results - Underground Mining LHD Application (courtesy Deutz)**

**Figure 16: CO and NOx Emissions (courtesy Deutz)**
Figure 17: DPM Real-Time Test Results (courtesy Deutz)

The drastic improvement in especially the DPM values even after 1 000 hours can be clearly seen. According to Deutz the cost of the filtering system is in the region of R150 000.

Although this cost is deemed high if compared to an engine replacement or engine overhaul, it is considered that the cost can be justified. It is noted that on some LHD machines, especially the low-profile machines, space is limited and there might not be enough space for the fitment of this filter. On several other models, however, as well as diesel underground locos, there would be enough space to fit such a filter to Tier 1 and Tier 2 engines.

It is therefore suggested that in light of the fact that the cost of this filter is less than the rebuilding cost of a typical engine, that in cases where it is possible, machines should be converted to operate with this type of filtration. In the light of the running cost of the filter system being very low and the maintenance easy, the resistance in the mines to the use of this filter, would not be high.

It should be noted that this OEM is not specially endorsed by the project team but is used as an example of the continuous technological advances made by OEMs. There are other suppliers with similar solutions. The discretion lies with the mine to evaluate different systems according to their needs on a continual basis as both the needs and the technologies advance.
15 APPENDIX B: PROPOSED SEVEN-STEP GUIDELINE

Refer to the Project CoE150602 Report for clarity, supporting information and factors that need to be in place to allow the effective implementation of this proposed guideline.

15.1 STEP 1: IMPLEMENT DIESEL FUEL SUPPLY CHAIN MANAGEMENT (SCM)

15.1.1 Description & Overview of Step

In the context of this guideline, SCM refers to the entire chain from diesel procurement through to usage, i.e. from purchase to transport, storage, handling, monitoring, down to the ultimate dispensing of the diesel into the diesel tank for combustion by the diesel engine in operation. Each of these phases should have adequate quality management practices and procedures in place in order to ensure that the diesel that gets used in operation is of sufficient quality.

In the context of DPM emission control, diesel quality refers to the sulphur content of the diesel as well as the presence of other unwanted substances or particles. Lower sulphur content (in ppm), within the diesel produces lower DPM content in the exhaust emissions from the diesel engine. It is therefore advised to use Low Sulphur Diesel Fuel (LSDF) with a 50 ppm sulphur content, or where possible and available to use Ultra-Low Sulphur Diesel Fuel (ULSDF) with a sulphur content below 50 ppm (such as the 10 ppm available in South Africa from Sasol). Other types of diesel are also available that may be assessed for their potential use and potential consequences on emission levels and engine health etc.

It should be clearly noted that using LSDF/ULSDF, and ensuring that the quality of the diesel used in the engines is indeed as it should be, would already produce a positive impact in reducing DPM emission levels. Switching from 500 ppm to 50 ppm or lower typically leads to roughly 10% reduced DPM emission levels, while the difference between 50 and 10 ppm has been found to be negligible. Other harmful emissions are also reduced when using lower sulphur diesel.

Furthermore, a decrease in diesel consumption results from the use of a higher quality diesel fuel (as per the ISO cleanliness ratings\(^5\)). The reason for this stems from the fact that the increase in cleanliness rating results in a decreased number of larger particles in the diesel. Larger particles clog the diesel filters of the machines at a faster rate, while the smaller particles (4-6 micron) lead to injector damage which results in increased diesel consumption due to irregular spray pattern.

To monitor and control diesel quality, throughout the supply chain, it is advised that the diesel purchased and used should comply with SANS 342:2006\(^6\) and an ISO Cleanliness rating of 18/13/12\(^7\). Any samples taken throughout the supply chain or through random sampling on the mine should also comply with these standards. If a sample does not comply with these

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\(^5\) ISO Cleanliness Rating/Code is used to quantify particulate contamination levels per milliliter of fluid and is expressed in 3 numbers (e.g. 19/17/12), where each number represents a contaminant level code for the correlating particle size. This code includes all particles of the specified size and larger.

\(^6\) SANS 342:2006 reference link

\(^7\) ISO Cleanliness Code 4406:1999
quality criteria then the cause of the contamination should be identified and rectified to eliminate its downstream effects.

Ultimately, however, the diesel in the fuel tank of the diesel machine should also adhere to the quality criteria provided in SANS 342-2016\(^8\). This is not limited only to the bulk tanks but should include the final point of discharge and end-use.

Apart from a direct impact on DPM emission levels and on diesel consumption, implementing effective supply chain management to ensure that the required quality for diesel is maintained will also improve engine health. Common problems that result from poor diesel quality, linked to injector malfunction and a resulting increase in DPM emissions, include:

- **Water in the diesel** – Water has no lubricity properties. Water in diesel was illustrated to act as an abrasive substance that damages diesel injectors. Whenever even a micro droplet of water enters the needle passage, the result is cold seizure and scuffing. This scuffing causes the needle to become sticky in its operation, which adversely affects the spray pattern and causes higher DPM emissions in the exhaust. This is often a result from poor filtration at the bulk tank or in the line up to the dispenser. Other causes may include diesel tank lids that are not closed properly, or not put back in place at all, or water entering through the diesel tank vent on the machine when cleaned with a high-pressure cleaning system.

- **Contamination of the diesel** – Similar to water, other particles (especially fine mineral and silica particles in dust) that enter the diesel will have a damaging effect on the diesel injectors and ultimately cause increased emission levels as well as reduced engine performance and health. Dust particles can however also enter various other parts of an engine (through the air intake or through contaminated oil) if good housekeeping practices are not employed. This could damage the engine in different areas and lead to detrimental consequences in engine health and emission levels. When oil is added to diesel, it causes deposit build-up in the injectors from the additive package within the oil itself.

- **Lubricity of the diesel** – Lower Sulphur diesel is normally associated with lower lubricity. This is often exacerbated when poor quality diesel is used. Lower lubricity increases wear within the engine, leading to reduced engine health and poorer emission levels.

Implementing effective SCM practices will reduce the probability of these issues occurring. However, by sampling the diesel directly in the diesel tanks of the machines it can be identified whether there is a problem within the SCM or even with diesel monitoring or general housekeeping practices. In this event, the root cause should be identified and rectified.

In summary, using good quality diesel, that is also LSDF/ULSDF instead of high Sulphur content diesel, will lead to significant improvements in DPM emission levels, diesel consumption and engine health. Implementing this step successfully is also a requirement in order to implement the subsequent steps of this guideline effectively.

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\(^8\) SANS 342-2016 reference [link](#)
15.1.2 Potential Challenges and Opportunities

Table 26: Step 1 – Implement Diesel Fuel SCM: Summary of Potential Challenges and Opportunities

<table>
<thead>
<tr>
<th>Potential Challenges</th>
<th>Potential Opportunities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lacking knowledge of diesel quality specifications.</td>
<td>Good quality diesel will likely lead to lower diesel consumption.</td>
</tr>
<tr>
<td>Poor working relationship with diesel supplier(s).</td>
<td>Good quality diesel will potentially lead to lower maintenance cost.</td>
</tr>
<tr>
<td>Management insisting on purchasing lower cost diesel alternatives without performing the necessary quality assessments.</td>
<td>Good quality diesel will potentially lead to increased engine life and a higher machine availability.</td>
</tr>
<tr>
<td>Old infrastructure (diesel tanks, diesel bowsers, pipes and pipelines, utility vehicles, etc.) contaminating the diesel.</td>
<td>Good quality diesel will potentially reduce the risk of a catastrophic engine failure.</td>
</tr>
<tr>
<td>Lacking training and skills for personnel dispensing the diesel.</td>
<td>Consistently using good quality diesel will have a positive impact on overall operating costs.</td>
</tr>
<tr>
<td>Additional skills and training requirements for SCM and quality assurance.</td>
<td>Using lower Sulphur content diesel will reduce DPM emission levels considerably.</td>
</tr>
<tr>
<td>Sub-optimal diesel filtration on the diesel machine itself.</td>
<td>Using LSDF/ULSDF allows the use of newer technology engines with higher Tier ratings.</td>
</tr>
<tr>
<td>Reduced diesel lubricity leading to increased wear on components.</td>
<td>Using LSDF/ULSDF improves the effectiveness of retrofit emission control technologies.</td>
</tr>
<tr>
<td>Potentially higher cost for LSDF/ULSDF from certified providers.</td>
<td></td>
</tr>
<tr>
<td>Potentially limited and unsustainable supply of ULSDF (&lt;15ppm).</td>
<td></td>
</tr>
<tr>
<td>Potential to get leaking diesel pump seals in older engines when using LSDF/ULSDF.</td>
<td></td>
</tr>
<tr>
<td>Changes in additive requirements may occur which would add additional costs.</td>
<td></td>
</tr>
<tr>
<td>Global companies often have contracts in place with service providers in a global context. In terms of diesel suppliers, this may bring challenges for local desired changes in a given product (e.g. switching to 10-ppm diesel but the company has a contract in place with a different diesel supplier for 50-500ppm globally).</td>
<td></td>
</tr>
</tbody>
</table>

15.1.3 Effective Implementation

The following outlines the suggestions to ensure effective implementation of this step:

- Procure and use only LSDF/ULSDF (50 ppm or lower Sulphur content diesel).
- Purchase diesel from a reputable and certified provider.
- Ensure diesel transport to site is done by a reputable service.
- Leverage on collaborative relationships with the diesel suppliers to ensure that quality diesel is supplied.
- Implement quality management procedures throughout the diesel SCM process to ensure that diesel of the correct quality is dispensed into the diesel tanks.
Implement quality management procedures to ensure that contamination sources are eliminated and managed. This includes procedures associated with bulk tank filtration, Utility Vehicles (UVs) with clean tanks and correct filtration, clean dispensers, clean diesel tanks on the machines, properly sealing diesel caps, etc.

Ensure that the necessary training and skills are in place to support effective SCM.

Ensure that the necessary skills, practices and procedures are in place to perform the required quality assurance.

Implement a filtration system on key points within the diesel supply chain, e.g. kidney systems (some of the current potential suppliers of filtration systems include Donaldson, iCerMax, Parker Store, SupaFuel, etc.).

Implement monitoring systems, to monitor for contamination, water content, or diesel specifications as per ISO (ISO Cleanliness Code 4406:1999) and SANS (SANS 342:2006) standards. This must be supported with the correct procedures governing monitoring.

Conduct regular maintenance, cleaning (good housekeeping) of storage and dispensing units.

Assess, choose and use applicable (and prescribed by the OEM) additive solutions/packages.

Management commitment to quality diesel supply over a pure cost focus.

Where possible, use only similar diesel types on an engine under all conditions (even if sent off-site).

15.2 Step 2: Conduct Fleet Assessment & Determine the Gap

15.2.1 Description & Overview of Step

Following a successful implementation of SCM and diesel quality assurance, the next steps for DPM emission control should be planned. However, planning can only start when the correct information is available for decisions. Toward this end, it is necessary to complete a gap analysis to identify what action steps to take and to plan the successful execution thereof. This gap refers to the difference between the desired end-goal for DPM emission levels and the current emission levels from individual equipment within the diesel fleet in operation.

It is necessary to perform a full assessment of the diesel fleet as well as an analysis on the emission levels of each individual diesel engine. The outcomes from these assessments will assist with planning the transition toward achieving the desired emission levels, as well as to ensure sustainable emission control. These outcomes will also support effective maintenance practices, which form the required foundation for any sustainable DPM control program. The information required from the fleet assessment should include:

- Machine type, the OEM, and the machine model.
- Engine OEM/make and model.
- Engine and equipment/machine serial number.
- Year of engine manufacture.
- Engine Tier level and expected emission levels as per specifications.
- Current engine operating hours.
- Whether it is the original engine or whether the engine has been repaired/refurbished.
- If the engine has been repaired/refurbished/overhauled, what exactly was done and when (date and how many operating hours ago).
- Time (number of operating hours and expected date) until a required engine rebuild.
- Total expected engine life left (operating hours and expected end of life date) and date of next expected engine replacement.
- Total expected machine life left (operating hours and expected end of life date).
- Measured levels of emissions (in the context of this project, particularly DPM levels).

The information needs to be captured in a live database that is continuously updating the baseline for the fleet and its resulting DPM emission status.

The measurement and monitoring of the DPM emission levels per individual engine should be conducted during regular service intervals (typically every 2-3 weeks) in order to perform engine fault analyses and to ensure that DPM control measures in place are up to date. DPM sampling and monitoring should be done according to prescribed methodologies by an accredited body to ensure that accurate measurements are obtained.

The outcomes from these full assessments, including having determined the existing emission baseline, will then serve the following purposes:

1. Measure engine performance, health and emission levels according to OEM prescribed specifications. This will determine whether an engine is operating outside of specification or not. The machines can then be grouped based on requirements, such as not in need of attention, in need of minor adjustments, in need of major repair/refurbishment, or in need of engine replacement. This will identify which engines to focus on in order to achieve operation within specification. The primary aim of this is to ensure that DPM emission levels are within the expected ranges for every engine, which will make planning for DPM control more effective. However, engines that operate within specification also experience better performance, reduced diesel consumption, longer engine life and improve health in general.

2. Determine the gap to be bridged toward the desired DPM emission levels. This identified gap should be used for the decision-making in terms of what measures and action steps to implement as per the following steps of the guideline.

### 15.2.2 Potential Challenges and Opportunities

<table>
<thead>
<tr>
<th>Potential Challenges</th>
<th>Potential Opportunities</th>
</tr>
</thead>
<tbody>
<tr>
<td>All the required information not being available or difficult to gather.</td>
<td>Assistance from an OEM with required information and procedures.</td>
</tr>
<tr>
<td>Additional costs for regular assessments &amp; emission monitoring.</td>
<td>Rectification of engines to operate within OEM specification may improve engine &amp; machine health and operating life.</td>
</tr>
<tr>
<td>Additional personnel, capable of performing the necessary tasks, may be required.</td>
<td>Rectification of engines to operate within OEM specification may improve diesel consumption.</td>
</tr>
</tbody>
</table>
Lack of understanding of, or access to, a suitable DPM emission testing methodology. Misdiagnosis of engine faults and causes.

### 15.2.3 Effective Implementation

The following outlines the suggestions to ensure effective implementation of this step:

- Follow prescribed procedures or methodologies during the fleet and emission assessments.
- Acquire the support of the OEMs to obtain lacking information and improved understanding regarding engine operation and the resulting impact on emission levels.

### 15.3 STEP 3: REPAIR ENGINES TO ACHIEVE OEM BASELINE SPECIFICATION

#### 15.3.1 Description & Overview of Step

Engines that are found, from the outcomes of Step 2, to operate outside of OEM specification (i.e. hard starting, smoking, higher fuel consumption than a similar machine, higher oil consumption, erratic idling, noisy tappets, etc.) should be repaired as required. This step is important for the following reasons:

1. Engines operating outside of OEM specification produce higher emission levels than what should be reasonably expected, based on the engine’s standard. Therefore, having all diesel engines operate within specification will both reduce DPM emission levels (if the baseline was worse than prescribed specification), and will allow more effective planning for emission control based on an accurately determinable fleet baseline.

2. Engines operating outside of OEM specification also have poorer operation, health, diesel consumption and expected operating life. All of these factors contribute not only to an increase in harmful emissions, but also to an increase in operating and maintenance costs. Therefore, having all diesel engines operate within specification will bring financial benefit.

3. Engines operating outside of OEM specification also cause retrofit technologies, such as DPM filters, to block up faster which causes increased maintenance requirements and reduced benefit from such technologies.

For these reasons, it is advised to ensure that the current diesel engines operate within prescribed specification before implementing any of the following steps of this guideline. Once this has been achieved, tests have indicated that the baseline for emission levels in an operation is significantly reduced. This also reduces the gap to be bridged by subsequent action steps in a DPM emission control program, leading to reduced costs for such an initiative as well as improved benefits obtained from the existing diesel fleet.
15.3.2 Potential Challenges and Opportunities

Table 28: Step 3 – Repair Engines to OEM Specifications: Summary of Potential Challenges and Opportunities

<table>
<thead>
<tr>
<th>Potential Challenges</th>
<th>Potential Opportunities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adequately trained technicians/artisans to correctly diagnose the root cause of excessive emissions.</td>
<td>Rectification of engines to operate within OEM specification may already significantly improve DPM emissions.</td>
</tr>
<tr>
<td>An external company refurbishing/repairing the engines may not have the correct expertise/dynamometer/emission testing equipment etc.</td>
<td>Potential to reduce operating and maintenance costs.</td>
</tr>
<tr>
<td>No service indicators after the inlet filter.</td>
<td>May reduce ventilation demand resulting from lower emission levels, leading to reduced operating cost.</td>
</tr>
<tr>
<td>Poor ventilation at the face may cause overheating of the engine. This causes incomplete combustion, leading to a smoking engine (i.e. higher emission levels).</td>
<td>May provide a better baseline to address in terms of reducing DPM emission levels.</td>
</tr>
</tbody>
</table>

15.3.3 Effective Implementation

The following outlines the suggestions to ensure effective implementation of this step:

- To ensure that engines operate at OEM specification for prolonged periods, apply the proposed Guideline for Effective Diesel Engine Maintenance (Refer to Section 10.4 of the Project CoE150602 Report):
  - Perform Exhaust Gas Analysis.
  - Repair/Refurbish Engines to Achieve OEM Baseline Specification.
- Ensure that the necessary skills are in place to perform the required repairs optimally.
- Good fault-finding skills are required to identify the root causes that need to be addressed in order to repair an engine effectively and at the lowest cost possible.
- If an external company is used for the engine repairs, ensure that is reputable and accredited by the OEM as an engine rebuilder (who also has the necessary tools, e.g. dynamometer, emission analysers, etc.)
- Obtain information of reputable suppliers/service providers to assist with this step from other mining operations or from the OEMs.
- Employ the appropriate prescribed practices and procedures to ensure that OEM warranties are not jeopardised.
- Start with the worst machines/engines, this will achieve the highest impact on DPM reduction within the shortest time.
- Start on a small scale even if a large number of repairs are necessary to ensure quality work and avoid unnecessary reworks.
- Ensure that the ventilation and temperature at the working face underground is not detrimental to engine/machine health.
15.4 **STEP 4: IMPLEMENT RETROFIT SOLUTIONS**

15.4.1 **Description & Overview of Step**

One of the solutions to be considered is the implementation of emission reducing retrofit technologies/solutions. There are various retrofit solutions available and an operation is advised to consider all alternatives based on fleet requirements and on the specific DPM emission gap for that operation.

Implementing such a solution may sufficiently reduce DPM levels without performing an engine replacement. The additional implementation, following an engine replacement, of a retrofit solution can further reduce emissions closing the DPM gap that should be addressed. Retrofit solutions require that the engine should be in good operating condition, i.e. operating within OEM specification as advised in Step 3. If this is not true for the engine then the retrofitted solution will block much faster, leading to it losing its efficiency for emission reduction and requiring more intensive and regular maintenance that will influence cost and equipment availability.

Some retrofit solutions are, in general, maintenance intensive. If maintenance is not done effectively, regularly and according to standard this solution may not prove sustainable or cost effective. There are solutions (particularly some DPF’s) that are easy to maintain. An example of a DPF product is from Deutz Diesel Power and this can simply be cleaned by hosing the filter out with water. Cleaning of these retrofit solutions should be done according to prescribed procedures in order to avoid releasing the captured DPM without proper control measures, causing excessive exposure within another environment.

For DPFs, in particular, there have been major advancement in technology and efficiency over the last few years making this a potentially viable solution. There are challenges associated with the implementation of after treatment / retrofitted technology to consider, such as compatibility with the machine or engine and with worker adoption. Cases have been noted by stakeholders where operators remove retrofitted devices (such as a filter) during operation and then replace it at the end of the shift.

15.4.2 **Potential Challenges and Opportunities**

Table 29: Step 4 – Implement Retrofit Solutions: Summary of Potential Challenges and Opportunities

<table>
<thead>
<tr>
<th>Potential Challenges</th>
<th>Potential Opportunities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Additional capital cost required.</td>
<td>After treatment (retrofitted) solutions on the exhaust reduce or even completely capture the excessive smoke/soot released upon engine startup.</td>
</tr>
<tr>
<td>Many, especially the older, equipment/machines have limited engine space that may not allow installation of a retrofit solution.</td>
<td>Some retrofit (after treatment) systems/solutions are easy to maintain.</td>
</tr>
<tr>
<td>Engines with a mechanical diesel pump will only have a warning indicator if the DPM backpressure rises to the maximum limit. This makes it challenging to determine whether maintenance (e.g. filter cleaning) is due without a physical inspection.</td>
<td>Potential for major DPM emission reduction if used and maintained properly.</td>
</tr>
</tbody>
</table>
Potential Challenges

Electronically controlled fuel systems can cut the engine if the retrofit technology is not operating as per design, e.g. if the DPF is blocked.

Expertise to evaluate and select optimal products/solutions may be lacking.

The skills to install retrofit solutions, especially on a large scale, may be lacking.

Managing the backpressure of DPFs by the operators/technicians may be difficult.

Ensuring that the appropriate maintenance/cleaning takes place may prove difficult, which would greatly hinder effectiveness.

Some retrofit (after treatment) systems/solutions are maintenance intensive (i.e. costly and impacting on equipment availability).

Requires that the engine operate within OEM specification for optimal functionality.

Worker adoption/acceptance and deliberate sabotage or removal.

Large-scale supply of specific retrofit /after-treatment systems may be difficult.

Often requires that an engine first be repaired before installation can take place.

Potential Opportunities

Potential alternative to engine replacement.

Expertise to evaluate and select optimal products/solutions may be lacking.

The skills to install retrofit solutions, especially on a large scale, may be lacking.

Managing the backpressure of DPFs by the operators/technicians may be difficult.

Ensuring that the appropriate maintenance/cleaning takes place may prove difficult, which would greatly hinder effectiveness.

Some retrofit (after treatment) systems/solutions are maintenance intensive (i.e. costly and impacting on equipment availability).

Requires that the engine operate within OEM specification for optimal functionality.

Worker adoption/acceptance and deliberate sabotage or removal.

Large-scale supply of specific retrofit /after-treatment systems may be difficult.

Often requires that an engine first be repaired before installation can take place.

15.4.3 Effective Implementation

The following outlines the suggestions to ensure effective implementation of this step:

- Perform retrofit evaluation and selection in collaboration with experts and/or with the machine and engine OEM.
- Ensure the correct maintenance practices and procedures are in place and being followed.
- Evaluate the cost vs. benefit of implementing retrofit solutions as opposed to, as well as in addition to, the replacement of engines with newer technology engines.
- Implement solutions on a small scale at first to trial implementations in terms of impact and sustainability as well as to develop the necessary skills and manage change as required.
- Plan the implementation of this step carefully in collaboration with the OEM(s).
- Ensure the operators understand how the technology works and what it is for.
- Ensure regular discussions with both operators and technicians take place to identify issues that may hinder the effective and sustainable adoption of a retrofit technology.
- It is advised to only implement this step if Steps 1 to 3 have been implemented successfully.
15.5 **STEP 5: REPLACE DIESEL ENGINES WITH LOWER EMISSION TECHNOLOGY ENGINES**

15.5.1 **Description & Overview of Step**

Another approach to reducing DPM emission levels is to replace older technology engines (particularly Tier 0 or Tier 1 rating) with newer technology engines that adhere to Tier 2 or higher emission standards. Higher Tier rated engines have a lower baseline for emission levels. This will significantly reduce the emission baseline and require a much smaller gap to be bridged through other control measures.

It is important to note that Tier 2 and Tier 3 standards provide for the same DPM emission limits, while Tier 3 engines also provide reduced levels for other harmful emissions. Some OEMs promote their Tier 2 engines while other OEMs instead promote their Tier 3 engines for implementation. Tier 4 engines are often not promoted in the South African mining industry since the diesel used in operation is often too low quality for these engines to use. However, if Tier 4 engines are used it is important to ensure that Step 1 of this guideline is followed as deviations will result in even more severe consequences. Operations should also make use of the additional additive, as prescribed by the OEM, for the internal cleaning of injectors and high-pressure pumps. The cleaning additive removes the IDID that develop in these engines.

Some engines (depending on brand and model) can only be replaced by certain other model engines, leading to restricted “choice” in terms of Tier ratings or engine models. For example, newer engines may not be amenable to older equipment due to space and configuration limitations. Unintelligent/non-electronic equipment are particularly difficult to replace with new electronically controlled engines due to the absence of electrical harnessing, space for the ECM or space for the exhaust filtration system for higher Tier engines. Replacing intelligent (electronically controlled) engines with other (newer) intelligent engines can also be difficult since the entire harnessing and ECM should be replaced as well to ensure compatibility with the machine.

On some of the older machines, often only a Tier 2 engine can be used to replace a Tier 0 or Tier 1 engine. On newer machines, it may be possible to replace older engines with a Tier 3 engine, if there is sufficient space for the exhaust filtration system as well as the required ECM and electrical harnessing. A Tier 3 engine supplied without an exhaust filtration system may then require a retrofit EAT system.

As such, it is critically important for an operation to communicate and collaborate closely with their preferred service providers (OEMs) in order to conduct a thorough assessment of which option(s) would be best suited for specific equipment and the required emission outcome.

Newer technology engines do not necessarily provide increased machine availability due to the engines being more sophisticated, electronic, and in need of higher levels of maintenance. Machine availability is a function of the effectiveness of the maintenance regime. Maintenance intensity and requirements in turn also differ between engine types and models (also age). As such, a statement cannot be made on the relationship between older and newer technology engines without considering the levels of maintenance required. It can be concluded that if effective maintenance practices are in place, then the assessment of newer engines should not be penalised on the basis of potentially lower availability.

Replacing older engines with newer engines requires careful evaluation. There are various factors and constraints related to machine and engine compatibility that requires consideration. On older machines with mechanical engines the required electronics (wiring
and control modules etc.) are not in place and they have to be installed along with a newer technology engine, making it more complex and difficult to ensure suitability to the machine (assuming sufficient space is available for installation). On newer machines with electronically managed engines, there may be compatibility challenges due to machines and engines not being manufactured to ensure compatibility. Different electronics and software often mean that replacing engines is not a plug-and-play solution.

**15.5.2 Potential Challenges and Opportunities**

Table 30: Step 5 – Replace Engines: Summary of Potential Challenges and Opportunities

<table>
<thead>
<tr>
<th>Potential Challenges</th>
<th>Potential Opportunities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Older equipment may not be amenable to have newer technology engines installed within them due to compatibility and/or space issues.</td>
<td>Reduced ventilation requirements resulting from reduced emission and heat outputs.</td>
</tr>
<tr>
<td>Newer technology engines may experience operational interruptions (increased maintenance, breakdowns, reduced availability, total failures, etc.) if good quality diesel is not used to fuel them.</td>
<td>Reduced diesel consumption from newer engines.</td>
</tr>
<tr>
<td>Older equipment with mechanical engines, may require a total machine upgrade including engine control modules and electrical harnesses etc.</td>
<td>Reduced requirements for emission controls and a smaller gap to bridge through these control measures.</td>
</tr>
<tr>
<td>It may be necessary in some cases to do an engine replacement underground, which has potential challenges with logistics.</td>
<td>Renewed engine-operating life.</td>
</tr>
<tr>
<td>It may be necessary for some machines to have their engines rebuild at the OEM’s site, which will have logistical challenges and production impacts.</td>
<td>Developing a replacement kit to take to a mining operation for onsite replacements is possible.</td>
</tr>
<tr>
<td>OEMs need to plan and develop capacity if large-scale engine replacements are required, leading to potential time constraints.</td>
<td></td>
</tr>
<tr>
<td>It is often more difficult to replace one electronically controlled engine (newer technology engine) with another due to incompatibility between electronics and software.</td>
<td></td>
</tr>
<tr>
<td>Engine replacement sometimes causes machines or engines to operate outside of specification.</td>
<td></td>
</tr>
<tr>
<td>High capital outlay required.</td>
<td></td>
</tr>
</tbody>
</table>

**15.5.3 Effective Implementation**

The following outlines the suggestions to ensure effective implementation of this step:

- Decision-making should be based on cost benefit analysis to quantify financial benefits. Key factors to consider during such an analysis are the life of mine, operating life left of the fleet and of each of the engines, impact on operating costs, additional
supporting requirements, the cost of alternative solutions vs. their impact and whether they can sustainably be maintained, etc.

- Do not replace engines unless required and based on the individual gap analysis. Various other DPM control measures (as explained within this guideline) need to be considered as part of the final solution. However, it should be clearly understood whether an alternative measure is a short-term solution or a sustainable solution. Non-sustainable solutions require replacement with sustainable solutions as per the measures proposed in this guideline.

- Plan to replace engines when they are due for a replacement or when an engine is due for a rebuild/refurbishment that is in line with the engine’s operating lifecycle.

- Consider total equipment life and replacement of the equipment instead of an engine replacement (when feasible).

- Evaluate the new engine and existing equipment compatibility. Obtain advice and recommendations from the OEM(s).

- In particular, consider the match of the engine output to the vehicle load requirements. Diesel engines perform at their best efficiency and lowest emissions when they operate between the peak power and torque band (i.e. within the operational window as prescribed by the OEM).

- Evaluate the supplier (engine OEM) and ensure that credible suppliers are used with good after sales services.

- Assess the commercial availability of the engine and sustainability of parts supply.

- Evaluate the maintenance and rebuild costs and requirements of a new engine.

- Evaluate the necessary skills or upskilling requirements for a new engine.

- Consider the life of project and cost for a transition to newer engines within a fleet or portion of a fleet.

- Assess the impact on health and safety that will result from engine replacement.

- Evaluate potential resale options for equipment and engines (the old and the new in terms of replacement schedule).

- Collaborate closely with the OEMs to ensure that replacement, especially on a large scale, is planned and executed effectively.

- Consider which OEMs to engage with for a replacement process. Often it is best to engage with the OEMs of the equipment for which the engine should be replaced, since they work in close collaboration with the engine OEM of their choice.

- It is advised to only implement this step if Steps 1 to 3 have been implemented successfully.

### 15.6 STEP 6: IMPLEMENT OTHER EMISSION CONTROLS

#### 15.6.1 Description & Overview of Step

Apart from the control measures discussed above, there are alternative mitigation measures that can be implemented prior to embarking on the chosen optimal DPM emission control program. These mitigation measures should be considered through the various levels of risk.
controls specific to the operation. In most cases, these controls are a means of mitigating the effects from DPM exposure and ultimately another more sufficient and sustainable control method should be put in place. However, even after successful implementation of a DPM control program, these mitigation measures may still be employed to support good practice for improved air quality.

Over the past 15 years, considerable research has taken place to develop suitable control technologies, especially for vehicles operating in confined areas (e.g. underground mining). Proven control technologies and practices, apart from what has already been covered, further include (CoM, 2012; Perkins, 2005; Mans, 2017; and, OHSA, 2012):

- Effective and efficiently designed and planned ventilation;
- Real-time ventilation flow adjustment systems (connected to real-time monitoring sensors);
- Air conditioned (filtered) operators’ cabins to reduce operator emission exposure;
- Operating practices and fleet management / dispatch;
- Driver and workforce education;
- Sufficient employee and operator training and awareness;
- Positioning workers in upstream ventilated environments where possible;
- Using effective DPM monitoring (what gets measured gets done);
- Gradually implementing/transitioning to non-diesel equipment;
- Personal protective equipment; and,
- Focussed management and administrative practices. Examples include:
  - Limiting vehicle speeds (Note that for speed limitations it is not advisable to attain this through the prevention of higher gear usage. The practice of forcing equipment to only operate in lower gears causes the engine to operate at excessive engine speeds, which increases engine wear as well as DPM emission output. Speed control is best done electronically);
  - Constraining vehicle idling time; and,
  - Controlling the number of vehicles operating in an underground area through efficient scheduling activities.

15.7 STEP 7: IMPLEMENT OTHER NON-DIESEL ALTERNATIVES

15.7.1 Description & Overview of Step

Investigating non-diesel alternatives (electrical-, battery, gas-powered, hybrids, etc.) fell outside the scope of this project. However, some of these alternatives may provide a beneficial solution in terms of harmful emission reduction as well as lower equipment-based operating costs. Such alternatives have to be considered on a case-by-case basis as the criteria for evaluation and selection depends on the specific needs of an individual operation.

From the engagements with the OEMs, it was found that the majority believe that electric or battery-electric equipment/machines are the future. It is the opinion of the authors that such equipment should require consideration through careful evaluation. Studies done by the OEMs indicated that electric/battery equipment will not only eliminate the current harmful emissions
from diesel engines, but will also cause a dramatic reduction in ventilation and cooling requirements which make up a large component of operating costs (Reynders, 2018). Electrically driven equipment is also likely to be far less maintenance intensive and have a lower probability of breakdown. Maintenance requirements will, however, differ with more intensive and higher-level skills being required.

A feasibility analysis is advised on electric/battery vehicles to determine the viability of implementation as compared to alternatives. Factors to consider include, but are not limited to:

- The current timelines and lifecycles of existing diesel fleets;
- The alternative DPM control program and the costs and implementation lifecycle(s) thereof;
- Potential technology implementation constraints.
16 APPENDIX C: LOCAL CAPACITY ANALYSIS – STAKEHOLDER ENGAGEMENT QUESTIONS

1. If you have to replace, convert or upgrade an engine, who will do (or who does) the required work?

2. What is your capacity to replace an existing engine with your product (with a higher Tier engine)? What is the product/approach? E.g. if 70% of your clients request replacements from Tier 0/1 to Tier 2/3, what is your capacity to satisfy this demand?

3. What is your capacity to retrofit (e.g. DPM filter installation) an existing engine with your product? What is the product/approach? E.g. if 70% of your clients request retrofit installations, what is your capacity to satisfy this demand?

4. What challenges and opportunities do you see with regards to retrofitting? (E.g. what about space limitations in engine compartment and in driver cab instrument panel?)

5. What challenges and opportunities do you see with regards to engine replacement (broadly outlined, e.g. fuel supply, capital outlays, but improvement in health etc.)?

6. What is your future outlook on diesel engines and alternative energy mining vehicles?

7. Where are your retrofit parts manufactured? Do you believe these could be manufactured locally (if not already)?

8. What is your opinion on the supply of 50ppm and 10ppm diesel supply to the South African mining industry? Can increased demand be met?
17 APPENDIX D: ENABLING OR SUPPORTING FACTORS FOR THE GUIDELINE

Before implementing a program designed to achieve reduced DPM emission levels, consideration should be given to all aspects that should be in place to enable the desired transition or that would support the transition. These aspects will be discussed in the following sections.

Achieving reduced DPM emission levels will not simply depend on a transition phase, e.g. through new engine implementation or retrofit installation, but continuous and effective maintenance management will also be required to ensure that the end-results are maintained.

17.1 APPROPRIATE CULTURE, DISCIPLINE and change management

While disseminating knowledge on soft issues falls outside the scope of this project, it is recognised that these aspects will have a critical impact on the success of any DPM emission control initiative. For this reason, it is noted that in order to effectively run a conversion or engine upgrade program, it is important to develop the necessary discipline that would support employee adherence to prescribed practices and procedures. These include those prescribed for maintenance, sampling and monitoring, as well as other supporting practices that impact emission control.

Resistance to change is another aspect that may hinder the effective adoption of any guideline toward reduced DPM emission levels. This may include, for example, a resistance to instilling discipline in one’s work and adhere to the required high standards to ensure that a diesel fleet operates optimally. To combat this, it is necessary to implement a management of change initiative along with the technical program in order to build the required culture in support of this goal. For example, it is important to align an operation’s culture to support, drive and sustain good “housekeeping” practices in support of effective maintenance. Implementation of the MOSH Behaviour Change Process\(^9\) is recommended.

17.2 APPOINITION OF A PROJECT CHAMPION WITH THE APPROPRIATE TEAM

It is advised to appoint a project champion to drive the DPM reduction initiatives using the proposed guidelines or other means found suited to the operation. Such a champion has to take on the responsibility of achieving set emission level goals and should have the necessary skills and competence to ensure the required discipline and culture in support of the initiative. It should preferably be a senior person with great energy and passion for the cause he/she has to champion.

The project champion should also have a dedicated support team. This may include, but is not limited to, an internal machine specialist, the fleet foreman, HR/training head, [diesel] supply chain manager, and a strong support network of preferred suppliers and service providers whenever internal expertise needs to be supplemented.

\(^9\) Online reference [link](#).
17.3 APPOINTMENT OF A CHAMPION MINE

Although not a requirement, appointing a champion mine to implement the proposed guideline for achieving reduced DPM emission levels would assist the mining industry with obtaining valuable practical implementation knowledge and advice. This could help refine the current guideline and identify potentially omitted points during the research project. Additional challenges and opportunities may become known that may assist other operations with their own transitions or with DPM emission level control in general. Implementation of the MOSH Leading Practice Adoption System\(^\text{10}\) is recommended.

This report does not prescribe or promote any single mining operation to be appointed as a potential champion mine for implementing the outcomes of this project. However, an example of an enthusiastic operation that strives toward reducing DPM emission levels and obtaining improved diesel machine fleet operation is Kwezi Shaft. For this reason, Kwezi Shaft was chosen for regular testing on a chosen sample of the operation’s diesel fleet by the project team. The primary aim of these tests was to determine the benefits that can be obtained when engines are properly adjusted as far as exhaust pollution is concerned, as well as the effects that may be obtained when engines are correctly maintained. These tests greatly helped in quantifying some of the points raised in this report regarding the proposed guideline.

17.4 CONTAMINATION & QUALITY CONTROL

The multiple downstream impacts of poor quality diesel were explained in detail. This supported and illustrated the importance of consistently using good quality diesel fuel. Maintaining proper diesel management systems and practices is critical for emission control, to ensure that machines operate optimally and achieve prolonged component life. During the stakeholder engagements, the consensus from the majority of OEMs was that about 30% of engine failures were attributed to poor quality diesel.

Diesel provided by the refineries adheres to prescribed standards, however, within the supply chain right down to dispensing the diesel into the machines, contamination of the diesel occurs. Contamination and quality degradation of the original diesel may occur anywhere from:

- Purchasing diesel fuel from certain suppliers (stakeholder engagements have identified that diesel from less reputable suppliers is sometimes mixed with other substances to reduce cost, which negatively impacts the quality);
- Transporting the diesel to a mining operation (various poor practices have been noted from stakeholders, ranging from transport agencies or drivers selling off diesel and filling up the tank with paraffin or oils, to containers not being cleaned properly after transporting a load of higher ppm diesel and thereby increasing the ppm content of the following batch of diesel - which should have been at a lower ppm quality);
- Storing of the diesel (poor housekeeping, contamination control and sampling methods often reduces the diesel quality while still in storage);

\(^{10}\) Online reference link.
- Transporting the diesel to and filling up diesel machines (dirty equipment is often used or the caps are not put back in place to shield the diesel tank from external contamination);
- Taking samples or monitoring diesel levels (often the diesel gets contaminated with particles during this process if good practices are not utilised).
- Cleaning of diesel tanks and breather pumps (high-pressure water has resulted in water entering into the diesel tank).

If the diesel companies take proper care, diesel is delivered on specification to the mine stores. The primary issue then becomes the diesel transport from the bulk reservoir of the mine to the vehicle’s tank. Very often, this process introduces particle contamination of the diesel, or the addition of water to the diesel, which acts as an abrasive substance with detrimental effects.

To quantify the issue of contamination, consider the following example where the project team conducted an inspection of defective injectors. These injectors were taken out of diesel engines on a mine in the Rustenburg area in order to send them back to the OEM for a fault analysis. Three of them were obtained and these injectors were stripped and inspected under a microscope. Figure 18 shows the three needles (note the discolouration on the needle tips).

It was found that the damage to the injector needles did not indicate any damage due to particle contamination of the diesel. However, the observed abrasive damage indicated that small droplets of water must have entered the injector. These droplets caused some scuffing damage on the needles. Figure 19 shows the damage due to water droplets on the injector shanks at 20 times magnification. The result was that the injector was spraying poorly, which in turn adversely affected the exhaust gas composition. Through the inspection by the mine workshop, these defective injectors were detected and subsequently replaced which had a positive impact on emission levels.

![Figure 18: Three removed and damaged injector valve needles](image-url)
Figure 19: Water droplet damage on injector at 20 times magnification

Figure 20 shows examples of damage to injectors from dust particles. This damage also causes an adversely affected spray pattern, washing away the lubricant film from the cylinder liner walls, and often diluting the engine lubricant as well. Adding to this, the changes in the spray pattern causes poor combustion within the engine.

Figure 20: Dust damage on injectors

Poor combustion seriously affects the exhaust gas quality, while the lack of proper lubrication of the pistons and bearings causes failures of bearings and or seizure of the pistons. The result is often a seized bearing or piston or a hole struck in the engine block.

On the modern “common rail” engines the same problems occur, but to an even higher degree. The common rail engines operate at 1500 to 2500 bar injection pressures, with the next group of engines anticipated to operate at 3000 bar. To be able to reach these very high pressures, the clearances between the control valve and body, as well as between the needle and tip body has to be in the region of 1 to 1.5 micron. On older engines, which operated at around 150 to 200 bar, the clearances were in the region of 2 to 3 micron. The modern engines are therefore more susceptible to damage due to particle and water contamination of the diesel.
In addition to the above aspects, the modern common rail engines also experience problems with Internal Diesel Injector Deposits (IDID). This problem is caused by breakdown of diesel at the high pressures and temperatures in the system. The result is stickiness on the control valve and needle of the injector, with the same poor end-result as far as exhaust pollution and engine life is concerned. An additive, prescribed by the OEM, can be used to counteract IDID.

However, before final breakdown the engine emits unacceptably high exhaust emissions for a period, which are well above the standard emission levels that may be expected based on a defined Tier level. This makes planning for DPM control difficult, since it is nearly impossible to accurately define what combined DPM emission levels a working diesel machine fleet actually produces. If this condition is detected early enough, costly repairs and poor exhaust emissions can be avoided.

To overcome the problems due to diesel contamination, some mines are filtering their diesel and oil in their bulk reservoirs on a continuous basis. This is typically done through a kidney system (see Figure 21) which can both determine the ISO cleanliness value and clean the diesel tank to a pre-set value. This practice is highly advised for all operations.

![Figure 21: Kidney System example](image)

Various available technologies focus only on diesel sampling and monitoring. Similarly, sampling and monitoring of engine oil quality is another critical aspect to have in place since poor oil quality will degrade engine health and lead to increased emission levels. Figure 22 shows examples of such devices.
Contamination control spans a wider area than only diesel and includes all parts and consumables that are subject to contamination. Often dirt or dust may, for example, enter filters or oils if proper care is not taken during maintenance or repair activities. All of which can have adverse effects on the operational parameters and resulting emission levels of the engine.

17.5 ADHERE TO REQUIRED PRACTICES AND PROCEDURES

Implementing effective maintenance practices and procedures is critical to successfully maintaining a well-functioning machine that ensures that emission controls put in place are sustainable.

These include effective maintenance, engine and emission monitoring, diesel sampling, and proper systems and control measures employed to ensure adequate quality control and cost control of the repair of the machines. A good data capturing and record keeping system is also advised to ensure that any required historical information can be obtained efficiently and accurately at any point in time.

17.5.1 Sampling & Monitoring

Various operations were identified that are already using diesel with a maximum amount of 50ppm Sulphur. This decision is usually taken in order to improve the exhaust emission qualities of the fleet of engines, even though it comes at a higher cost. However, as discussed, regardless of the diesel quality purchased it is still critical to assess the actual quality before using it to fuel a diesel engine underground. As such, it is necessary to regularly assess samples of diesels and lubricants that are used, to ensure that the quality is to specification and that it is uncontaminated before being used.

Sampling is usually done at the bulk tank where diesel is delivered to the mine by the diesel suppliers. However, it is important that the point of sampling within the total supply chain
should actually be at the tank of the machine. Since this is the point where the engine obtains its diesel and other consumables (oil, lubricants) before combustion, this is the most critical point to ensure that quality is monitored and specifications achieved.

Furthermore, it is important to monitor engine exhaust gasses, through using exhaust gas analysis, to measure the content of DPM (EC & TC), hydro carbons and exhaust gases, CO, CO\(_2\), NO, NO\(_2\), etc. Exhaust gas monitoring allows an operation to develop a baseline status for the different exhaust emissions. This can be used with future planning and control to maintain acceptable levels of exhaust gasses. These records can be used for a trend analysis and to identify faulty engines. Exhaust gas analysis forms part of fault analysis on the engine itself, which is an important aspect of effective engine maintenance. Research indicated that regular exhaust gas testing has greatly assisted mining operations globally to quickly and easily identify problematic machines/engines, which may then be rectified immediately to mitigate detrimental health impacts.

Refer to the final report for the SIM 150601 project for prescribed DPM emission testing practices, with a proposed combination to be implemented between the following five methodologies:

- NIOSH 5040;
- Airtec Real-time DPM;
- Sub-micron PMC analysis;
- Electrochemical gas sensors; and
- Denuder tubes.

In summary, aspects requiring appropriate monitoring include, but are not limited to:

- Diesel quality in the tank of the vehicle.
- Diesel consumption of the machine per shift.
- Oil consumption of the machine per shift.

Additional aspects to monitor relating to engine maintenance include:

- The variation in exhaust gas qualities between service intervals in the workshop;
- Service indicators (pressure drop indicators) to indicate when air filters are blocking.

If the exhaust gas analysis indicates a deterioration of the exhaust gas quality, then further investigation to determine the root cause of the problem is required. Exhaust gas analyses typically includes tail pipe emission tests. It should be noted that it is necessary to conduct these tests while the engine is idling as well as when it is under load. For manual gearboxes, testing should include idling and quick acceleration test conditions. For loaders, lifting the bucket up against the stops will exert sufficient force from the hydraulic pump against the relief valve, which will also load the engine to some extent.

Emission monitoring through exhaust gas analyses will enable the prescribed step (Step 2) in the guideline, “Conduct Fleet Assessment”. The aim of this step is to understand what the current baseline performance is for diesel equipment within a fleet, as well as what emission levels need to be reduced. This has two purposes:
1. Understand what DPM emission levels are being dealt with in order to assess and identify the appropriate site-specific approach to reducing the levels to acceptable standards.

2. Assess whether the engine(s) performance is within the OEM standard performance specifications and if not make the required adjustments to meet these specifications again.

### 17.5.2 Maintenance

When conducting maintenance, it is critical to ensure that the OEM prescribed procedures are adhered to in order to achieve the desired quality in outcomes that lead to expected levels of DPM emissions and to the expected component/machine life. It is also important to make use of appropriately trained technicians, who are specifically trained on the practices and procedures for the specific model of engines that are in operation on the mine.

It is important for technicians to use the up to date manuals provided by the OEM as specifications of engines are often updated by the OEMs (online manuals greatly assist in this regard). If the latest manuals are not used, the engines may not be adjusted to the correct OEM specification ensuring optimum performance.

Implementing the required practices and procedures for maintenance is necessary to support sustainable execution of effective maintenance.

### 17.6 Conduct Effective Maintenance.

Effective maintenance, of new engines or retrofit devices to reduce DPM, remains critical. This will allow the diesel engines to operate at planned, defined and expected emission levels. If maintenance is not done effectively as per the necessary practices and procedures, then the baseline emission levels (e.g. at Tier 2 level), may again be exceeded and reach unacceptably high levels (e.g. at Tier 0 level or worse).

It is also important to have a maintenance management system in place that keeps a record of quality control and the completed planned maintenance of the fleet. If an accurate record keeping system and maintenance management is not used, it is possible that the maintenance schedule is not adhered to, leading to the equipment engines deteriorating and resulting in poor exhaust emissions as well as decreased performance or even breakdown.

During the maintenance services, it is important to perform an exhaust gas analysis and attend to detected defects. Whenever an engine is rejected due to unacceptable exhaust gas compositions, the technicians must assess the engine to determine the cause of the deviation and then affect the necessary repairs and adjustments. Such required repairs or adjustments may be in addition to the standard planned maintenance (i.e. consumable and part replacements). The engine will require retesting, before returning to the operations of the mine.

Although this type of restorative maintenance might seem to have a cost and machine availability implication for the mining operation, the fact that the engines will be operating at an optimum level, will result in better performance, lower diesel consumption, less in-service failures, and ultimately improved machine availability. From experience and on-site engagements, the benefits from these gains have been found to offset the costs of repairs on the engine.
Restoring the engines to the original OEM specifications is a highly important point that is often omitted. The stakeholder engagements identified some of the reasons for this omission as a lack of understanding of cause-and-effect and of engine fault analysis.

In a test conducted by the project team, seemingly clear exhaust still contained high levels of DPM. This is in contrast with a common belief that only dark smoking engines are a problem that requires an intervention and that as long as no visible smoke is observed the engine must be operating according to specification.

This observation is based on an initial test that was carried out on 17 July 2018 in collaboration with DisproTech on a Tier 2 engine, with a Saxon “Diesel-Particulate-Mass-Analyzer” and Infralyt ELD “Diesel-Exhaust-GasAnalyzer”. The tests indicated that although the exhaust seemed to be visually clear, the DPM levels were still very high (despite the engine being fitted with an OEM DPM filter). The exhaust analysis results, for Particulate Mass Concentration (PMC) for DPM and that of CO, are shown in Figure 23 for non-loaded and in Figure 24 for fully-loaded conditions. The DPM results were:

- Non-loaded: DPM = 11 mg/m³
- Fully-loaded: DPM = 52 mg/m³

These results highlight the importance of performing DPM emission testing while the engine is under load in order to identify the true DPM emission levels exhausted during operation. Note that the early spike seen in the graph corresponds to the initial acceleration of the engine to reach a set rpm (in order to test under loaded conditions). At first this acceleration produces a high amount of emissions that are not sufficiently burnt, before the process stabilises while the engine runs at a constant rpm.

**Figure 23: Results from exhaust gas analysis, indicating DPM and CO levels under non-loaded (high idle) conditions**
Figure 24: Results from exhaust gas analysis, indicating DPM and CO levels under fully-loaded conditions

The tests were done a day after the equipment was serviced, i.e. these readings are directly post maintenance. Another exhaust emission test was done after the machine was in operation for two weeks and the DPM emission levels had increased up to 134 mg/m³ under fully loaded conditions. This is shown in Figure 25.
Figure 25: Results from exhaust gas analysis, two weeks later, indicating DPM and CO levels under fully-loaded conditions

Similarly, exhaust gas was from another engine was tested pre- and post-maintenance to determine the impact on DPM emission levels from maintenance and restoring an engine back to OEM specification. For this engine the difference in DPM concentrations, (tested under loaded conditions), were:

- Pre-service: DPM = 43 mg/m$^3$
- Post-service: DPM = 21 mg/m$^3$

These results highlighted the positive impact of effective maintenance, since the DPM reduction was the result of replacing engine oil and the oil and air filters.

The harsh underground conditions that these machines operate in cause emission levels to increase within a short period post maintenance. To be able to effectively reduce emissions, a range of adequate emission control measures need to be in place and maintained.

17.7 MACHINE OPERATION TO BE WITHIN OPTIMAL OPERATIONAL ENVELOPE

Engines are designed to operate within a specific “operational envelope”, which means that the engine should not idle for long periods, nor should it be overloaded continuously in operation. In the operational envelope, the engine operates with the lowest possible fuel consumption, which will also reduce emission levels. Furthermore, the engine will provide a longer service life, which will lower the engine’s operational cost.

This may be attributed to a lack of discipline or simply to a lack of understanding of cause-and-effect, i.e. of operator behaviour on machine health and emission levels. It may also be due to mechanical issues, such as a concern that the engine would not start again after it was turned off.
It is necessary to identify the root causes leading to engines not operating within the operational envelope and to implement corrective measures. Corrective measures may range from addressing soft issues to performing the necessary engine repairs.

17.8 Knowledge and understanding relating to DPM implications

To support DPM emission control both during and after an intervention program, such as the transition guideline proposed in this report, it is necessary to ensure that employees involved in such a program have the required knowledge and understanding. This knowledge and understanding needs to include why, what and how to do things that manage the implemented control measures. This is especially true in terms of understanding cause and effect relating to DPM, i.e. what aspects or behaviour reduce or increase emission levels.

Contrary to the older generation of diesel engines, the more modern engines require more knowledge and understanding of the engine operation, the combustion process as well as the [exhaust] pollution aspects. It is therefore necessary for technicians as well as their supervisors to be trained in fault finding, contamination control, root cause analysis, etc.

Increased needs for knowledge and understanding expand beyond the requirements for the mechanics/technicians and also include machine operators. Having a good understanding of how operational behaviours and machine treatment affects component life, maintenance and repair requirements, as well as DPM emissions greatly helps with building the desired culture. Training is advised in this regard to adequately support the needs of a DPM control initiative/program.

Some key points to understand are highlighted in order to illustrate how the quality of exhaust gas from a diesel engine is affected by different factors during operation. Consider the following points:

- Whenever a diesel filter becomes blocked, this causes a flow restriction in the diesel supply to the engine. The result of this flow restriction is that the pressure at the inlet of the high-pressure pump can be too low (i.e. an elevated suction pressure), which can in turn result in cavitation and damage to the high-pressure pump. A high particle load may even lead to the filter media being damaged, which then allows dirt to enter the injectors.

- In a recent failure analysis performed by project team members, it was found that due to restrictions in the flow to the high-pressure pump, cavitation led to the failure of the cam follower rollers in the pump. This resulted in the total failure of the high-pressure pump.

- Problems at the high-pressure pump can very often also lead to problems at the injectors.

- Particle contamination and small water droplets in the diesel can also lead to damage of the high-pressure pump as well as the injectors.

- Whenever damage to injectors occurs, the operation of the injector is adversely affected. This in turn affects the combustion in the engine and results in poor exhaust quality (i.e. worse DPM levels).

- Another aspect (often overlooked) is the fact that excessively high temperatures of the coolant or of the diesel can result in injector problems.
▪ When the diesel temperature is too high, cavitation of the injector components occurs. The drastic drop in the lubricity of the diesel at the high temperatures, causes damage to the components of the injector. The result is that the spray pattern is adversely affected.

▪ A poor spray pattern can result in poor exhaust gas conditions, but can also lead to the washing away of the lubricant film on the cylinder liner. This can lead to piston seizure and catastrophic engine failure.

▪ In order to lower the diesel temperature, many of the modern common rail engines are equipped with return diesel coolers to cool the diesel down on the way to the tank. It should be noted that on common rail engines a larger amount of diesel is supplied to the injectors to facilitate its cooling. This cools diesel is then returned to the tank, where it has to dissipate the heat to the environment. In confined conditions such as underground, this is not always easily achieved and the diesel coolers are therefore installed.

▪ In cases where diesel coolers are not already fitted, it is good practice to never allow the tank of the vehicle to reach levels below 25% of the tank’s capacity. Below 25%, capacity the retention time of the diesel in the tank becomes too short and the diesel overheats, resulting in the problems discussed. Figure 26 shows an example of injector damage from overheated diesel.

▪ Whenever an exhaust gas analysis indicates that the engine is not performing to the required levels, technicians have to make use of manuals and their training to determine what is the cause of the deviation. Such a deviation could be a result of faulty or damaged injectors, worn piston rings, a faulty turbo, or poor adjustment of the engine, or other causes.

▪ Technicians must therefore apply their skills and analytical abilities to do a root cause analysis of the problem. The root cause should be identified prior to effectively making the required adjustment or replacement of components, in order to address the core issue and not simply treat the symptoms.

▪ The above does not only apply to newer technology engines, such as common rail engines or Tier 3 and Tier 4 engines, but also applies to the older generation of diesel engines.

▪ It is, for example, important for the technician to be able to accurately distinguish from the colour of the exhaust gas smoke whether it is an injector problem, a restricted inlet air filter, or worn piston rings, in order to identify an appropriate starting point for further analysis.

▪ Black coloured exhaust smoke usually indicates unburnt high temperature diesel. This may in turn be attributed to a restriction of the inlet air, resulting in insufficient amounts of air for proper diesel combustion, or it could be mal-adjustment of the injector pump (i.e. over-fuelling).

▪ White smoke in the exhaust usually indicates cold combustion. This means that the diesel is not effectively atomized to combust completely. This adversely affects the power output, diesel consumption, and exhaust gas quality of the engine.
Blue smoke in the exhaust is most often indicative of worn or broken piston rings, a faulty turbocharger, or worn valve guides. Any of these defects allow oil to enter the combustion chamber and adversely affects the exhaust pollution.

In the light of the above it is necessary for managerial and supervision level decision-makers to have the required cause-and-effect understanding of factors that affect DPM emissions as well as general engine health. It should be stressed that engine health is directly related to emission quality, which is why effective maintenance forms the foundation of any DPM emission control program. See Appendix E for more substantiating information to improve knowledge and understanding regarding engine health and maintenance.

![Figure 26: Damage to injectors due to overheated diesel](image)

17.9 APPROPRIATE SKILLS AND TRAINING

Transitioning toward reduced DPM emission levels requires that the enabling skills be in place for the required technological capability and for sustained effective maintenance. As technology advances, the requirements for skills and training changes accordingly. Artisans can no longer be trained on a once-off basis as with older technology engines. Current technology requires additional training and refresher courses for technicians to suit changes in skills requirements.

The more modern diesel engine, especially the high Tier ranges, are much more sophisticated than previous generation engines. It is important to make sure that these engines are kept at their optimum operational conditions. There are different settings on the same engine range for different applications and furthermore there are settings that differ between different types of engines. This makes it necessary to train and refresh technicians that are working on these engines, on a regular basis. It should also be ensured that they are properly trained on the specific equipment models that they have to repair and maintain.

Due to the sensitivity of the adjustments to the diesel engines, it is important that the operators, or other unqualified staff, never be allowed to change any of the settings on the injection pump or other engine settings. It is often the case that the operators require more power (often due to blocked filters retarding the engine) and they then (without authorisation) adjust the diesel pump in order to provide a power increase. This results in the deterioration of the quality of the exhaust gas and has a detrimental effect on the life of the engine since the engine will be over-fuelling, which can lead to premature engine failure.
Furthermore, the older ranges of engines only required the use of mechanical tools, the more modern diesel engines also require the use of computers (laptops for in-field use), to analyse the engine and to do the necessary adjustments. As such, it is important to train the technicians in the necessary skills required to maintain and adjust these engines as well as in basic computer literacy.

With engines becoming more sophisticated to suit growing needs (e.g. legislative, environmental and health requirements, such as emission limitations), it is more important than before to maintain the engines to the optimum standard. This necessitates that the required skills for effective maintenance should be in place. See Appendix F for more details on relevant skills, identified skills gaps, and recommendations for skills development.

17.10 INFORMATION PROVIDED BY THE MACHINE OPERATOR

An effective information feedback system should be in place between machine operators and technicians (or the broader maintenance staff). A culture should be instilled where the operators have sufficient understanding of how to do basic fault analysis and the ability to report on deviations from the baseline standard of engine operation without negative backlash.

Often the machine operator will only complain about the performance of the machine/engine when production is affected substantially. This indicates that there is a lack of effectiveness in the feedback system between the operator and the maintenance staff as well as proper understanding by operators of cause-and-effect on their machines and in detecting issues with the machines as they arise (prior to it becoming a serious hindrance).

It is important to train the operators to observe the performance of the engine and to give feedback to the maintenance technicians. This will lead to (or assist in) maintenance being conducted when required and in a pre-emptive manner.

Another important aspect is to train operators to operate the machine within its designed operational envelope. As explained earlier, long periods of idling or overloading of the engine should be prevented as this will affect engine performance, engine health and have a corresponding negative impact on emission levels.

The primary factors that an operator can report on include, but are not limited to, the following basic aspects:

- **Poor machine/engine performance.** This may be due to an unwanted engine condition such as poor adjustment or faulty injectors etc.

- **Difficulty in starting the engine at the start of the shift.** The modern diesel engine should start very easily without any difficulty. If the engine does not start easily and properly, there might be need for adjustment or repairs.

- **Engine smoking at starting conditions or when working under load underground.** The diesel engine should operate under all conditions without any smoke from the exhaust. When visible smoke is observed, this must be reported and attended to by the technicians.

- **Overheating of the engine.** Due to the many adverse effects, that overheating of the engine can have, it is very important for the operator to advise the maintenance staff if the engine tends to overheat. Often operators merely switch the engine off for a while and then continue to work once it cooled off sufficiently. Many cases have been observed where this behaviour has led to engine failure.
- Regular topping-up of engine oil. This typically indicates that further investigation is required since regular oil consumption is not within standard operating specification.

17.11 **COLLABORATION WITH OEMs**

In order to get the best service from any type of diesel engine it is important to consult with the engine supplying OEMs. Since the OEMs have the latest settings and procedures for proper maintenance of their diesel engines, it is highly advised that a collaborative relationship be maintained. The OEMs should also be consulted during the early phases of decision-making on engine replacement and/or after-treatment (retrofitted) solution options and alternatives.

A mining operation’s technicians should also be trained by the OEMs directly, to ensure appropriate skills transfer takes place. This will greatly assist in ensuring that the engines will be operated and maintained at the best operating conditions and to the required specifications.
18 APPENDIX E: SUBSTANTIATING INFORMATION FOR IMPROVED KNOWLEDGE AND UNDERSTANDING REGARDING DIESEL ENGINE HEALTH AND MAINTENANCE

18.1.1 Fuel supply

At present diesel fuel and oil is supplied by fuel/energy companies and delivered to the mines. The quality specification for diesel fuel, namely SANS 342-2016, specifies the quality of the fuel at the point of delivery, in this case at the mine.

Once the fuel is offloaded in the facilities of the mine, the fuel has to be transferred to fuelling points underground. This can happen by means of a piping system, or by fuel containers (bowsers). This can be taken into the mine through the mineshaft system or are carried down into the mine using utility vehicles. It often happens that the fuel gets contaminated in the supply chain, on its way down to the point of consumption underground. It is suggested that the fuel specification be enforced at the point where the fuel is supplied into the vehicle tank.

This aspect was discussed in detail with fuel supply stakeholders, and it was identified that the fuel companies would be willing to assist the mining companies with training of staff and inspection of facilities to ensure that only good quality clean fuel is loaded into the vehicle tanks.

It was further established that a large number of the mines still make use of 500 parts per million (ppm) sulphur diesel. The reason for this situation is that the price of 500 ppm sulphur diesel is slightly lower. According to Total, the fuel industry in South Africa can easily supply all the mines with 50 ppm sulphur diesel fuel.

It must, however, again be reiterated that there is no reason why the older range of engines such as Tier 0 and Tier 1 cannot be operated on low sulphur (50 ppm) diesel. To achieve the reduction in exhaust gas pollution that the lower sulphur fuel would ensure, it is suggested that no 500 ppm sulphur diesel should be used underground. Discussions with Total SA and Sasol indicated that although 10 ppm diesel fuel would provide more benefits as far as exhaust pollution is concerned, the availability and cost could presently be a problem in some instances.

It is, therefore, suggested that all underground mining machines should be operated on 50 ppm diesel fuel. Wherever possible, 10 ppm sulphur diesel should be considered for use.

From a maintenance point of view, the older generation of engines will not suffer when they are running with lower levels of sulphur in the fuel, but will in fact benefit, due to the longer life that can be obtained from the lubricating oil.

The newer generation of engines that are now being phased in, cannot really operate on 500 ppm sulphur diesel. The sulphur acts as a poison for the exhaust gas catalyst of the Tier 3 and higher engines. The use of 50 ppm sulphur diesel for all underground machines, would therefore be beneficial to all engines.

Regarding the other aspects around diesel, apart from the sulphur aspect, the following important points should be noted.

The development of the modern diesel engine necessitated higher injection pressures and this resulted in smaller clearances in the injectors as well as in the high-pressure pumps of the engines. These clearances are now in the region of 1 to 2 microns. Whenever particle
Contamination (typically silica dust) of the fuel occurs, the result is the suspensions of very hard silica particles in the fuel. This results in score marks that are caused on the tight-fitting components, which causes the needle of the injector as well as the control valves to become sticky.

For ease of reference, Table 31 provides the relative sizes of different particles. This illustrates the importance of good filtration.

### Table 31: Relative Sizes of Particles and Comparison of Dimensional Units: Familiar Objects

<table>
<thead>
<tr>
<th>Substance</th>
<th>Micron</th>
<th>Inch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grain of Table Salt</td>
<td>100</td>
<td>0.0039</td>
</tr>
<tr>
<td>Human Hair</td>
<td>70</td>
<td>0.0027</td>
</tr>
<tr>
<td>Lower Limit of Visibility</td>
<td>40</td>
<td>0.00158</td>
</tr>
<tr>
<td>White Blood Cells</td>
<td>25</td>
<td>0.001</td>
</tr>
<tr>
<td>Talcum Powder</td>
<td>10</td>
<td>0.00039</td>
</tr>
<tr>
<td>Red Blood Cells</td>
<td>8</td>
<td>0.0003</td>
</tr>
<tr>
<td>Bacteria (average)</td>
<td>2</td>
<td>0.000078</td>
</tr>
</tbody>
</table>

The damage on the needle and control valve, very often results in a poor spray pattern which in turn results in poor combustion of the fuel, with excessive exhaust gas pollution. Figure 27 illustrates the damage that dust particles can cause on the needle of a diesel injector.

![Figure 27: Diesel Injector Needle Damage due to Dust Particles](image)

In this particular case (Figure 27), the tractor engine was equipped with a two-micron filter before the injectors, but because of the fact that the fuel was contaminated during the handling process, the damage to the injectors resulted. The result of the injector damage, was that at 600 hours from new, all the injectors on the engine had to be replaced. Figure 28 shows the typical difference in the spray patterns of a good injector (a) compared to a damaged injector (b).
The source of the contamination was established and it was caused by the fuel being transported in a mobile tanker without any proper breathing and with a dirty nozzle also picking up dust during transport (Figure 29).

It is therefore a common practice on good functioning installations on big mines that the fuel is delivered to bulk tanks, where it is continuously filtered by a “kidney system” filter. This ensures that the fuel that is eventually delivered to the vehicles is clean. At Sishen Mine of Kumba Iron Ore and the Grootegeluk Mine of Exxaro, for instance, the diesel fuel in the bulk tanks is filtered to a 1 micron standard on a continuous basis.

It is therefore suggested that the fuel handling system on the mines be arranged in a similar way to the logistics diagram in Figure 30.
Figure 30: Best Practices on Diesel Logistics (courtesy Deutz)

To achieve good fuel quality control, it is important to have a responsible person to manage the supply chain of the fuel from the point of delivery to the point of the vehicle tank. It is further suggested that in-line filters, with a coalescent section, be installed at the dispensing point. The coalescent section will remove all water droplets from the fuel. Due to level changes in storage tanks, moist air is drawn in from the atmosphere and during temperature changes the dew point is reached and water droplets enter the fuel. Poor handling of fuel can also cause water contamination. Figure 31 indicates such filters.

Figure 31: (a) In-line Parker filter; (b) In-line Icermax filter
18.1.2 Water

A big problem that faces mines as far as diesel fuel is concerned, is the fact that the conditions underground are such that high moisture levels are quite common. One of the properties that is very important in the injection process of diesel into the engine, is the fact that the fuel must have sufficient lubricity properties.

It should be noted that all the components in the injection system can only be lubricated by the fuel, as there is no other way of lubricating components such as the pump, the injector needle, the control valve etc. For this reason, lubricity additives are added during the refining process of the fuel to ensure that the fuel will operate properly in the engine.

It should further be noted that water has no lubricity properties at all. When even a very small micro droplet of water enters the space between the needle and the tip body, or the control valve and the control valve body, scuffing and seizure occurs.

Figure 32 (a and b) shows typical damage caused by water in diesel fuel. If the droplets of water are bigger and therefore the amount of water is more than only a few micro droplets, it is even possible that the injector tip can explode (Figure 32 b).

Figure 32: (a) Needle Damage due to Water; (b) Injector Tip Damage due to Water

It is therefore of utmost importance to keep water out of the fuel under all conditions. For this reason, it is necessary to install filters with moisture removal properties. The filters shown in Figure 31 above is an example of such filters.

It is also suggested that good filtration as well as moisture removal equipment be installed on the vehicle itself, to ensure that the engine is only supplied with clean fuel without any water. The effect of the presence of water in the diesel is that the internal components of the injectors become sticky, due to scuffing damage. This adversely affects the spray pattern of the injector. The result of this poor spray pattern is that poor combustion takes place and this causes a drastic increase in the pollution of the exhaust gas.

Another aspect of a faulty injector due to stickiness of the needle and control valve is the fact that the size of the droplets injected into the combustion chamber is too big to burn out in time. In severe cases the fuel is injected in the form of a liquid jet of fuel, instead of a fine mist. The oil film on the cylinder liner is then diluted. The result of this type of spray pattern is dry rubbing between the moving piston and the cylinder liner. Piston seizure then usually occurs. The result of such a seizure is very often destruction of the engine block.

If the injected droplets of fuel are too big and the oil film on the cylinder liner is diluted to some extent, the oil in the sump of the engine eventually gets diluted as well. This dilution causes a
drastic drop in the viscosity of the oil and usually some of the bearings of the engine then fail due to the low viscosity of the lubricating oil.

Another aspect of the fuel to be considered is the temperature of the fuel that is supplied to the injectors. On modern “Common Rail” injectors, additional fuel is supplied to the injectors, purely for cooling. The amount of fuel, could be as high as 40% to 50% additional fuel.

Due to the high pressures of the system and the hot environment, the return fuel to the tank is very hot after cooling the injectors. In the case of the Delphi Euro 7 injectors, the temperature of the return fuel to the tank is 220° C. The high fuel temperature causes scuffing of the injector components, which again badly affects the spray pattern.

The high temperature of the fuel also leads to more severe cavitation in the injector, especially on the needle seat. This seriously affects the spray pattern and combustion. Several engine failures have occurred, where the piston seized due to oil being washed away from the liner walls. Figure 33 gives an indication of the seriousness of the problem and the result on the engine.

![Figure 33: Example Failed Engine Parts](image)

It is therefore often necessary to install fuel coolers to cool the fuel before it is returned to the tank. It is furthermore recommended that the machines should not be operated with less than 25% of fuel in the tank. The fuel must cool down further in the tank and if the tank level is below 25%, then the retention time in the tank is too short and the fuel will gradually heat up until problems occur. A vehicle should never be allowed to run until the tank is empty, as damage will definitely be caused.

In light of the above it is of the utmost importance to ensure that the injectors remain in a good condition. One of the ways to achieve this is to supply the engine with cool, good clean fuel, without any water contamination.
Another aspect to consider, is the fact that when combustion does not take place properly and completely, the engine normally suffers from a loss of power output. This results in the operator putting his foot harder down on the accelerator pedal and this causes an increase in the fuel consumption of the machine. It is therefore vital to ensure that the combustion in the engine takes place correctly and efficiently, to ensure the biggest output from the engine and the lowest pollution levels. This is achieved by maintaining the machines according to the OEM prescribed standards, as well as by considering the additional factors covered in this report.

18.1.3 Diesel Additives (Additised Diesel)

The fuel that is refined and produced by the refineries requires some additional additives (referred to as additised diesel) to ensure that the fuel fully complies with the specification and requirements of the engine. One of the common additives is a lubricity additive, to ensure that all the components in the injection system are properly lubricated during the functioning of the engine. Other additives are used to prevent oxidation of the fuel, as well as to limit the foaming of the diesel fuel when it is handled etc.

Apart from the necessary additives to meet the specification, additional additives include a cleansing additive that are often used to prevent internal diesel injector deposits (IDID), which can in time adversely affect the functioning of the injector. Due to the fact that these additional additives cost money, some of the mines are using fuel that does not have the additional additives. On the older generation of diesel engines, it is possible to get away without the use the additives for some time.

In the case of the modern common rail diesel engine, however, the build-up of IDID becomes a serious problem. In this regard, please refer to the article in the SAE journal by the Delphi injection company that describes the formation of these deposits in detail.

In a recent failure analysis, it was found that due to the build-up of deposits on the inside of a high-pressure common rail injector, the injector started malfunctioning and the end result was that the engine failed catastrophically. The modern high-pressure common rail injector uses a control section, which is activated by a solenoid from the engine management system. This control valve then regulates the flow to open and close the needle valve and facilitate injection. This control valve also uses high pressure fuel to close the valve. In modern common rail systems, it is not uncommon for such an injector to inject fuel four to six times or more, per engine cycle. Figure 34 illustrates the operation of the injector.

11 Online link to article
In the failure analysis, referred to previously, internal injector deposits had built up on the inside of the injector and caused the control valve as well as the needle to become stuck. Figure 35 illustrates the excessive build-up of deposits on the inside of the injector, as well as the destruction of the engine.
The engine shown in Figure 35 was totally destroyed. In the replacement engine, fuel with an additional additive to specifically clean the insides of the injectors was used. The engine has since done several thousand hours, without any more problems.

After experiencing several engine problems and injector failures on their big tractors, one of the major tractor companies is now insisting that farmers use the same type of additive in their fuel, for the cleaning of the injectors on a regular basis to ensure proper functioning of their engines.

It is therefore recommended that only additised fuel be used because several of the high compression common rail engines are already in-service underground. The majority of the engines in use underground are still Tier 1 and 2 and as such may not directly benefit as much from the additives. The additising is however essential for the higher tiers of engines that are entering underground service. The additised fuel will assist in keeping older generation injectors clean.

While additised diesel not only has benefits, but also is in some sense a necessity, it should be clearly noted that this report refers to additives added by the fuel refineries and contained within the fuel supplied. Additional after-market additives that can be obtained should be
carefully evaluated through critical testing on their performance and impact. While good aftermarket additives are available, there are also products that lead to detrimental impacts on the engine that could result in negative mechanical as well as emission consequences.

**18.1.4 Filtration**

The aspect of fuel filtration was discussed in preceding sections. It must however be stressed that proper filtration on board the vehicle, of the fuel, air and lubricating oil is of the utmost importance. To improve the lubricating oil condition, Sishen Mine of Kumba Iron Ore, has fitted additional filtration for oil and fuel in addition to OEM filters on the mining vehicles. The oil is filtered in the bulk tanks by means of a “kidney system” to about 2 micron cleanliness. Then apart from the normal oil filters that the OEM prescribes, additional oil filters are installed on the engine in the vehicle.

The fuel is also filtered in bulk by a “kidney system” and then additional filters are installed on the vehicle with 1-micron filtration capacity. The result of the lube oil filtration, is that the engine wear is drastically reduced. The extent of the reduction is such that some engines on the big dump trucks, the crankshaft was returned to service after 52 000 hours, still in standard condition, without regrinding. It would then do service for another 26 000 hours.

In the case of a wheel dozer on the Sishen Mine, the OEM suggested engine overhaul after 15 000 hours. Due to the positive oil analysis tests, the engine was run up to 28 000 hours, before it was stripped. The condition of this engine was such that it could have easily done another 5 000 or more hours. In this regard refer to the paper by Mr Piet Hoffman from Sishen Mine, delivered at a conference of the SA Institute of Tribology¹².

The filtration of the inlet air is also of the utmost importance for the proper operation of the diesel engines underground. When the air intake of the engine is not filtered properly, airborne dust particles enters the engine and this causes excessive wear on the cylinder liners and pistons rings. Due to the fact that the dust particles become trapped in the oil film on the cylinder liner, a grinding paste is formed and the piston rings are worn away rapidly. Some of the dust that got trapped in the oil film also contaminates the lubricant oil in the sump of the engine and the particles cause excessive wear on the bearings and crankshaft.

As far as exhaust gas pollution is concerned, the fact that the rings wear away, causes poor sealing of the piston rings, which lowers the compression and increases the blow-by past the piston rings into the sump of the engine.

Another aspect is that some of the lubricating oil then starts to move to the top of the piston and gets burned during the combustion process. This lubricating oil does not burn properly like diesel and this poorly burnt lubricating oil forms a smoke which is exhausted into the working atmosphere underground. If the filter on the other hand gets blocked, the air flow through the filter to the engine is restricted and the engine is supplied with inadequate supply of air.

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¹² [Online link](#) to conference programme.
The smaller amount of oxygen available in the combustion process, then causes the combustion not to be complete and a higher fraction of hydro carbons is exhausted through the exhaust system. This further pollutes the atmosphere underground. It is therefore an absolute necessity to only use good quality filters on the air, fuel and lubricating systems of the engines.

A fact that is not generally known is that these filters deteriorate over time and deteriorate faster when the storing conditions in the stores of the mine is not correct. These filters must never be exposed to high temperatures for long periods, otherwise the filter media becomes brittle and with the pulsating flow of the engine, the air filter paper can start forming cracks which would ruin its filtering function.

18.1.5 Cooling System

A diesel engine is designed to operate at a constant temperature of the coolant liquid. This temperature is usually in the region of 80 to 95ºC. A thermostat is installed in the cooling system to keep the coolant temperature constant even under different loads on the engine. If the coolant temperature should increase higher than the designed value, a few engine defects can develop.

In the first instance, the pistons would expand more than the block of the engine and would start rubbing and scuffing on the cylinder liners. This usually smears over into the ring band of the piston, which seriously affects the sealing capacity of the piston rings. The result of such sticky piston rings is that the compression is now lower than it should be and proper fuel combustion does not take place. The injected fuel is however still at the same level and the unburned fuel is then exhausted with the exhaust gases. This contributes to the exhaust gas pollution mainly in the hydro carbon and carbon monoxide region of the gases.

The high temperatures of the cylinder head of the engine, due to the occurrence of overheating, also adversely affects the injectors of the engine. The needles as well as the control valves become sticky and the injection process is seriously impacted.

The high temperature of the engine due to overheating also affects the lubrication of the engine. Due to the higher temperature the viscosity of the lubricating oil drops drastically and the oil film thickness in the bearings decreases dramatically. The result of this is that contact occurs between the white metal of the bearings and the journal of the crankshaft. The end result is usually seized or failed bearings, which can often lead to total engine destruction. It is, therefore, very important to ensure that the cooling system on the engine functions properly and that overheating of the engine does not occur.

The cooling liquid of the engine should not be normal tap water, but should be properly prepared cooling liquid, which is water with the addition of several additives. The purpose of these additives is that both corrosion is prevented and that the boiling point of the water is raised above the normal boiling point of additive-free water. The higher boiling point of the liquid also helps to prevent cavitation in the engine cooling system. The coolant also fulfils the function of lubrication of the water pump etc.

The practise of filling up the cooling system with any water that can be found underground, should be seriously discouraged. The pH of the water underground is very low due to a number of reasons, one being the use of explosives in the mine and this can cause excessive corrosion. It is necessary to top up the cooling system if required with properly treated coolant. It is again repeated that overheating the engine or running it at excessively high temperatures
can affect the operation of the injectors of the diesel engine and this can also seriously contribute to the pollution from the exhaust of the engine.

18.1.6 General

Another problem that faces the mining industry is that a large proportion of the underground vehicle fleet still utilizes old generation engines, namely Tier 0 and Tier 1 etc. These engines are not electronically controlled and therefore they contribute significantly to underground air pollution. Some of these machines are so old that it does not economically warrant replacing the engines with newer generation engines. In many cases the machines are built in such a way that the newer generation of engines, with their extra peripheral equipment, will not fit into the old machine.

The number of these older generations of machines is such that the mining industry would not be able to afford to replace all these old machines at present. A solution must therefore be developed to improve the exhaust gas pollution of the older generation of machines in the immediate term. This will provide time to gradually replace these older engines with better quality diesel engines.

A further problem that often occurs on the older generation of mechanical injection systems is that operators illegally change the settings on the injection pump to increase the fuel flow and the speed of the engine, to be able to operate faster with the same machine. Although this aspect is normally frowned upon by the maintenance personnel, the practise still exists in some sections.

The fact that the injection pump settings are changed away from the OEM values, does give slightly more power, but it causes excessive fuel consumption and dramatically increases the air pollution and smoke.

Due to the wide variety of engines used in the South African Mines, the maintenance staff are not always necessarily properly trained to maintain specific engines to exact OEM standards.

There are no test facilities on the mines and especially not underground to test and verify that all the settings on the engine are to OEM specification. Engines set to correct OEM specifications will reduce exhaust gas pollution. Due to cost factors of maintenance by the OEM's, as well as the drive from the mining houses to help small and micro enterprises, maintenance work is often outsourced to small outside companies. The staff of these small companies are usually qualified artisans, but they may not have been trained to attend to specific engine maintenance requirements and settings.
19 APPENDIX F: DIESEL ENGINE TECHNICIAN SKILLS
OVERVIEW AND SKILLS DEVELOPMENT
RECOMMENDATIONS

19.1 DIESEL ENGINE MAINTENANCE: FUNDAMENTAL SKILLS

19.1.1 Maintenance Skill Levels: Overview

This section deals with the skills levels required to undertake diesel engine maintenance. Figure 36 provides a graphical representation of the route taken when developing skills and knowledge. The base of the triangle indicates the required basic education as this is the starting point of all skills development.

Thereafter it proceeds to Formal Qualifications, which would be those done after the completion of basic education, which could be at either a Grade 9 (NQF 1), Grade 10 (NQF 2/N1), Grade 11 (NQF 3/N2) or Grade 12 (NQF 4/N3) level. Included in this portion of the triangle is maintenance and engine replacement, as this is taught in the formal qualifications level. The functions that an artisan should be able to complete are indicated in the sections that refer to the NQF levels.

The OEM specific training is depicted as following on to the Formal Qualifications level. However, these two levels may run parallel. Retrofitting related skills come in at this level as retrofitting (installing after-treatment technologies) is OEM- and product-specific.

The top of the triangle represents Future Skills and deals with changes in technology. Non-diesel technologies are out of scope but are briefly discussed later in this report. Retrofitting is referred to here as well, since an OEM indicated that their current training does not provide these skills. Depending on market conditions, this may become part of future training programs, but will be highly product or technology specific.

Certain soft and technical skills have been identified as supporting skills, i.e. supplementary to the current formal qualification, that are required by artisans. These skills were highlighted in the stakeholder engagements as areas of skills gaps that the OEMs attempt to address during the OEM specific training period.
More in-depth details of these levels are discussed in the sections that follow.

19.1.2 Basic Education

Basic education encompasses all school levels from Grade R to Grade 12, and adult literacy programmes (Department of Basic Education, 2018).

The South African Education System has a number of pathways for learning, from schools to TVET colleges, the equivalencies of these pathways are described in Table 32.

Table 32: Education Level Comparison

<table>
<thead>
<tr>
<th>Grade</th>
<th>NQF Level</th>
<th>NATED (N-Lvels)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>1</td>
<td>None</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>11</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>12</td>
<td>4</td>
<td>3</td>
</tr>
</tbody>
</table>

The Grades refer to levels in secondary school, the NQF (National Qualifications Framework) level refers to the framework for the overall qualifications system and NATED (National Accredited Technical Education Diploma) refers to N-levels, which fall under the Department of Higher Education and Training (DHET).

Basic education is the foundation of knowledge enhancement and is essential for success when moving on into higher education or into vocational/occupational training.
Technical occupations require Mathematics, Communication (verbal and written English competencies) and in some cases Physical Science to be understood at a particular level in order for a learner to be successful in the next phase of training/education.

The standard and pass rates of basic education have been identified as a major issue in South Africa for years. This can be seen in Figure 37, which shows the percentage of learners that achieved a final mark of 49% and lower as well as 50% or higher for Mathematics, English and Physical Science in 2017 (Department of Basic Education, 2017). From this figure:

- Roughly 45% of learners achieved a final mark of below 50% for English;
- Roughly 78% of learners achieved a final mark of below 50% for Mathematics; and,
- Roughly 72% of learners achieved a final mark of below 50% for Science.

![Figure 37: Learner Percentage Achievement](image)
Figure 38 provides a more in-depth look at the achievement of the learners on these three core subjects for the 2017 period (Department of Basic Education, 2017).
From Figure 38 it may be noted that the majority of learners achieved between:

- 20% - 29% and 30% - 39% for Physical Science;
- 10% - 19% and 30% - 39% for Mathematics; and,
- 40% - 49% and 50% - 59% for English.

The low level of Mathematics and Physical Science within basic education is highlighted by the MQA, the SETA (Sector Education and Training Authority) for Mining, as a main supply side concern for skills, as well as access to career planning. A key problem that further aggravates this challenge is the quality of education. Even when Grade 12 has been completed, it was noted that it is difficult for people to cope with further training or education (MQA SSP, 2016). This may be attributed to the quality of the subjects taught, which is not at the correct level and the low mark required to pass.

The Minerals Council (2018), highlighted the standard of basic education and the low pass rate as an area that is not on par with the requirements of businesses within South Africa, particularly those related to the Science, Technology, Engineering and Mathematics (STEM) disciplines. It was noted that the effect of this is that people entering these academic fields do not possess the necessary basic education to succeed in higher levels of education.

OEMs also mentioned that the quality of basic education is a major challenge. To address this, they often provide bridging courses for apprentices to be successful in their apprenticeship. This contributes to the reason why OEMs create their own talent pipeline and apply their own stringent measures and assessments during recruitment.

In an effort to improve the basic education level, the MQA has undertaken interventions to assist learners in Grade 10, 11 and 12 to complete Mathematics and Physical Science, these initiatives were confirmed by the Minerals Council (2018). In addition, the MQA has also undertaken career guidance initiatives to raise awareness around the career opportunities available in technical fields (MQA SSP, 2016). The career guidance initiatives also directly address an additional challenge, as mentioned by the OEMs as well, which is that learners that are high achievers in Mathematics and Physical Science are being directed away from artisan careers.

The Minerals Council (2018), also indicated that there is concern with the level of knowledge that educators possess at these levels, which might also require a development path.

### 19.1.3 Formal Qualifications

During the engagements with the OEM stakeholders it was identified that there are particular levels of activities, for engine maintenance and repair that relate to minimum or preferred skills levels. This preferred skills level is artisan level, who may also be referred to as technicians in practice as per the preference of the company.

An artisan is defined through the method required to become one, which is, as described by the Local Government Sector Education and Training Authority (LGSETA) OFO Handbook of 2018 (Enterprises University of Pretoria, 2018), as follows:

1. The completion of a structured learning programme/qualification consisting of knowledge, practical and work experience.
2. The successful completion of a trade test (external summative assessment).
The most relevant qualifications related to diesel engine maintenance and upkeep appear to be:


2. Diesel Fitter\(^{14}\) – “Maintains, tests, repairs and rebuilds diesel motors used for generating power in marine, mining, construction, industrial and rail transport applications” (SAQA, 2016).

An additional qualification identified by an OEM is that of the Heavy Equipment Mechanic\(^{15}\) who “Maintains, diagnoses faults in and repairs heavy equipment such as earth moving or mining equipment, including engines, mechanical parts and hydraulically or electrically powered systems” (SAQA, 2016).

These qualifications are artisan qualifications and for that reason the word artisan will be used for the duration of this report.

In order to become an artisan and/or technical expert it is necessary to undertake formal training in the relevant area. As mentioned earlier, in order to become an artisan, a structured learning programme must be undertaken followed by a trade test. It is also possible to follow a technical career through learnership training and part qualifications.

As mentioned by the Minerals Council (2018), the mining companies have centralized training centres in place to attempt to address the artisan skills shortages. Work readiness and soft skills remain in short supply from learners leaving the public training structure. Efforts such as the Anglo-American South Africa Education Programme attempts to improve on the levels of basic education. The dictum of the programmes is to re-imagine mining to improve people’s lives and shows the level of involvement the stakeholders are starting to take in this level of education (Mbazima, 2018). The thinking is that skills alignment and improvement should already start at an early age – creating a strong foundation to build on for the future.

This level of study is regulated by the QCTO, MQA and merSETA (which is the SETA for Manufacturing, Engineering and Related Services). In this instance, these stakeholders will vary according to the qualification being undertaken. These stakeholders also work hand-in-hand to achieve the skills development priorities within the country. Table 33 highlights their functions.

### Table 33: Government Stakeholders Occupational Qualifications

<table>
<thead>
<tr>
<th>Stakeholder</th>
<th>Type</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCTO (QCTO, 2018)</td>
<td>Quality Council</td>
<td>▪ Establishment and management of the Occupational Qualification Sub-Framework (OQSF)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>▪ Occupational qualifications development and maintenance</td>
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<td></td>
<td></td>
<td>▪ Accreditation of skills development providers and assessment centres</td>
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<td></td>
<td></td>
<td>▪ Assessment</td>
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<tr>
<td></td>
<td></td>
<td>▪ Certification</td>
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<tr>
<td></td>
<td></td>
<td>▪ Research and knowledge development</td>
</tr>
<tr>
<td></td>
<td></td>
<td>▪ Stakeholder management and advocacy</td>
</tr>
<tr>
<td></td>
<td></td>
<td>▪ Develop a skills plan</td>
</tr>
<tr>
<td>MQA,  merSEITA (NSA, 2015)</td>
<td>SETA (Sector Education and Training Authority)</td>
<td>▪ Implement its sector skills plan</td>
</tr>
<tr>
<td></td>
<td></td>
<td>▪ Promote learning programmes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>▪ Register agreements for learning programmes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>▪ Perform functions delegated to it by QCTO</td>
</tr>
<tr>
<td></td>
<td></td>
<td>▪ Disburse levies collected from employers and their sector</td>
</tr>
<tr>
<td></td>
<td></td>
<td>▪ Liaise with National Skills Authority on policy, strategy and sector</td>
</tr>
<tr>
<td></td>
<td></td>
<td>skills plan</td>
</tr>
</tbody>
</table>

The SETA's (including the MQA) are responsible for assisting in the implementation, and prioritisation, of the required skills training through grant pay-outs and the development of the Sector Skills Plan (SSP) from the Workplace Skills Plan (WSP) data. It is essential that organisations submit their WSP's to allow correct identification of skills priorities.

The QCTO is the responsible body for artisan development as well as the development and quality assurance of artisan qualifications. It is for this reason that a formal consultation was held with the QCTO and not with the MQA. The SSP of the MQA was utilised to discuss skills availability and particular skills challenges as this type of research falls within the responsibility of the MQA.

There is currently a transition period for qualification amendments. During this time, historical qualifications will slowly be phased out and replaced with realigned occupational qualifications. Currently the historical qualifications have been renewed for a further 5-year period, but it is envisioned that within the next 5 years all of these qualifications will be removed.

The QCTO recommends that all new learners should be registered on the realigned occupational qualifications. This process is part of the movement of quality assurance, and curriculum and qualification development from the SETA’s to the QCTO for occupational qualifications.

The historical qualifications fall into four categories (QCTO, 2018):

1. Unit standard based qualifications.
2. Non-unit standard based qualifications (outcomes based).
3. Provider based qualifications.
4. National N Certificate (N4-N6) and National Diploma.

The process of realignment is described as follows by the relevant QCTO pamphlet reproduced in Figure 39.
The realigned qualifications will differ from the historical qualifications as they will now consist of three components (Realignment of historically registered qualifications into occupational qualifications, 2018):

1. Knowledge/theory;
2. Practical skills; and,
3. Work experience.

There are no restrictions related to industry requesting changes and/or updates to qualifications. All requests will be considered; however, the change/update would need to be sufficient to allow for the updating of a qualification.

During the engagements with stakeholders, as mentioned in step 3 of the realignment process above, the QCTO engages with industry, training providers and industry experts to ensure that the qualification development process is inclusive and relevant.

This change to qualifications is essential as during the engagements with the OEMs it was highlighted that the current qualifications do not address the requirements in terms of practical and workplace experience. Furthermore, learners do not have sufficient exposure to skills such as proper tool usage.

The Minerals Council (2018) discussed the concept of ‘modules for employability’ as due to the expansion and contraction of the sector there is constantly a change in the demands for skills. This can only be done if there is a clear understanding of what makes artisans unemployable.

The MQA SSP Update of 2016 contains a section on the employability of graduates which had the following findings:
1. Graduate artisans are not work-ready as they do not have sufficient knowledge and experience in new technology, their practical training is inadequate and workplace experience is too generic.

2. Non-mining graduates lack Mining and Minerals Sector (MMS) related experience. The realigned qualifications are, however, now more generic in order to improve cross-sectoral employability of artisans. A potential effect on industry is that organisations will have to do increased industry, company and/or product specific training to align artisans to their needs. This has already been identified by the MQA as per point 2 above.

During the discussion with the Minerals Council (2018) it was suggested to develop skills programmes that can be implemented to top-up the skills required for the occupation in relation to industry requirements. These types of programmes would be done at the company specific training level.

Even from an OEM view point, they might develop technology that requires specialised training and the reality is that public institutions may not be aligned and equipped to deliver on these programmes. The term used is that of blended learning, and not just in the manner of delivering education/training programmes, but to have skills programmes that are not traditionally aligned to a single occupation but rather to a mix of occupations (i.e. a mechanic also learning about digitisation/electronics). There was also the suggestion to look into a mixed trade approach, where the foundations of various trades are overlapped or combined.

The QCTO, together with the relevant stakeholders, have realigned the Diesel Mechanic (see Table 34), Diesel Fitter (see Table 35), and Heavy Equipment Mechanic (see Table 36) qualifications.

These realigned qualifications have a number of modules in common and each has a certain number of specialist modules. Those modules that are specific to each qualification are highlighted in each table.
<table>
<thead>
<tr>
<th>Qualification</th>
<th>Knowledge Modules</th>
<th>Practical Skills Modules</th>
<th>Workplace Experience Modules</th>
<th>Exit outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NQF Level 2</td>
<td>NQF Level 3</td>
<td>NQF Level 4</td>
<td>NQF Level 2</td>
</tr>
<tr>
<td>Diesel Mechanic (Qualification ID: 97592)</td>
<td>Work place fundamentals</td>
<td>Vehicle, equipment and propulsion systems</td>
<td>Advanced vehicle and equipment systems</td>
<td>Work safely and respond to emergencies</td>
</tr>
<tr>
<td></td>
<td>Foundational concepts of mechanics</td>
<td>Electrical systems and basic electronic, hydraulic and pneumatic principles</td>
<td>Problem solving and engine optimization</td>
<td>Use tools and equipment</td>
</tr>
<tr>
<td></td>
<td>Vehicle and equipment fundamentals</td>
<td>Cut and join metals</td>
<td>Remove, test, repair and relift engines and vehicle components</td>
<td>Diagnose and repair electronically controlled vehicle systems</td>
</tr>
<tr>
<td></td>
<td>Basic engine systems</td>
<td>Remove and install mechanic components (Gaskets, seals, bearings and locking devices)</td>
<td>Repair processes for vehicle sub-systems</td>
<td>Diagnosis and repair hydraulic and pneumatic systems</td>
</tr>
</tbody>
</table>
Table 35: Summary - Diesel Fitter (Qualification ID: 98822) (QCTO, 2018)

<table>
<thead>
<tr>
<th>Qualification</th>
<th>Knowledge Modules</th>
<th>Practical Skills Modules</th>
<th>Workplace Experience Modules</th>
<th>Exit outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NQF Level 2</td>
<td>NQF Level 3</td>
<td>NQF Level 4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vehicle, equipment and propulsion systems</td>
<td>Advanced vehicle and equipment systems</td>
<td>Work safely and respond to emergencies</td>
<td>Dismantle, assess and reassemble diesel engines and engines sub-assemblies</td>
</tr>
<tr>
<td></td>
<td>Foundational concepts of mechanics</td>
<td>Electrical systems and basic electronic, hydraulic and pneumatic principles</td>
<td>Problem solving and engine optimization</td>
<td>Use tools and equipment</td>
</tr>
<tr>
<td></td>
<td>Vehicle and equipment fundamentals</td>
<td>Cut and join metals</td>
<td>Diagnose and repair electronically controlled vehicle systems</td>
<td>Engine repair and commission processes</td>
</tr>
<tr>
<td></td>
<td>Basic engine systems</td>
<td>Remove and install mechanic components (Gaskets, seals, bearings and locking devices)</td>
<td>Work with automotive and electronic components</td>
<td>Work with fluid components</td>
</tr>
</tbody>
</table>
## Table 36: Summary - Heavy Equipment Mechanic (Qualification ID: 97582) (QCTO, 2018)

<table>
<thead>
<tr>
<th>Qualification</th>
<th>Knowledge Modules</th>
<th>Practical Skills Modules</th>
<th>Workplace Experience Modules</th>
<th>Exit level outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NQF Level 2</td>
<td>NQF Level 3</td>
<td>NQF Level 4</td>
<td>NQF Level 2</td>
</tr>
<tr>
<td>Work place fundamentals</td>
<td>Vehicle, equipment and propulsion systems</td>
<td>Advanced vehicle and equipment systems</td>
<td>Work safely</td>
<td>Dismantle, assess and reassemble heavy equipment diesel cylinder heads and sub-assemblies</td>
</tr>
<tr>
<td>Foundational concepts of mechanics</td>
<td>Electrical systems and basic electronic, hydraulic and pneumatic principles</td>
<td>Problem solving and engine optimization</td>
<td>Use tools and equipment</td>
<td>Dismantle, assess and reassemble heavy equipment power train systems</td>
</tr>
<tr>
<td>Vehicle and equipment fundamentals</td>
<td></td>
<td></td>
<td>Remove and install mechanic components (Gaskets, seals, bearings and locking devices)</td>
<td>Remove, test, repair and refit heavy equipment components and parts</td>
</tr>
<tr>
<td>Basic engine systems</td>
<td></td>
<td></td>
<td>Work with electrical and fluid power components</td>
<td></td>
</tr>
</tbody>
</table>
19.1.4 OEM Specific Training

In general, there are Basic, Intermediate and Advanced levels of maintenance practices. In some cases, the OEMs prefer to undertake as much as possible of the maintenance themselves. The reason being that maintenance is a revenue stream for their organisation.

However, product specific training is provided to clients that have purchased machines from the OEM on a basic and/or intermediate level.

In addition, anyone that works on any engine would need to make use of the manual that is provided by the OEMs. This is tracked by the OEM for their own staff that conduct maintenance activities for clients.

OEMs also provide specialised training to their apprentice artisans during their development and throughout their careers.

19.1.4.1 Product Specific Training for Clients

Every OEM with whom engagements were held indicated that they undertake product specific training.

One of the OEMs indicated that those attending the product specific training should have a technical background, in this case specifically Diesel Fitter or Diesel Mechanic. This may vary, but it is generally an artisan. Whilst this is quality controlled by the OEM in terms of their own staff, it is not policed in terms of client staff as this is considered to be the client’s responsibility.

Assessments are undertaken after every course and there is a minimum percentage required to obtain a pass mark. If the mark is achieved then a certificate of competence is provided, if not, a certificate of attendance is provided to the client staff.

Refresher courses are also provided by some of the OEMs, one OEM mentioned it as being every three years. Whilst a different OEM indicated that they utilise an online system that indicates a level of competence that slowly declines over time and is improved again with every course that is successfully completed.

In some cases, OEMs provide free audits on client machinery that are within warranty. They also provide feedback on the quality of the maintenance work conducted by the client.

19.1.4.2 OEM Staff/Artisan Product Specific Training

As OEM apprentices progress through their formal training they are allowed to undertake more complex tasks and activities. This is typically performed under supervision before the apprentice is qualified. Once qualified, the artisans will require ongoing product training as the products develop and change and as new products and technologies are introduced.

Figure 40 provides further information on the relationship between formal qualification training and the job functions.
NQF Level 2 is the first year of the artisan training and teaches skills that allow the job function of engine maintenance.

NQF Level 3 is the second year of training and teaches skills that allow the job function of engine replacement.

NQF Level 4 is the third year of training and teaches skills related to electronics and advanced systems. The skills required to undertake the job function of retrofitting is not covered by the formal qualification curriculum and would need to be done by the OEM as part of OEM specific training.

More than one OEM indicated that there are gaps in certain technical and soft skills. These skills are inadequately covered in the artisan qualifications and OEMs find that they have to address the gap to ensure competence.

The use of more generic qualifications creates a further gap in terms of industry specific training, which would need to be addressed by every organisation individually.

**19.1.5 Future Skills Requirements**

During the engagements with the OEMs the question of changing skills as the Tier levels progressed was a point of discussion. Overall the OEMs indicated that there is not a major skill change required from Tiers 0 to 3, except for increased requirements in electrical and electronic skills. In terms of Tier 4 level, it was indicated that a higher level of electronic skills is required. However, as indicated by the OEMs, Tier 4 is currently not promoted in South Africa due to the poor quality of fuel as a result of contamination at some point in the supply chain.
Alternative fuel/energy sources are another aspect to be considered when discussing DPM reductions and was also briefly mentioned by the OEMs. This will not be discussed in detail in this report as it is out of scope of this project, however, the changing skills requirements for non-diesel technology should be considered by industry and all relevant stakeholders.

The gaps in soft, technical and industry skills that are mentioned in the previous section also form part of future skills requirements as these are not sufficiently catered for in the generic qualifications and must be addressed by every OEM individually.

19.2 DIESEL ENGINES: SKILLS AVAILABILITY

19.2.1 Maintenance Skills

The skill set of a Diesel Mechanic and Diesel Fitter are cross-sectoral, meaning that these skills are not confined to one sector. As a result, it was determined that in order to maintain due diligence it would be essential to consult the SSP of both the MQA, and merSETA, for a skills availability comparison.

The SSP is a research tool utilised by all SETA’s to determine skills needs and priorities within South Africa. It is based on the information provided by companies in the WSP’s that are submitted to the SETA’s on an annual basis.

According to the MQA 2017/18 SSP update, the occupation of Diesel Mechanic has been indicated as “hard to fill”. This means that employers struggle to find suitable candidates. Challenges typically include scarcity, geographic location, employment equity criteria and industry attractiveness (where the mining industry is particularly deemed as an unattractive industry by job seekers). For Diesel Mechanics, the specific reason given for the deficiency is the gap in electrical knowledge and updated technology (MQA SSP, 2016).

The merSETA SSP update of 2017/18 utilises higher level categories when discussing hard to fill occupations, which makes a direct numerical comparison difficult. However, Diesel Mechanic is listed in the top 10 scarce skills (merSETA SSP, 2017).

The merSETA SSP update of 2017/18 does not list the occupations of Diesel Fitter and Heavy Equipment Mechanic as scarce occupations.

The OEMs indicated that, in general, they create their own skills pipelines through internal apprenticeships. This approach aims to address the stated low availability of skills. The low availability was not necessarily attributed to a low labour supply alone, but also to poor educational standards, and a lack of workplace and/or practical exposure.

This self-creation of a talent pool allows the OEMs to manage the quality of the apprentices from an early stage and, by using intensive recruitment and screening processes, to ensure that attracted talent are more likely to cope and succeed. This induces lower turnover rates, which was another challenge highlighted by the OEMs.

In some cases, the development of the talent pool starts as early as Grade 10, with the training focus placed on mechanical capability and skills.

19.2.2 Retrofit Skills

The OEMs were asked to indicate the ability of their employees to perform retrofit (exhaust after-treatment) installations. These skills are not covered in the general qualifications. The overall indication was that company and product specific training would be required to conduct these tasks. It was highlighted that an apprentice in their final year would only be allowed to
do engine replacements and retrofit installations under supervision. Furthermore, all staff (qualified or apprentice), would need to make use of the product specific manuals for guidance.

Some OEMs prefer to only undertake advanced activities, such as major engine repairs and replacements, and leave the basic and intermediate maintenance practices to the client.

19.3 DIESEL ENGINE MAINTENANCE: SUPPORTING OR ENABLING SKILLS

Beyond the skills and qualifications discussed so far, stakeholder engagements highlighted that there is need for other skills that are not sufficiently covered by existing education and training. These skills were classified as ancillary skills that are necessary to support or enable the formal qualifications and training. The following sections will discuss these skills requirements, that are recommended for development in support of effective maintenance and ultimately in support of an effective DPM emission control programme.

19.3.1 Technical skills

The OEMs indicated that there are specific technical skills, those skills that are required to perform specific tasks related to a job/function, that are essential to effective maintenance practices. These skills are not always part of a graduate’s or client staff member’s skill set.

The technical skills, that were identified as important for effective maintenance and that are not sufficiently covered by the basic education, formal qualifications, or necessarily sufficiently covered by OEM specific training, can be grouped into the areas listed in Table 37, which is a consolidation of all stakeholder feedback.

<table>
<thead>
<tr>
<th>Skill</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fault Finding</td>
<td>Determining the cause of an engine problem/failure. Refer to appendix A for a practical example.</td>
</tr>
<tr>
<td>Contamination Control</td>
<td>Using methods to ensure that engine fluids are not contaminated by outside sources such as water and dust.</td>
</tr>
<tr>
<td>Problem Solving</td>
<td>Determining the solution to a problem/challenge through the use of a problem-solving technique. Root-cause analysis was mentioned specifically. There is a technical focus within the qualification but understanding the reason behind faulty machinery is still lacking. Newly qualified artisans normally might understand the maintenance and repair functions, but not the cause and effect of the entire system.</td>
</tr>
<tr>
<td>Quality Control / Assurance</td>
<td>A measure of excellence and/or being defect free and fit for intended purpose (Business Dictionary, 2018). It forms part of the module related to performance of work.</td>
</tr>
<tr>
<td>Computer Literacy</td>
<td>The ability to make use of a computer and related technology on a basic level, such as the operating system, and software (Techopedia, 2018). It forms part of the module related to workplace fundamentals.</td>
</tr>
<tr>
<td>Gross Motor Skills</td>
<td>The coordination of large muscle groups to perform technical tasks (Sciencing, 2017).</td>
</tr>
<tr>
<td>Fine Motor Skills</td>
<td>The coordination of precise muscle movements to perform technical tasks (Sciencing, 2017). This was mentioned as a further challenge, particularly with the need to move from gross motor skills to fine motor skills with the changes in technology.</td>
</tr>
</tbody>
</table>
19.3.2 Soft Skills

Soft skills, which are interpersonal and character traits, are complementary to technical skills. Table 38 lists the particular soft skills identified as essential through all of the stakeholder engagements.

<table>
<thead>
<tr>
<th>Soft Skill</th>
<th>Definition (Investopedia, 2018)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Communication</td>
<td>Creating meaning through the sharing of ideas, knowledge and feelings (Workplace communication, 2018). This is now dealt with to a certain extent in the formal qualifications. It forms part of the module related to workplace fundamentals.</td>
</tr>
<tr>
<td>Team work</td>
<td>Working together to achieve a goal (Business Dictionary, 2018). This is now dealt with to a certain extent in the formal qualifications. It forms part of the module related to workplace fundamentals.</td>
</tr>
<tr>
<td>Leadership</td>
<td>The ability to guide and influence others (TechTarget, 2018)</td>
</tr>
<tr>
<td>Supervisory</td>
<td>Overseeing an activity or person to ensure that the task is completed correctly (Collins Dictionary, 2018)</td>
</tr>
<tr>
<td>Motivation</td>
<td>Factors that create the energy and desire for individuals to undertake certain activities or behaviour (Business Dictionary, 2018)</td>
</tr>
<tr>
<td>Work Readiness</td>
<td>“The foundational skills needed to be minimally qualified for a specific occupation as determined through a job analysis or occupational profile” (ACT, 2013). Newly qualified artisans do not possess the foundational skills required for entering the workplace.</td>
</tr>
</tbody>
</table>

There appears to be a general impression of a gap in the industry of employees being committed to do quality work. It was noted by stakeholders that there is little concern for the machinery being operated, which creates a culture that is not conducive to good maintenance practices or in fact machinery operation. Addressing this through appropriate supervisory management of change practices will be crucial in order to support effective maintenance practices.

19.4 Skills Development Recommendations

Based on the knowledge obtained during this project phase and the engagements with all stakeholders, the following skills development recommendations are proposed:

- Ensure that any employee that deals with maintenance practices is trained accordingly from a formal qualification viewpoint.
- Explore the creation of a talent pipeline through academies or other training institutions.
- Investigate programmes/initiatives to improve the standard of Mathematics and Physical Science within the basic education level, this may be done as a joint venture with the MQA, within their geographic region.
- Involve industry in the development, update and redesign of qualifications that are relevant to their specific maintenance needs.
- Make allowances for apprentices, from their own academies or other training institutions, to gain workplace experience within their organisations.
- Include OEM specific training results into their performance appraisals to encourage the achievement of competence rather than attendance.
▪ Address the identified lack in supporting technical skills and soft skills in either formal qualifications or through their own (OEM or mine) training channels.

▪ Create a change initiative that is aimed at continuous improvement, employee engagement and learning.

▪ Employees that deal with maintenance should have access to manuals, which is best practice and if possible online manuals to allow for easier access, and must consult the manuals at all times, regardless of skill level.

▪ Ensure the proper use and handling of machinery and implementation of maintenance practices on machinery.

▪ Ensure the implementation of proper maintenance practices as per required intervals on machinery.

▪ The best practice model of the OEM in terms of use and maintenance is continued as far as possible once the machine is out of warranty.

▪ Undertake the required refresher courses as offered and recommended by the OEMs.

▪ Utilise a platform such as the Mining Equipment Manufacturers of South Africa (MEMSA) to create a multi-stakeholder communication forum for skills and qualification discussions.

▪ Continually investigate the potential skills development change required, should alternative energy be implemented.

▪ Integrated and systems thinking should form part of the curriculum.

▪ Investigate the development of skills programmes that can be implemented to top-up the skills required for the occupation in relation to industry requirements.

19.5 CONCLUSION: SKILLS GAPS AND DEVELOPMENT RECOMMENDATIONS

From the results contained within this Milestone report, the following can be concluded:

▪ A gap has been identified in basic education and soft and technical skills, as shown by Figure 41, which are:
  o Technical skills that are essential to effective maintenance, that have been indicated as lacking, are fault-finding, contamination control, problem-solving, quality control and computer literacy.
  o Soft skills are also essential to employee success. The skills that have been found to be lacking are communication, teamwork, leadership, supervisory and motivation.
Figure 41: Gaps identified in the skills development process

- Skills development starts from basic education, as this is the platform for all other education and training to be based upon. Currently the pass rates for Mathematics and Physical Science are very low and the standard of basic education is low. This reduces the quality of skills available and has a negative impact on the quality of maintenance practices.

- A person conducting maintenance should have some form of formal qualification to allow this person to correctly and effectively undertake maintenance practices.

- Skilled labour is not readily available to the market and OEMs implement their own initiatives and programmes to create their talent pipelines.

- The current formal qualifications in place are sufficient to qualify individuals to undertake effective maintenance from a knowledge viewpoint. However, further attention should be given to electrical and electronic skills due to changing technology and the requirements of higher tier level engines.

- Formal qualifications also require better quality practical components to prepare apprentices to be successful in the workplace and equip them with basic technical skills.

- The new occupational qualifications developed by the QCTO, and all relevant stakeholders, now identify three distinct sections of the training: knowledge, practical and workplace.

- All OEMs undertake product-specific training. This is an essential supplement to any formal education undertaken following the basic education phase. The OEMs
implement strict assessment policies and standards for successful completion of such components of training.

- A culture of continuous improvement, employee engagement, learning and change management is essential to create an environment conducive to positive maintenance practices.